

Printed Electronics: The Next Inkjet Revolution?

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Submitted to the Alfred P. Sloan School of Management  
In Partial Fulfillment of the Requirements for the Degree

**MASTER OF SCIENCE IN MANAGEMENT OF TECHNOLOGY**

AT THE

**MASSACHUSETTS INSTITUTE OF TECHNOLOGY**

JUNE 2003

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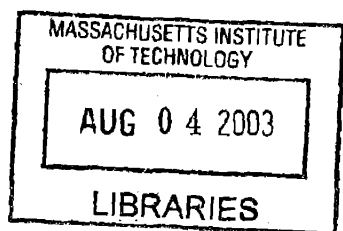
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Page 178

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## **ABSTRACT**

Inkjet printing has proven to be a remarkable disruptive technology. From its humble beginnings in 1984 it has grown to become the dominant technology for personal computer-based printing. However, after almost two decades of strong growth, the inkjet printing market is maturing. Companies large and small are now beginning to explore use of inkjet in a diverse range of new applications ranging from manufacture of next generation flat panel displays and low cost circuits to generation of biochips and fast-prototyping of 3-D objects. These new applications present existing inkjet players with exciting opportunities to leverage their knowledge and assets to exploit these new markets.

This thesis explores the opportunities for inkjet technology in two emerging industries: 1) next-generation flat panel displays based on organic light-emitting diodes and 2) low cost, disposable circuits required for products such as radio-frequency identification tags and smart cards. These are likely to be the two biggest opportunities for non-traditional applications of inkjet technology. In both cases, inkjet provides a flexible, low cost manufacturing method that is a very compelling alternative to the expensive wafer fab processing required to produce today's flat panel displays and circuits. Each of these industries is analyzed in considerable depth to provide context for assessing the disruptive potential of inkjet. The potential of inkjet to become an important enabling technology is then analyzed using ideas and frameworks from the management of technology literature.

Both organic LED displays and low cost circuits appear likely to become disruptive technologies. The best early opportunity for non-traditional application of inkjet technology appears to be in display manufacturing. Here the technology fit with inkjet capabilities is good and the strength of competing manufacturing technologies is relatively weak. Establishment of inkjet as an important production method for low cost circuits appears more challenging. The technology fit is not as good and competing low-cost technologies are further along in their development. It is recommended that existing inkjet players first address the display opportunity to gain experience with transitioning inkjet from a consumer printing technology to one well-suited to high-volume electronics manufacturing. Once this capability has been demonstrated the bigger challenges in circuit manufacturing can be addressed.

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## ACKNOWLEDGMENTS

I would like to thank my wife Katherine and daughters Valerie and Stephanie for their love and support during our one year adventure to MIT and the Boston area. They put up with this one year disruption to their lives with patience and aplomb. I hope all the studying I did while I was here set a good example for the girls !

I am grateful to Professor Weil for his role as my thesis supervisor. Our regular discussions and his thoughtful feedback on my work contributed to my learning and to a better end product. I would also like to thank my thesis reader Professor Joseph Jacobson as well as Jim Stasiak at Hewlett-Packard for valuable technical discussions and for reviewing my work.

Finally I would like to express my appreciation to Hewlett-Packard for sponsoring me to attend the MOT program. In particular I would like to thank Joe Dody and Kathy Miller for their support and encouragement.

## Table of Contents

Chapter 1 – Introduction.....	6
Chapter 2 – Management Literature Review.....	22
Chapter 3 – Inkjet Opportunities in the Flat Panel Display Industry.....	66
Chapter 4 - Inkjet Opportunities in the Low Cost Electronics Industry.....	124
Chapter 5 - Summary & Conclusions.....	166

# Chapter 1

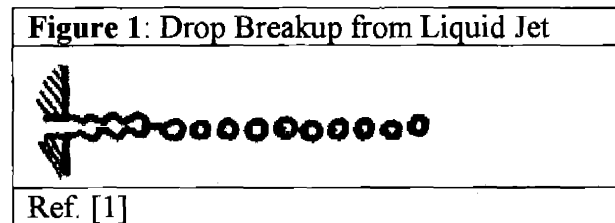
## Introduction

### Table of Contents

<b>1. Inkjet History.....</b>	<b>7</b>
<b>2. Inkjet Disruption.....</b>	<b>9</b>
<b>3. The Future of Inkjet.....</b>	<b>14</b>
<b>4. Thesis Organization .....</b>	<b>15</b>
<b>5. Inkjet Technical Background.....</b>	<b>17</b>
<b>6. References.....</b>	<b>19</b>

# 1. Inkjet History

The idea of printing with a jet of ink is not new. Many of the physical principles behind inkjet printing were understood back in the 19<sup>th</sup> century. In 1878 Lord Rayleigh studied the breakup of liquid jets into droplets upon application of a small disturbance, such as pressure wave, to the liquid. [1] See Figure 1. His discovery, however, was largely forgotten for almost 90 years. It was not until the early 1960s that Richard G.



Sweet at Stanford hit upon a means to create a practical printer based on Rayleigh's principles. [2] Sweet discovered that the droplets that formed from a continuous stream of fluid emanating from a nozzle could be electrically charged by passing the fluid stream through an electrode. Further, he found that the charge on each droplet could be controlled independently. The trajectory of each drop could thus be varied by passing the stream through a uniform electrical field; the amount of deflection of each individual drop depended upon its unique amount of charge.

The electrical field only varies drop trajectory along a vertical axis; however, by mounting the drop generator on a movable carriage that can scan across the paper horizontal positioning of the drops can also be achieved. Such an embodiment was brought to market by the A.B. Dick Company as the world's first inkjet printer.[2] IBM followed with their Model 6640 printer, which used a similar drop steering mechanism. This IBM printer was capable of printing text characters of typewriter quality.

These early products are called continuous inkjet printers because they rely on a steady stream of droplets. Only a small fraction of these drops are needed for printing; the rest are deflected away from the paper into a gutter where the ink is collected and recirculated back to a reservoir.

Continuous inkjet technology, though elegant, proved too complex to be widely adopted in computer printers. Instead, this technology found a niche in commercial labeling where it is widely used today in applications such as printing addresses on magazines and bulk mail and labeling consumer products with expiration dates, lot numbers and other data. [3] Continuous inkjet printers for commercial labeling range in price from \$15,000 to above \$50,000. [3]

Inkjet technology would require further evolution before it was ready for use in mainstream computer printing applications. This evolution began with independent and almost simultaneous discoveries by scientists at Canon and Hewlett-Packard in the late 1970s. Legend has it that in 1977 a Canon engineer accidentally touched a syringe of liquid with his soldering iron and was surprised to see a small amount of liquid ejected from the syringe as a result. [4] This accident resulted in what was perhaps the first observation of the phenomenon known as thermal inkjet.

A similar discovery occurred at Hewlett-Packard one year later. In this case an engineer was testing a metal film by zapping it with electricity. A small amount of liquid trapped beneath the film began to boil and spurted out. [5] Both companies quickly recognized that the thermal inkjet phenomenon could become the basis of an important, new printing technology and began serious, independent efforts to commercialize it.



Thermal inkjet has the significant advantage of being a “drop on demand” technology; i.e., ink drops are not emitted continuously but instead only when needed for printing. This attribute eliminates the need for additional systems to capture and recirculate unused ink.

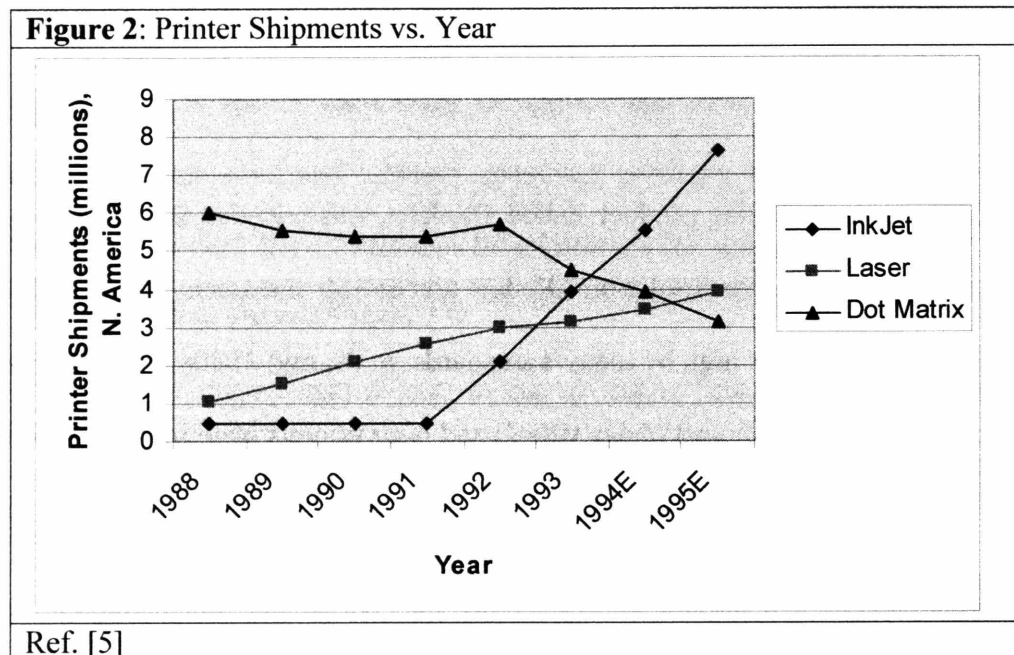
Although Canon had a one year lead in making the initial discovery and establishing early patents, Hewlett-Packard brought the first thermal inkjet printer to market in March 1984. [5, 6] Canon introduced their initial “bubblejet” printer a year later.[7]

HP’s groundbreaking product, called ThinkJet, was priced at \$495; it had just 12 nozzles and could print low resolution (96 dpi) text at 150 characters per second. [6, 8] Although the price sounds high by today’s standards, in the mid-1980s printers were very expensive. Letter quality impact (daisy wheel) and laser printers were in the \$2000-\$4000 range. [9, 10] Only lower quality dot matrix printers could be purchased for less than a thousand dollars.

## **2. Inkjet Disruption**

In spite of their attractive low price, these early inkjet printers left much to be desired. They were slow, had poor print quality and required special paper.[5] Further, resolution was poor and ink smearing and nozzle clogging were significant problems. Initial adoption was slow; the inkjet value proposition at that time was not sufficiently compelling to take much market share away from either laser or impact (dot matrix and daisy wheel) printers. See Figure 2. Nonetheless, inkjet had two very compelling secondary attributes, small size and low noise level.

Compared to impact printers inkjet units were almost silent; also, they were not much bigger than a typewriter and thus fit easily on a desktop. [11] These secondary attributes were important to users that were beginning to use personal computers and word processors and appreciated the convenience of having a printer on the desktop instead of down the hall in the computer room.



Hewlett-Packard and Canon continued to improve their inkjet products. The first color inkjet was introduced in 1987 (HP's PaintJet) and by 1990 both HP and Canon had introduced plain paper models with performance comparable to dot matrix printers. [12, 13]. As inkjet technology was improving during the 1980s, manufacturers of dot matrix printers (Seiko Epson, Oki Electronics) paid little heed. Demand for dot matrix printers was strong and margins were good; they saw no need to make major investments in "inferior" inkjet technology. Instead they focused engineering effort on improving their dot matrix products and squeezing more profits out of this maturing technology. [5, 14]

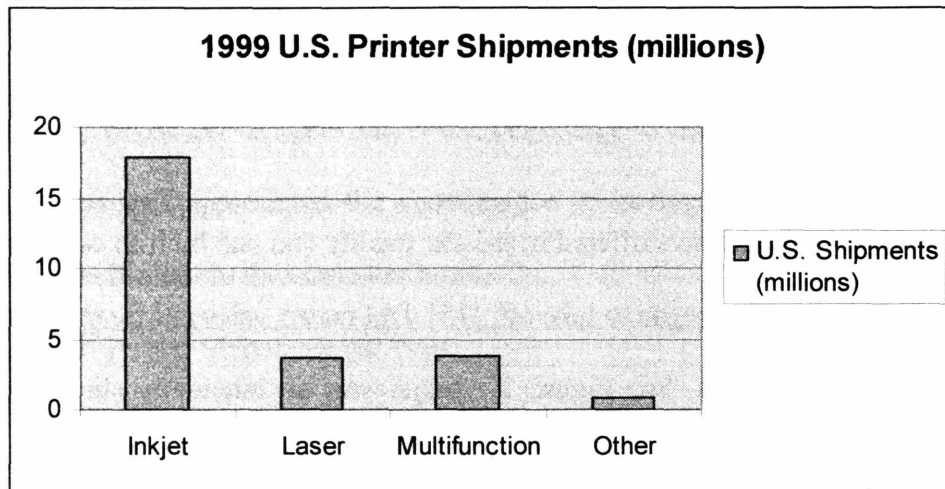
By 1990 Epson did manage to develop its own drop-on-demand inkjet technology based on a piezoelectric rather than a thermal drive mechanism. Piezo-based inkjet printers were, however, considerably more expensive than competing thermal inkjet products.

By 1992 inkjet printers offered near-laser quality text and built-in color capability for about \$1000 and sales began to take off. [15] Dot matrix sales fell for the first time in the face of this disruption. See Figure 2. Inkjet was an inherently simpler and less expensive technology that had, over time, surpassed the performance possible with dot matrix technology. The aspects of the dot matrix technology itself made it more expensive than inkjet and inherently limited resolution.

Dot matrix technology is based on a grid of electromagnetically driven wire hammers that mark the paper by striking a ribbon. The constant pounding requires rugged design of the printer chassis and carriage to maintain acceptable tolerances in the face of considerable vibration loads.[16] Inkjet printing is non-impact and thus allows for lighter, less costly printer designs. Further, dot matrix resolution is inherently limited by the spacing of wire hammers in the printhead grid (3-4 per millimeter). [2] Inkjet resolution, on the other hand, is limited only by the droplet size itself. These limitations of dot matrix technology could not be overcome by further incremental improvements.

Growth of inkjet printers accelerated throughout the 1990s as the technology made further improvements in both speed and print quality. By 1999, 68% of all printers shipped in the U.S. were inkjets. [17] Laser printers accounted for 14% and the once-dominant impact printers accounted for only 3%.[17] See Figure 3.

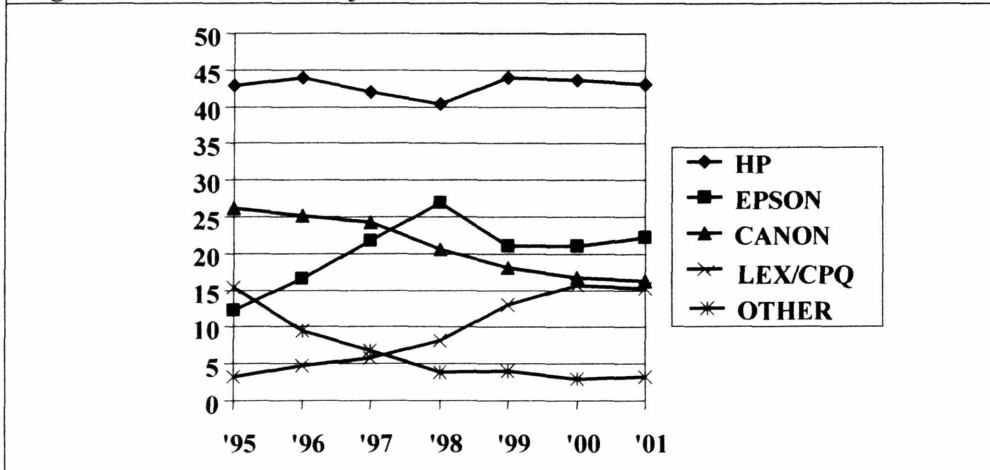
**Figure 3: 1999 U.S. Printer Shipments**



Ref. [17]

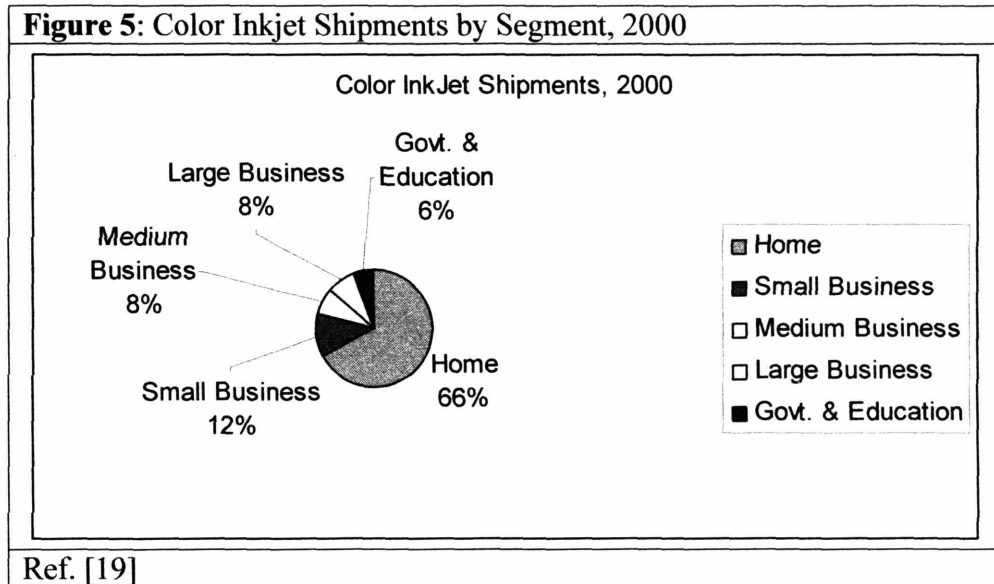
From its humble beginnings as an accidental discovery inkjet had become a huge business. In 2000, the global market for inkjet printers and supplies was \$26.6B and is forecasted to reach \$40B by 2005. [18] Revenue from ink supplies alone generated \$12.5B in 2000 and is predicted to reach \$22B by 2005. [18] Worldwide market share of the major competitors in the inkjet printing industry is shown in Figure 4. Hewlett-Packard is the market share leader; other major players include Epson, Lexmark and Canon.

**Figure 4: Worldwide Inkjet Market Share, 1995-2001**



Ref. [8]

This remarkable growth was fueled by the widespread adoption of personal computers in homes and small offices. See Figure 5. Customers buying a personal computer frequently buy a personal printer to go with it; most of the time this printer is an inkjet. For these customers inkjet offers an unbeatable value proposition of black and color printing at a low price.

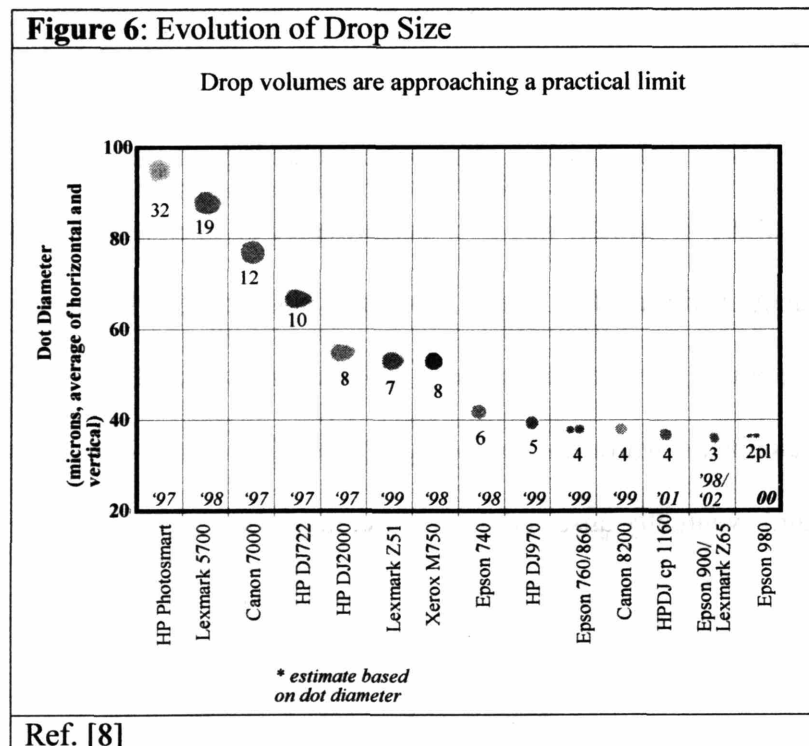


Inkjet printing was clearly a disruptive technology in the classic “Innovator’s Dilemma” sense.[20] It initially had poor performance on attributes that the mainstream market cared about (print quality, speed, smearing) but strong performance on secondary attributes (noise level, size) of interest to a new class of customers. It was thus largely ignored by incumbents while the technology gradually improved to meet mainstream requirements and eventually unseated the mature, incumbent technology.

### 3. The Future of Inkjet

Today the inkjet printing industry is itself approaching maturity. The major competitors have reached parity on most performance attributes of interest to customers (speed, print quality, etc.) and are now competing chiefly on the basis of price. This trend toward performance parity is illustrated in Figure 6 for drop size. Decreasing drop size was important to improving quality of color graphics and photos. Once the drop size was decreased below the visual threshold (about 5 picoliters), photographic image quality was realized and there was little reason to further shrink the drops, especially since doing so adds cost.<sup>1</sup> The fact that Dell has decided to enter the inkjet printer market is another sign that the industry is maturing and that inkjet printers are becoming a commodity item.

[21]



<sup>1</sup> Cost increases with smaller drop size because the number of nozzles and firing rate must be increased to maintain throughput (ink flux) requiring additional interconnects and electronics.

Although inkjet technology appears to be reaching the top of the S-curve in traditional printing applications, there are signs that this technology could become a key enabling technology in new, emerging industries. Inkjet's incredible ability to precisely meter picoliter quantities of liquid and place droplets on a substrate with an accuracy of a few microns appears to have value that transcends traditional printing applications. Expanding the notion of what constitutes "ink", opens up a variety of interesting new possibilities for inkjet. Companies, universities and national labs are investigating use of inkjet technology in such diverse applications as three-dimensional printing, biotechnology, and production of electrical, optical and MEMs devices. [22-24] The interesting question is whether or not inkjet, which proved to be a disruptive technology for traditional printing, could become a disruptive technology again in a different industry.

## **4. Thesis Organization**

This thesis explores in some depth two of the most exciting non-traditional applications of inkjet technology, next-generation displays and low cost electronics. In the case of displays, inkjet can be used to print organic light-emitting diode (OLED) materials on flexible or rigid substrates. Displays based on OLEDs appear to have the best shot at unseating liquid crystal displays (LCDs) as the dominant flat panel technology for displays both large and small. Inkjet may offer a very low cost means of manufacturing the displays of the future.

Low cost electronics refers to circuits that can be built on flexible substrates without use of traditional wafer fab processing. Production of these circuits has more in

common with printing newspapers then fabricating today's silicon chips. Inkjet technology can be used to print conducting, insulating, and semiconducting materials directly on a substrate, thus avoiding the costly lithography and vacuum processing steps usually required to make chips. Such low cost production methods could enable ultra cheap, even disposable, circuits for radio-frequency identification (RFID) tags and smart cards. Such products could revolutionize shopping, inventory management and the way we use products and services in general. Low cost electronics may also enable more affordable solar cells, displays and non-volatile storage for digital appliances.

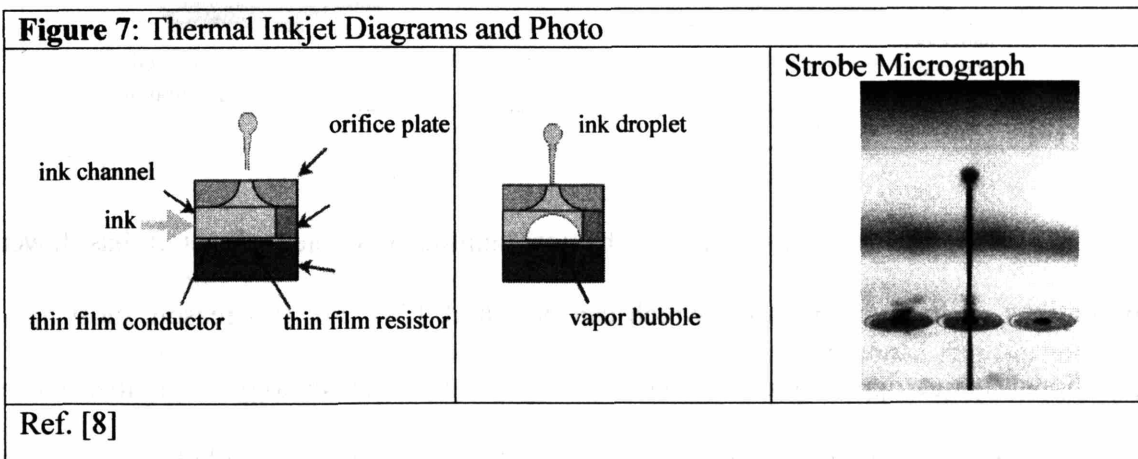
This thesis is organized into five chapters. This chapter is intended to provide some history and background on inkjet printing to set the stage for discussion of non-traditional applications of the technology. Chapter 2 consists of a review of the relevant technology management literature related to disruptive technology, technology diffusion and commercialization of disruptive technologies. Chapter 3 is devoted to inkjet opportunities in the display industry and Chapter 4 to inkjet opportunities in the low cost electronics industry. In both cases, a fairly detailed analysis of the industry and incumbent technologies is presented in order to provide context for analysis of opportunities for inkjet. Chapter 5 compares the inkjet opportunities in the two industries and assesses whether or not these opportunities are disruptive. Investment recommendations for existing inkjet players are also presented.

This chapter concludes with a short technical discussion of the two major types of drop-on-demand inkjet technology, thermal and piezoelectric. These technologies are mentioned frequently in later chapters and it is important to have a basic understanding of what they are and how they work.



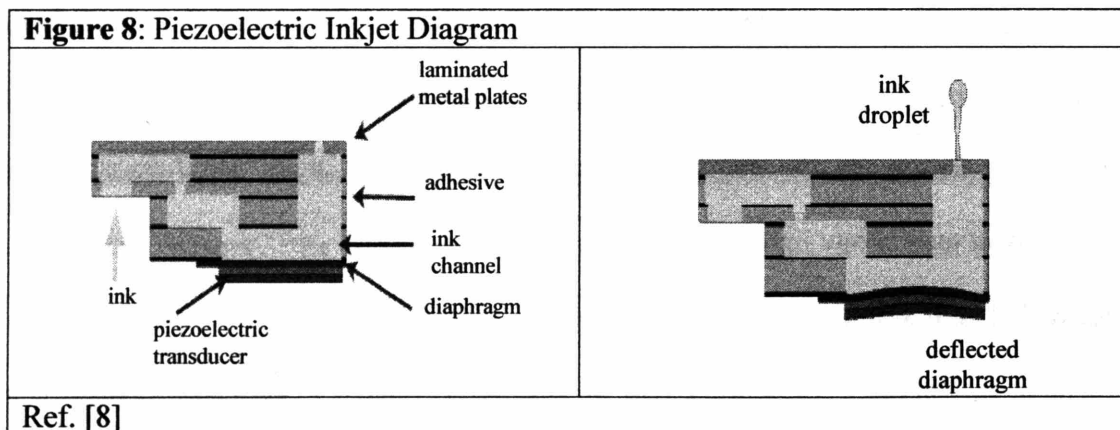
## 5. Inkjet Technical Background

Thermal inkjet is one of two types of drop-on-demand inkjet technology. Unlike continuous inkjet which requires a steady stream of droplets to be flowing at all times, drop-on-demand inkjet only ejects a drop when required for printing. There are no unneeded drops to collect and recycle. Thermal inkjet uses a tiny thin film resistor located within each nozzle to boil a thin film of ink. A narrow voltage pulse heats the resistor to above 300C in a few microseconds producing a vapor bubble in the ink.[25] The bubble expands and drives a droplet of ink out of the nozzle. As the bubble collapse it draws fresh ink into the nozzle firing chamber for the next shot. [26] There are no moving parts other than the ink itself. Drop firing frequencies as high as 18 kHz are possible with this approach. [8] See Figure 7. It is important to note that only a very small amount of liquid is boiled and that the temperature of the ejected drop itself is in equilibrium with the printhead (typically 40-60C) and is not particularly hot. With the exception of Epson, all the major inkjet competitors (HP, Canon, and Lexmark) use thermal inkjet technology in their products.



Epson's inkjet products are based on piezoelectric inkjet technology. Piezo inkjet differs from thermal inkjet in that a vibration plate connected to a vibrating piezoelectric crystal provides the energy for drop ejection. When the piezo crystal pushes the plate fluid is displaced and a droplet is forced out of the nozzle. When the crystal pulls on the plate, fresh ink is drawn into the firing chamber.[26] See Figure 8.

Thermal and piezo inkjet have different strengths and weaknesses. Thermal inkjet is less expensive to manufacture and supports higher nozzle densities. Designs with 600 nozzles per inch have already been commercialized.[8] The primary drawback with thermal inkjet is that the range of jettable liquids is limited to those that will boil on the thin film resistor and are not degraded by thermal heating. To date, thermal inkjet has been used chiefly to print aqueous fluids.



Since piezo uses a purely mechanical approach to eject drops it has fewer limitations on the type of fluids which can be jetted. [24] For this reason, most non-traditional inkjet applications to date have used piezo technology. Another piezo advantage is that it is possible to achieve variable drop size within a nozzle by varying the amount of deflection of the vibration plate. [27] Drawbacks to piezo include higher cost

and lower nozzle densities; both of these disadvantages are related to mechanical manufacturing processes which make miniaturization more difficult.

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## Chapter 2

### Management Literature Review

#### Table of Contents

<b>1. Introduction.....</b>	<b>23</b>
<b>2. Disruptive Technology.....</b>	<b>23</b>
<b>2.1 Types of Technological Innovation .....</b>	<b>23</b>
<b>2.2 Patterns of Disruption .....</b>	<b>27</b>
<b>2.3 Disruptive Technology and Industry Structure.....</b>	<b>29</b>
<b>2.4 Innovation in Nonassembled Products.....</b>	<b>32</b>
<b>3. Technology Diffusion.....</b>	<b>34</b>
<b>3.1 Adopter Categories.....</b>	<b>36</b>
<b>3.2 Diffusion of Process Innovations.....</b>	<b>39</b>
<b>3.3 Diffusion Models.....</b>	<b>40</b>
<b>3.4 Factors Influencing Technology Adoption by Firms .....</b>	<b>43</b>
<b>4. Commercialization .....</b>	<b>48</b>
<b>4.1 Challenges Faced by Incumbents.....</b>	<b>48</b>
<b>4.2 Organizational Strategies .....</b>	<b>51</b>
<b>4.3 Commercialization Strategies .....</b>	<b>55</b>
<b>5. Conclusion .....</b>	<b>59</b>
<b>6. References.....</b>	<b>61</b>

# 1. Introduction

As discussed in Chapter 1, demand mode inkjet printing has proven to be an important disruptive technology. Inkjet's unique ability to deliver minute quantities of a fluid to a substrate with very high spatial accuracy was critical to its success in printing applications and could prove to be important in other industries such as displays, low cost electronics and biotechnology. Whether or not inkjet can successfully move "horizontally" into other industries depends not only upon addressing key technical challenges but also upon technology management issues related to disruptive technology, technology diffusion and commercialization of new technologies. This chapter explores the important literature in these areas to provide context for discussion in later chapters of whether it makes sense to deploy inkjet technology in other industries and, if so, how best to go about it.

## 2. Disruptive Technology

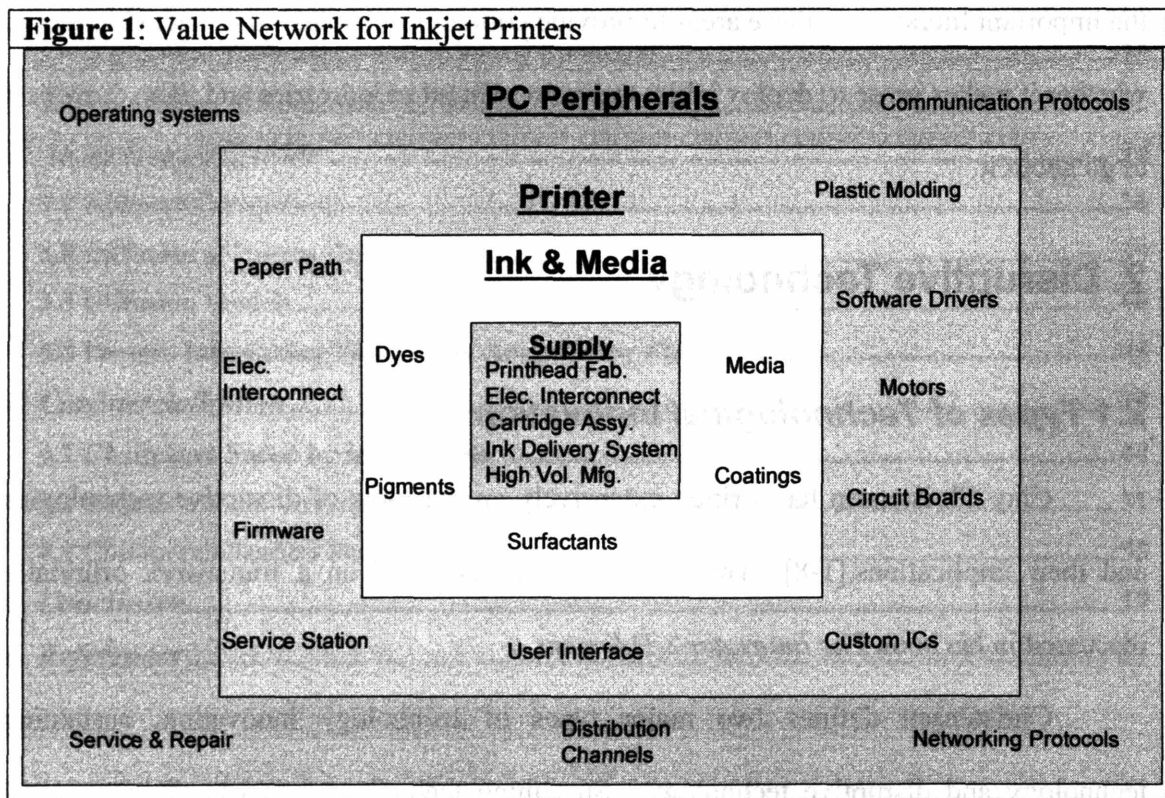
### 2.1 Types of Technological Innovation

Clay Christensen has written extensively on the topic of disruptive technologies and their implications.[1-8] This body of work is based on a framework originally discussed in his book *The Innovator's Dilemma*.

Christensen defines two major types of technology innovation: sustaining technology and disruptive technology. Sustaining technology consists of incremental improvements to an existing technology. These improvements are geared towards delivering products with better performance along established dimensions to be sold to

existing customers for higher margins. Disruptive technologies, on the other hand, are revolutionary and may initially offer neither better performance nor better margins.

Christensen suggests that disruptive technologies require a different value network or system of use than the sustaining technologies that they may displace.[9]. A value network is a system of producers and markets to which a given innovation contributes. If a new innovation does not have value within an existing value network or system of use it is difficult for incumbents to be successful. The value network can be thought of as a nested hierarchy of product architectures. Figure 1 shows how inkjet printers and supplies fit into the value network for personal computer peripherals.



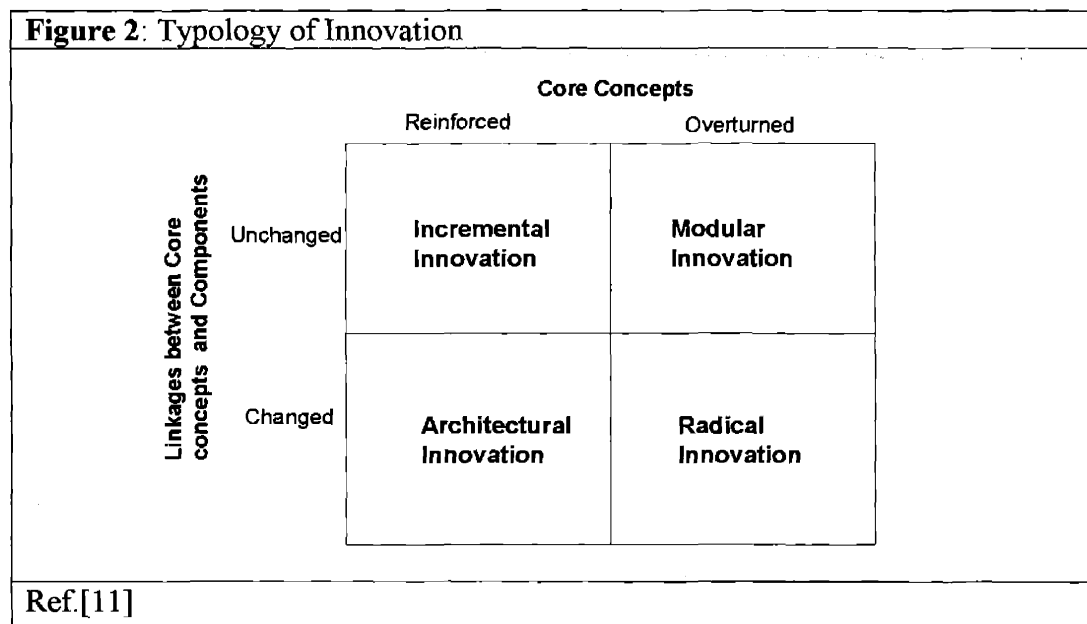
A firm must have competencies in each of the areas in the value network in order to be successful. Tushman and Anderson suggest that innovations that enhance existing competencies are typically initiated by incumbents and are sustaining innovations.[10]



Conversely, innovations that destroy or otherwise do not make use of existing competencies are typically initiated by new entrants and are disruptive innovations.

The development of non-impact printing technologies is consistent with these ideas. For example, the value network and related competencies for firms making dot matrix printers (e.g, Centronics, Okidata) is certainly very different from that in Figure 1; these firms were not the leaders in introducing non-impact technologies such as inkjet and laser printing.

Henderson and Clark take the idea of competence enhancing or destroying innovations and add to it the concept of linkages between core concepts and components to create a typology of innovation [11] See Figure 2.



The incremental and radical innovations are familiar from previous work but this typology introduces two new types of innovation, modular and architectural. Modular innovations involve new technology but don't significantly impact the relationship among key components. An example here would be the transition from analog to digital

cell phones. Architectural innovation, meanwhile, occurs when the innovation reinforces core concepts but changes the linkages among components. Competitor's architectural innovation can spell trouble for existing firms by appearing like straightforward evolution of existing designs, thus drawing no response. Subtle but important changes in the relationships between key components are often not immediately recognized until the firm is at a significant disadvantage.

An example of architectural innovation is the jet engine and its impact on the airframe industry. Jet engines did not merely displace propellers as a propulsion system but changed the relationship between the engine and airframe in important ways. Henderson and Clark point to examples of architectural innovation that occurred in the evolution of photolithographic equipment for the semiconductor industry. Here successive generations of equipment involved architectural innovations that led to changes in industry leadership. Many of the disruptive innovations in the disk drive industry that are discussed by Christensen are also architectural and not radical innovations.[6] In general, existing firms are able to successfully adopt and commercialize incremental and modular innovations, where linkages among important components are unchanged. They are much less successful with architectural and radical innovations; these are disruptive innovations which do not align well with a firm's organization and capabilities.

Fafii and Kampas have developed a practical tool for assessing a potentially disruptive technology.[12] This framework, which is intended to help incumbent firms assess competitive threats from new entrants, breaks the disruption process into six stages and identifies key factors at each stage. These six stages are foothold market entry, main

market entry, customer attraction, customer switching, incumbent retaliation, and finally, incumbent displacement. At each stage key factors are identified and rated according to the extent to which they disable or enable disruption and a weighted score is determined for each stage. The result is a pseudo-quantitative disruptiveness profile that provides a very nice summary of the potential for disruption to occur. The Fafii and Kampas framework builds upon and extends the ideas of Christensen and others to provide a useful tool that managers can use. The six stages to get to incumbent displacement make it clear that the path to success for a disruptive technology is not an easy one. Disruption can be disabled at any stage, leaving the incumbent firm at the helm.

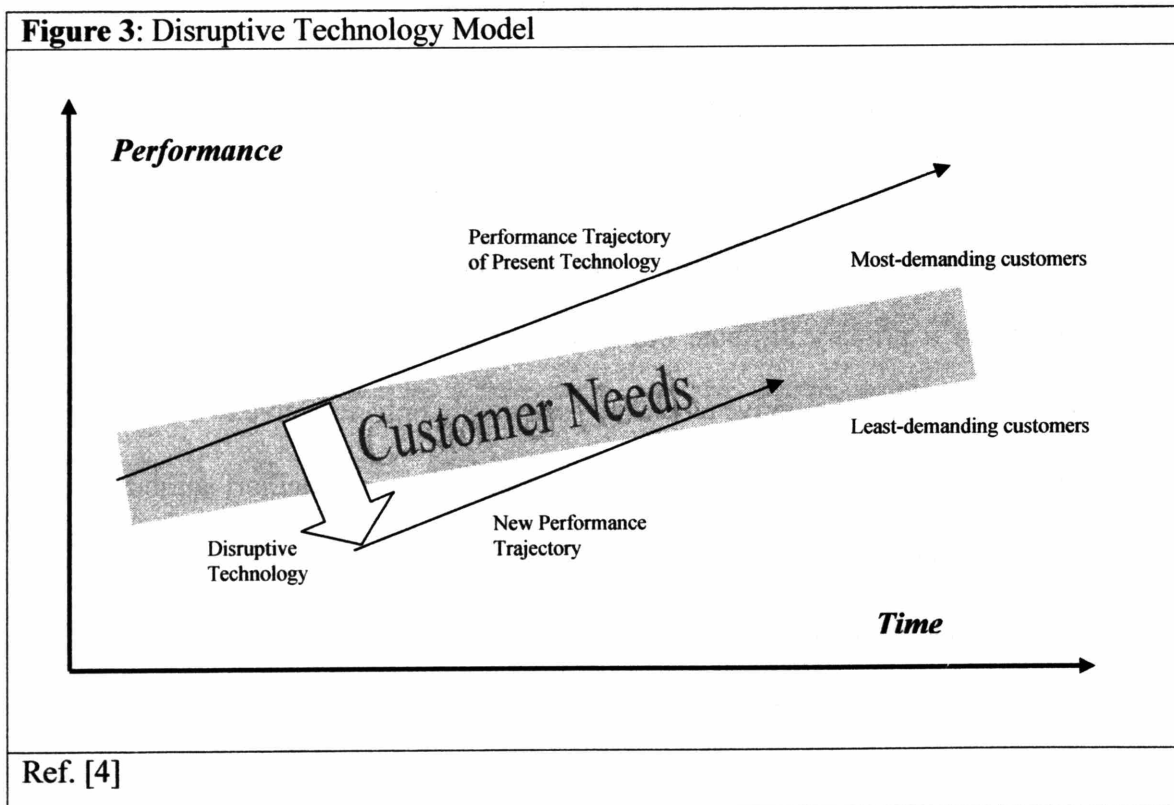
## ***2.2 Patterns of Disruption***

Christensen suggests that disruptive technologies often follow an “attack from below” trajectory into a market.[6] The disruptive technology often has lower performance on a primary attribute but better performance on one or more ancillary attributes. As such, the disruptive technology is initially only attractive to a niche market that values the performance of the disruptive technology on an ancillary attribute and is over-served by the dominant technology on the primary performance attribute. Firms with the dominant technology, meanwhile, continue to listen to their best customers and focus on incremental performance improvements to primary product attributes. The niche market served by the disruptive technology does not appear attractive or important to the firms with the dominant technology.

Often these dominant firms improve performance at a higher rate than the market can absorb. Although customers may welcome these improvements, they are typically unwilling to pay a premium for them and their attention shifts to value provided along

other dimensions of performance, such as those provided by the disruptive technology. Meanwhile the baseline performance of the disruptive technology improves over time until it meets the needs of a larger and larger share of customers. The former dominant firms are thus unseated by new entrants. See Figure 3.

Christensen’s “attack from below” paradigm is compelling and seems to fit well with disruptive innovations in the disk drive industry. Not all disruptive innovations, however, fit Christensen’s model. An expanded view of disruptive technologies is offered by Acee.[13]



Acee looks at a number of innovations in terms of their cost, traditional performance, and ancillary performance and finds a number that do not follow the Christensen dogma of lower cost, lower traditional performance and higher ancillary performance. See Figure 5.

<b>Figure 5: Disruptive Innovations</b>		
	<b>Higher Traditional Performance</b>	<b>Lower Traditional Performance</b>
<b>Higher Ancillary Performance</b>	<u>Higher \$:</u> Calculator / Slide Rule PC / Typewriter	<u>Higher \$:</u> Digital / film camera
	<u>Lower \$:</u> CD / vinyl album	<u>Lower \$:</u> Disk Drives (Christensen)
<b>Lower Ancillary Performance</b>	<u>Higher \$:</u> DVD / VCR	<u>Higher \$:</u> No market viability
	<u>Lower \$:</u> Low price, focused performance	<u>Lower \$:</u> OSB <sup>2</sup> /Plywood
Ref.[13]		

This expanded framework is very relevant for thinking about the ability of inkjet technology to “invade” other industries. For example, inkjet technology can be used to print circuits using a direct-write approach. Here traditional performance (circuit density and complexity) is currently far less than that possible with traditional silicon technology but there are significant ancillary benefits such as design flexibility, lower cost and the lack of need for photomasks and a wafer fab to generate the circuits.

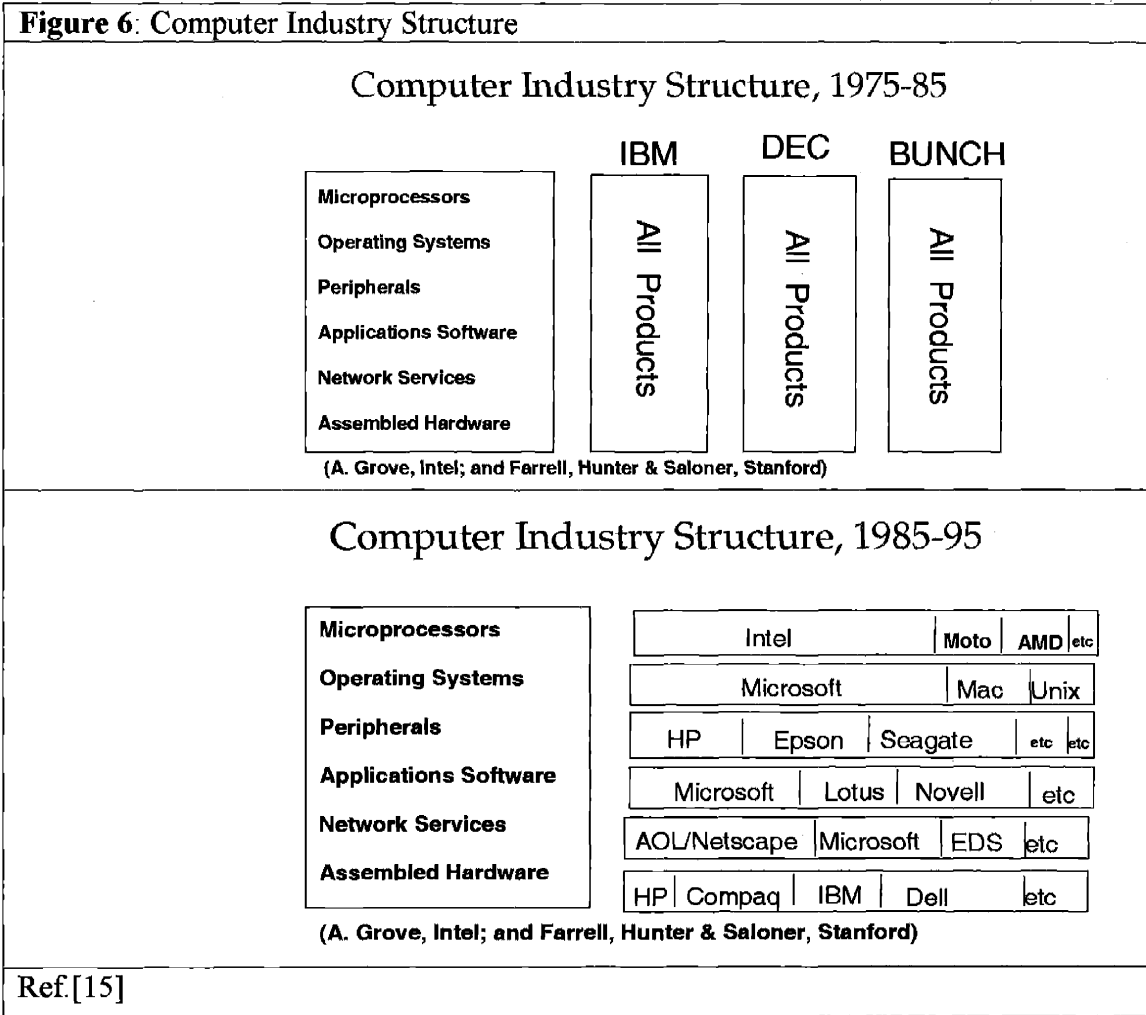
### **2.3 Disruptive Technology and Industry Structure**

Christensen has recently extended his framework to include the effect of disruptive technologies on industry structure.[4, 14] The idea here is that important ancillary attributes of the disruptive technology are often ease of use, product variety, ease of customization, and speed to market. These factors favor modular rather than integrated product architectures. Once basic product performance is good enough, independent companies will emerge which specialize in producing the various modular components. These companies work with other non-integrated firms that design and assemble end-use systems. This arrangement provides important advantages over

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<sup>2</sup> OSB stands for oriented strand board.

integrated firms in speed, cost, and flexibility. The end result is that the disruptive technology can lead to disintegration of industry structure. The disintegration is accelerated by the development of industry standards for the components. Such disintegration has happened in the personal computer industry.[15] See Figure 6.

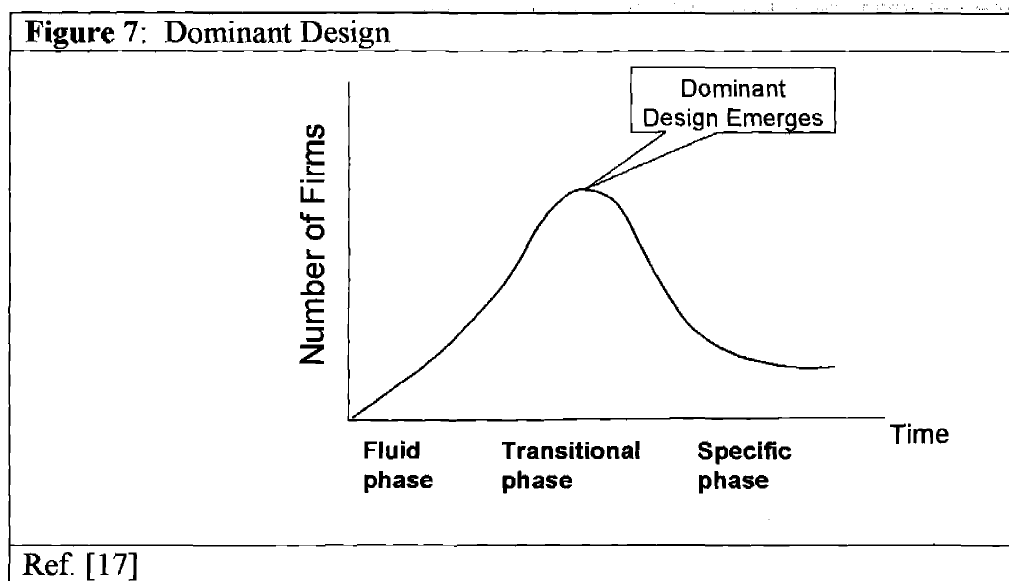


Such disintegration has not yet happened to a significant extent in the inkjet printer industry. The inkjet supplies business is an attractive target given the huge profits that it generates.[16] However, strong patent protection and the large capital investments required to manufacture inkjet cartridges have prevented disintermediation by smaller firms. Further, there is no industry standard for the electrical and mechanical

interface between the inkjet cartridge and the printer. There are smaller firms that offer inkjet refill kits and remanufactured cartridges but they have yet to take significant business away from original manufacturers. Third parties are, however, making significant inroads into the laser printer toner supplies business and the inkjet supplies business may eventually become similarly vulnerable to disintegration. Future applications of inkjet technology, such as printing of circuits, may work well in a modular architecture where firms with inkjet printing expertise could deliver part of the circuit manufacturing process without controlling the entire value chain.

Utterback has also done important work on the topic of disruptive technology and industry structure.[17] He introduces the concept of a dominant design, which is the design that is most strongly preferred in the marketplace. The dominant design is not predetermined but rather results from the complex interaction of technical and market choices. A firm's strategy, collateral assets (brand, channels, etc.), government policy, and communication with customers can all play a role in determining what design becomes dominant. The dominant design plays an important role in industry structure.

Prior to emergence of a dominant design there is a fluid phase with a large number of firms attempting to commercialize a variety of designs. Once a dominant design emerges a transitional phase begins where the number of firms exiting the industry, either through consolidation or failure, accelerates. In the transitional phase, surviving firms focus increasingly on process improvements since dominant product design has been determined. Finally, there is a specific phase as the industry matures. Here there the number of firms stabilizes at a low level with only the largest, most efficient firms surviving. See Figure 7.



For example, in the U.S. automobile industry prior to 1920 there were as many as 70 different firms making cars. In the mid-1920s a dominant design emerged based on the internal combustion engine and an all-steel enclosed body. The number of firms fell sharply in the following decade and then continued to decrease to the familiar Big Three. The auto industry has clearly reached the specific phase. Utterback argues that, in spite of the importance of dominant design in governing industry structure, its existence can be determined only in retrospect, not in the heat of the battle.

## ***2.4 Innovation in Nonassembled Products***

Utterback's work on the dynamics of innovation extends to innovation in nonassembled, or process-intensive, products.[17] Utterback defines nonassembled products to be physical goods, such as glass or steel, which have few discrete components.<sup>3</sup> Nonassembled goods tend to be process intensive and, as a result, the rate

<sup>3</sup> Utterback's framework is limited to physical goods and does not scale to purely digital products such as software and web services.



of process innovations quickly outstrips the rate of product innovations once a dominant design has emerged. With appearance of a dominant design the basic functionality of the product (e.g., glass, steel) can remain unchanged for long periods of time; firms focus instead on process innovations to improve product performance and reduce cost.

This work is directly relevant to future uses of inkjet technology since inkjet may become an enabling process technology to create displays or circuits. [17] Strictly speaking, displays and circuits are not nonassembled products like glass or steel but they share many of their important characteristics in that they consist of a relatively small number of discrete components and most of the cost of production is related to the process itself rather than to the cost of input components. Once a dominant design has emerged for displays or low cost electronics, inkjet technology would be among competing process innovations to create these products most efficiently.

Utterback finds that nonassembled or process-intensive products differ from assembled products in that process innovations can contribute to much larger cost reductions than for assembled products. For assembled products, the cost of the assembly process is relatively small relative to the components; process improvements here thus lead to only incremental cost reductions. Nonassembled products typically show discontinuous decreases in unit cost over time. There are sharp drops in unit cost when new process architectures are introduced followed by gradual decreases due to incremental process innovations. Although process innovations can offer significant cost reductions, they typically have high introduction costs. Implementing a new process innovation, such as float glass, often involves replacement of major pieces of capital equipment and can even require construction of entire new factories.

Utterback's work is quite relevant for evaluating the potential of inkjet as a manufacturing technology. Implementation of inkjet for patterning of circuits or display materials would be a significant change in process architecture and could potentially offer huge cost savings. A switch to inkjet based process tools would also involve significant new capital investment in order to realize the process cost savings.

### **3. Technology Diffusion**

The literature reviewed so far has clarified how disruptive technologies differ from sustaining technologies, explained types of disruptive technology and how they can affect industry structure, and revealed how innovation in process-intensive products differs from that for assembled products. The next important issue to investigate is diffusion of new disruptive technologies. That is, once a promising disruptive technology has emerged, how quickly will it be adopted? Rate of adoption of new technologies is important not only for the companies offering and adopting them but for economic and productivity growth in general.

There is a large and rich body of literature on the topic of diffusion of innovations that dates back to the work of Tarde in 1903.[18] Tarde is credited with developing a number of pioneering ideas that have been tested and developed by later diffusion researchers. Among them is the idea that adoption of new ideas follows an S-Curve.

Rogers' *Diffusion of Innovations* is among the first comprehensive books written on the topic.[19] Rogers reviews over 500 diffusion studies and attempts to find common threads. His work covers diffusion research in a variety of diverse areas including anthropology, sociology, education, and industry. The work focused on

diffusion of technologies in industry is of the greatest interest for this review but many aspects of the diffusion of ideas are common to all fields and are worth discussing.

Diffusion research across many fields reveals that adoption of new ideas, no matter how compelling, does not happen instantly, but instead follows an S-curve with slow adoption at first, followed by a period of rapid adoption and finally a gradually slowing of adoption rate as the potential market for the idea becomes saturated.[20] The time lag before an adoption reaches wide acceptance can be quite long; for example the tunnel kiln required 40 years to attain wide spread use in the pottery industry and hybrid seed corn took 14 years to achieve wide acceptance among farmers in Iowa.[19]

Rogers' identifies several stages leading to the adoption of a new idea. The first stage is awareness of the idea; initial awareness is often accidental but can become a driver of need. Awareness is followed by interest, which is characterized by deliberate seeking of more information on the idea. The next stage is evaluation, which is focused on weighing the costs and benefits of the idea and deciding whether to give the idea a try. Evaluation is logically followed by trial, and then, finally, by adoption. Note that rejection of the idea can occur at any of these stages, even after adoption if the innovation doesn't work out or otherwise live up to its original promise.

Sources of information are very important for the both the awareness and evaluation stages. Mass media is the most effective means of generating awareness, but for the evaluation stage personal communication is more important. Once the trial stage is reached, information obtained from personal experience with the innovation is what matters most. Of course, the characteristics of the innovation itself are of paramount importance.

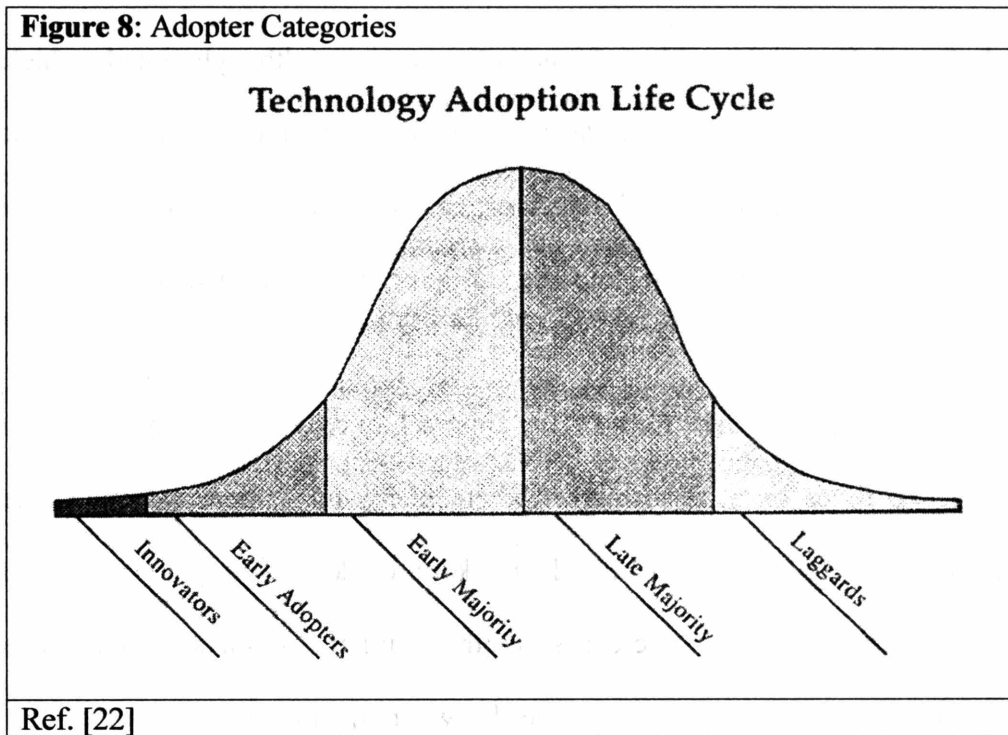
Innovation characteristics that result in faster diffusion include relative advantage (including contribution to profitability), compatibility, complexity, divisibility, and communicability.[19] Compatibility refers to compatibility with existing processes. Divisibility refers to the ability to try out the idea on a limited basis. Communicability is the ease with which the idea and its benefits can be described to others.

### ***3.1 Adopter Categories***

Rogers' important work in finding common threads in the wide variety of diffusion research extends to development of the adopter category framework.[19, 21] This conceptual framework suggests that the distribution of adopters is normal and that this bell-curve can be divided into five types of adopters, each with unique characteristics (See Figure 8).

Innovators are the first to adopt and are typically venturesome, curious risk-takers with the financial means to absorb a loss if the new idea doesn't succeed. Early adopters come next; they are less aggressive than innovators but appreciate the benefits of innovations and are comfortable adopting without well-established references. Early adopters are followed by the early majority. Early majority adopters are practical and prefer well-established references before adopting. Late majority adopters are similar to the early majority but are more skeptical and apt to wait until they feel they must adopt. The laggards make up the tail end of the adopter distribution. Laggards are tradition-focused and don't like new technology; they adopt last, if at all. The adopter categories are chiefly used for studying the adoption of products or ideas by individual consumers, but they have also been employed in trying to empirically determine characteristics of individual firms related to innovativeness.

**Figure 8: Adopter Categories**



Geoffrey Moore, in his popular management book, *Crossing the Chasm*, expands upon Rogers' idea of adopter categories.[22] Moore adds to the framework, which he calls the Technology Adoption Lifecycle, a "chasm" or gap between early adopters and the early majority. He claims that the success of a new product or innovation depends upon achieving adoption among the early majority group. Moore suggests that driving adoption into the innovator and early majority categories is relatively easy; these small groups are willing to try almost any new technology product. The challenge comes in selling the product to the early majority, where there is a difficult chicken-and-egg problem. The early majority requires well-established references from people like them before they will buy.

Moore extends the adopter category framework into a marketing model for high tech products. He suggests that the marketing plan follow the technology adoption

lifecycle from left to right. Moore's marketing strategy, although aimed at high tech products, also has relevance for driving adoption of new process technologies, particularly in vertical disintegrated industries; i.e., where a firm is attempting to license its process or sell a tool which embodies its process rather than using the process internally to create a product.

Moore's strategy calls for a D-Day approach to cross the chasm. This approach involves sharp focus on a niche market where plenty of support and service can be lavished upon early customers. The niche market provides a cluster of customers in one area who can serve as credible references for other, similar customers. The niche market also provides a well-defined target customer for whom the initial product offering can be optimized. Once a niche market has been identified, a compelling reason to buy must be established for customers. Moore suggests that this compelling reason should be a radical improvement in productivity in a well-understood area. This value proposition is the one most likely to convince those in the pragmatic early majority to adopt.

The early majority evaluate "whole products", not just hardware or software. This means that the product must include all service, support and accessories required to deliver on the full value proposition of the product. The early majority also prefer competition; competition allows them to comparison shop and is the sign of a safe, mature market. This expectation requires that the firm marketing the innovation define a market for the product in such a way that the compelling reason to buy can be clearly communicated. Market, not product-based, values are what matter to the mainstream early majority. Finally, Moore recommends a direct sales force to stimulate demand and market-leader, not bargain, pricing.

The work of Rogers and Moore is focused chiefly on adoption of innovations by individuals; some of these ideas seem inappropriate for firms adopting new processes. For example, adopter categories for firms are probably different than those suggested by Rogers. Economic forces should eliminate late majority and laggard firms who fail to adopt important innovations until most all the other firms in their industry have done so. Firms also require less “hand holding” than Moore suggests to cross the chasm. Firms have considerable resources and should be willing to adopt promising innovations before they are offered as a complete “turn key” solution by the vendor. Nonetheless, the work of Rogers and Moore provide a good background for understanding diffusion of innovations. Fortunately there is a sizable body of work focused specifically upon the diffusion of industrial process innovations.

### **3.2 Diffusion of Process Innovations**

Much of the historical work in this area is summarized in two important books: Davies' *The Diffusion of Process Innovations*, which examines the diffusion of 22 post-war process innovations in the U.K., and Nasbeth and Ray's *The Diffusion of New Industrial Processes*, which includes case studies of ten innovations in six European countries.[23, 24] A recent summary of work in the field is provided by Baptista.[25] From this work it is clear that different innovations in different industries vary in their diffusion patterns. Although generalization is difficult, there are some important common themes and frameworks.

For example, one common characteristic of process innovations, and of innovations in general for that matter, is that they are often not entirely new concepts but can instead result from the aggregation of a number of existing ideas. Their invention

and development is frequently accomplished by firms or individuals outside the industry. The view of a firm inventing a process for its own use, patenting it and then licensing to others is largely inaccurate. This characteristic is consistent with Utterback's observations of technological product innovations.[17] A second common theme to keep in mind is that most new process and product innovations are not widely adopted (diffused) and fail. The S-curve does not characterize the path of all innovations, only the successful ones. Rejection can and often does occur at any of the stages between awareness and adoption.

This literature indicates that there are three principal stages in the development of new process innovations. The first is the research and development leading to the invention and initial prototype. Next is the work required to turn the original invention into an innovation or commercial offering. The last stage is the inter-firm and intra-firm diffusion of the innovation. The overall speed of technical advancements is related directly to pace and level of activity at each of these three stages; overall the most important factor is the speed of diffusion.

### ***3.3 Diffusion Models***

The importance of speed of diffusion has led to much research in the area of diffusion models, which attempt to explain adoption S-curves and identify key factors which effect adoption rates. A recent article by Geroski provides an excellent summary of these efforts.[26] The most commonly found model used to explain technology diffusion is the so-called epidemic model. The central tenet of this model is that technology diffusion is gated chiefly by the spread of knowledge about the innovation;



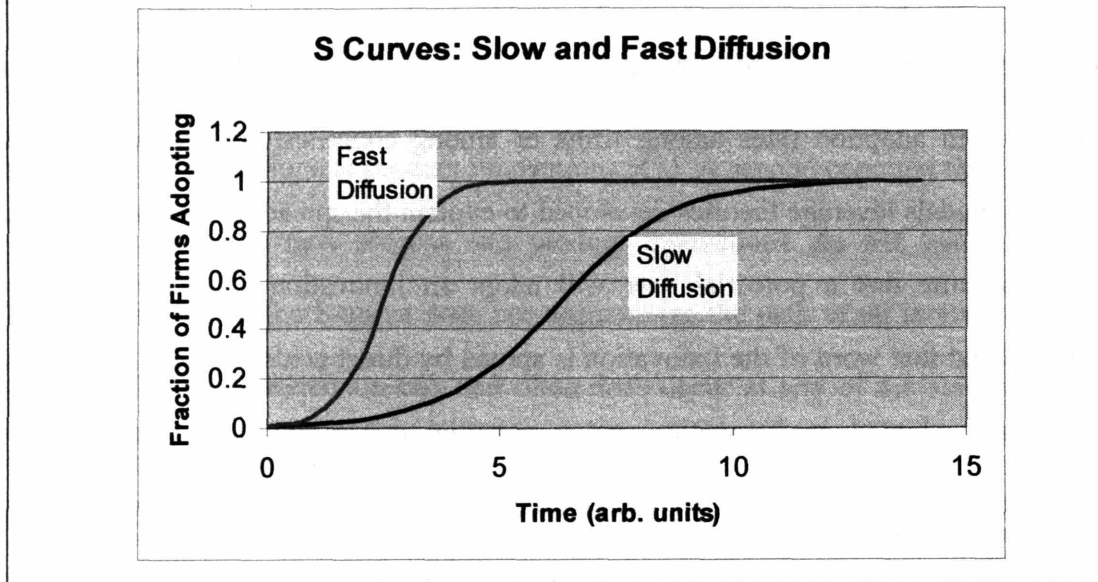
i.e., some firms simply learn about an innovation later than others. Epidemic models are inherently aggregate models that attempt to explain the number of adopters of a new technology over time. They are most useful for identifying factors that explain differences in adoption rates among firms or among countries. As its name implies, epidemic models leverage theories developed to explain the spread of disease. Epidemic models assume that a potential user will adopt an innovation upon learning of its existence and that word of the innovation is spread by direct contact between a user that has already adopted an innovation and a potential new user. The rate at which “uninfected” non-users adopt in a given period is thus related to the proportion of users in the industry population that have already adopted and the number of non-users yet to adopt. The resulting equation for adoption rate is

$$\frac{m(t)}{n} = [1 + \exp(-\alpha - \beta * t)]^{-1}$$

where  $m(t)$  is the number of firms adopting at time  $t$ ,  $n$  is the total number of firms in the industry,  $\beta$  is the parameter governing speed of diffusion, and  $\alpha$  is a constant of integration. This simple model predicts the S-curve or logistic curve frequently observed in experimental measurements of diffusion; this curve can be fit to experimental data to determine  $\beta$ ; regression analysis can then be used to investigate which exogenous factors (e.g., firm size, profitability) are correlated to  $\beta$ . See Figure 9 for examples of curves from this model for slow and fast diffusion.

Although epidemic models have yielded some useful insights, they have been criticized on a number of fronts. The fundamental weakness of epidemic models is the assumption that adoption is driven entirely by the availability of information about the

**Figure 9: S Curves**



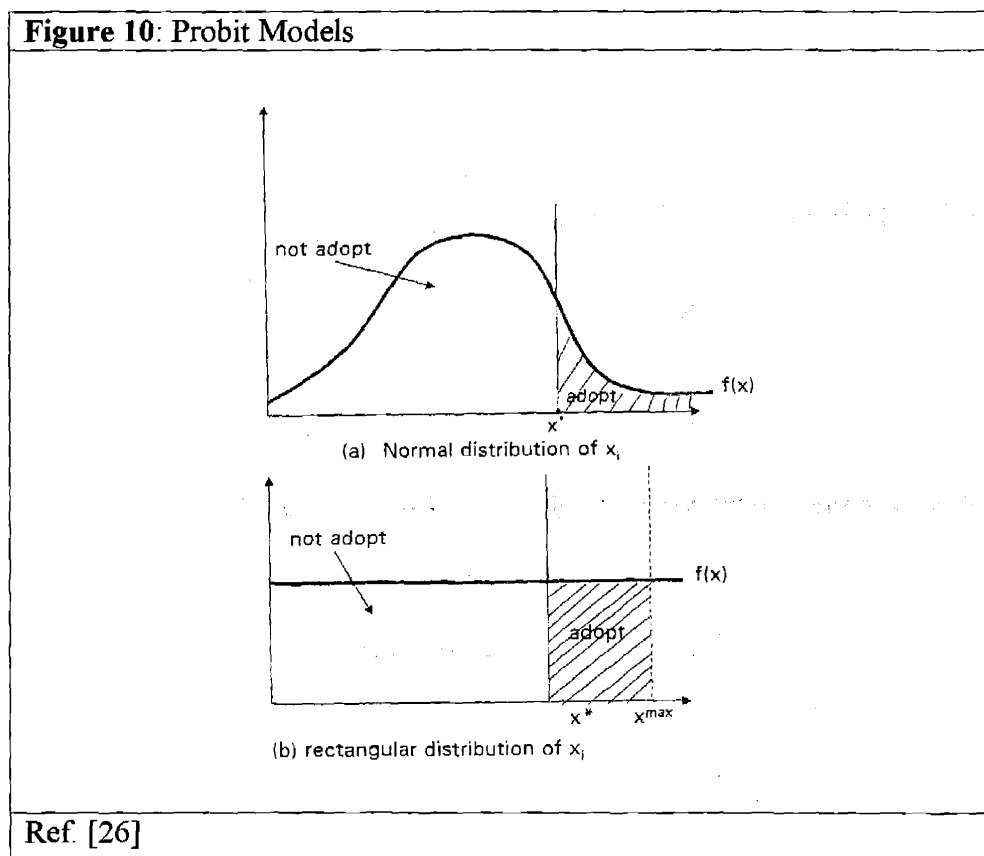
technology. In fact, technology adoption takes much longer than the time required for information about the technology to spread.

The epidemic model also regards users as a homogenous group of passive information recipients, rather than active information seekers and decision makers. Changes over time in the technology and its profitability for the firm are also ignored.

To address these shortcomings of epidemic models, another theoretical approach, called a probit model, has been developed which focuses on the time of adoption of new technology by individual firms. Unlike aggregate epidemic models, probit models are disaggregate in that the analysis is based on individual adoption decisions. Probit models assume that firms are heterogeneous and differ in some characteristic  $x_i$ , which affects their profitability of adopting a new technology. Firms will adopt a new technology when  $x_i$  exceeds some threshold value  $x^*(t)$ , which decreases over time. Values of  $x$  are distributed across the population of firms by some function  $f(x)$ . The

shape of the diffusion curve with probit models thus depends upon  $f(x)$  and  $x^*(t)$ . If  $f(x)$  is a bell curve then decrease of  $x^*(t)$  at a constant rate will generate an S-curve. If  $f(x)$  is a uniform (rectangular) distribution then  $x^*(t)$  must vary over time in order to produce an S-curve. See Figure 10.

Over the years researchers have used probit models to identify a number of interesting firm characteristics ( $x_i$ 's) that influence technology adoption decisions. Important factors are discussed in the following section.



### 3.4 Factors Influencing Technology Adoption by Firms

The decision of a firm to adopt a new process technology depends upon three categories of variables.[24]

- Innovation variables: variables related to the innovation's technical applicability and relative advantage (profitability).
- Company variables: financial resources of firm, size and structure of firm, firm culture, management attitudes towards new techniques.
- Environmental variables: variables related to firm's operating environment (network effects, suppliers, geography, networking).

The cost of adopting a new technology is obviously a key factor governing its relative advantage. One important cost is the vintage, or age, of existing capital equipment purchased to implement the old technology. Firms with older, fully depreciated capital equipment are more likely to switch to a new technology than firms with more recent capital investments in the old technology. Another influential cost is that of switching to the new technology. These switching costs include not only new capital investment but downstream costs related to adopting the new technology (marketing, developing new products based on the technology, etc.).

A very important switching cost is related to the firm's ability to learn. Firms with a strong learning culture will be able to understand and fully utilize the new technology much faster than other firms and will thus incur lower learning-related switching costs. Woiceshyn discusses the importance of organizational learning for technology adoption in the oil industry.[27] Costs of learning about the innovation prior to adoption are also important. Firms with lower learning and search costs will tend to adopt an innovation sooner. Environmental factors such as networking opportunities and geography effects provide important means of lowering these costs. Networking between potential adopters and adopters provides an important means of reducing risk

and uncertainty and speeding diffusion. These networking opportunities are most prevalent if the firms in a particular industry are clustered in a particular geographic area.

Regional networking effects among firms may help explain rapid diffusion of biotech innovations in the Boston area and of computer-related innovations in Silicon Valley. Networking between firms and universities can also contribute to reduced learning costs and faster technology diffusion.

It is not just technical knowledge which enjoys faster diffusion in geographic clusters of high tech firms but also marketing-related knowledge. For example, recent research shows that geographically clustered software firms introduce fewer products for their R&D investments but have higher sales per employee than isolated firms.[28] This research suggests that this difference is related to shared knowledge about customers and markets rather than diffusion of new technological innovations. Although the clustered firms introduce fewer products, these products are better tailored to customer needs and thus sell better, on average, than products developed by geographically isolated firms.

A commonly explored company variable is firm size. The bulk of experimental evidence suggests that larger firms adopt innovations earlier than smaller firms. The primary explanations offered to explain this outcome are that scale economies can make adoption more attractive for larger firms and that larger firms have greater financial resources and are thus better positioned to absorb the loss should the innovation fail. Large firms are also more likely to have technical staff capable of early evaluation of new process innovations.

Thomas, however, points out that this tendency for larger firms to adopt an innovation earlier than smaller firms only holds true only if the innovation does not

rapidly obsolete existing technologies and products.[29] In cases where the innovation is disruptive and *does* obsolete existing products, then smaller firms tend to adopt earlier. This is consistent with the work of Christensen (previously cited) and Utterback.[17]

Another important company variable governing technology adoption is the firm's expectations about the technology. Strong expectations regarding the innovation's ability to boost profits will hasten adoption. On the other hand, if the firm expects either the old or the new technology to improve in the near future, diffusion of the new technology will be slowed.

A crucial environmental factor that drives diffusion of new technologies is network effects; a good discussion of network effects can be found in *Information Rules* by Shapiro and Varian.[30] Network effects occur when the value of an innovation to a firm or individual is related to how many others have adopted the innovation. Network effects can result in either positive or negative reinforcing effects and can either dramatically accelerate or inhibit spread of innovations.

For example, positive feedback network effects played a major role in the ascendancy of Wintel-based personal computers. As the installed base grew there was more software available, more users with whom to share files and more resources for service and support. The growing installed base also resulted in reduced costs due to competition and scale economies. These factors drove further adoption which further increased the installed base thus creating a virtuous cycle. Conversely, Apple suffered from negative reinforcing network effects as more and more people bought Wintel machines. The vicious cycle of fewer users, less software, higher costs leading to fewer users has hurt Apple's market share.

Network effects have also helped Hewlett-Packard maintain its strong market share in inkjet printers. HP's large installed base leads existing retailers to devote more shelf space to HP's products and encourages new retailers to carry HP's printers and supplies. The wide availability of HP inkjet printers and supplies leads to increased sales and higher supply usage, which, in turn, provides money for HP to create more new products, thus further increasing the installed base. These network effects would make it difficult for a new entrant into the inkjet printing market. Lack of installed base would make it hard for new users to find printers and supplies thus hurting sales and depriving the new entrant of revenue needed to grow the business. Dell, a new entrant to the inkjet printer market, is attempting to overcome the powerful retailer network effects by selling printers and supplies through their well-established web channel.[31] This model depends on the risky assumption that customers will be willing to plan ahead and buy supplies on-line rather than running to the store when their cartridge runs dry.

Another important environmental factor influencing adoption is the suppliers of the new technology. They play a pivotal role in educating firms about the new technology; further, their pricing, service and support are important for driving adoption once awareness has been established. Suppliers are key players in the battle between the old and the new technologies. While suppliers of the new technology will aggressively push their innovation, suppliers of the old technology often respond by making incremental, yet significant, improvements of their own. Such incremental improvements to the old technology can clearly slow the diffusion of the new one. This "sailing ship" effect is well known and is discussed by Utterback in the context of the development of the electric light bulb and machine-made ice.[17]

This section has explored diffusion of innovations and, in particular, the key factors that drive adoption of new technology by firms. However, these firms can only easily adopt the new technology if it is successfully commercialized. The next and last section of this chapter discusses the challenges and strategies related to commercializing innovations.

## **4. Commercialization**

### ***4.1 Challenges Faced by Incumbents***

So far this review has focused on characteristics of disruptive technologies and important factors which influence their diffusion. A related topic which demands attention is the question of how can incumbent firms, particularly larger ones, successfully commercialize disruptive technologies that are not aligned with their core business. This topic is highly relevant for establishing inkjet as an enabling technology in areas other than traditional printing. The major inkjet firms such as HP, Epson and Canon, are large companies that have the knowledge and resources to explore non-traditional applications of inkjet technology but must do so without negatively impacting the highly profitable core business. The challenges that established firms face in trying to exploit disruptive technologies have been explored by a number of researchers. Ironically, it seems that the good management practices that helped grow and nurture the core business often cripple efforts to successfully create new businesses.

These good management practices that evolve to support the core business result in what Sull calls “active inertia” where organizations follow established patterns of behavior that worked in the past but are often inappropriate as markets evolve and new technologies emerge.[32] Firms that cannot make strategic adjustments to change and



persist in approaches that brought initial success often fail. Sull describes a dynamic of failure in which firms become locked into old strategic frames or assumptions about what is and is not important. The old frames become blinders which prevent the necessary adjustments to maintain competitiveness. Processes become hard-to-change routines; values become dogma and relationships become shackles. Polaroid and Firestone are among the once-great companies that were unable to escape this dynamic of failure and are no longer operating as independent businesses.

Christensen views this problem in terms of organizational capabilities that exist independent of the people and other resources in the firm.[6, 7] These organizational capabilities evolved to support the company's core business and are often not well-suited to commercialization of a disruptive technology. These organizational capabilities lie in three key areas: resources, processes and values. The capabilities migrate over time as firms grow. Startups and small firms are chiefly dependent upon resources, chiefly people and physical assets. While the firm is small, the founders and management team know all the employees and have first-hand knowledge of what is going on throughout the firm. As the firm grows, managers cannot personally stay abreast of all that is going on and processes must be developed to insure consistent performance of key tasks. These processes create the ability to do one set of tasks well but at the same time define disability in doing other tasks. These essential processes are the beginning of Sull's active inertia.

For example, a large inkjet company may have a rigorous process of market research and financial analysis to determine market size and opportunity before launching a new printer. This work can be done with considerable accuracy since the company

knows the market and the technology very well. Only the most promising opportunities are pursued and the expectations for success are high. This logical approach, which makes perfect sense for the core printing business, is not a good process for disruptive technologies. The markets for disruptive technologies often do not exist and thus cannot be rigorously analyzed. Further, chances for failure are high and expectations for a high success rate are unrealistic.

As a firm grows larger still values and culture become important. These values are a way of behaving that permeate a company and allow employees throughout the organization to make the right decisions in support of the core business. These values are, in essence, the DNA of large firms; they insure consistent firm performance even in the face of rapid growth and employee turnover. Persistent values in large organizations often include expectations for gross margins, the size of business opportunities, and acceptable failure rate, which are not consistent with most new businesses based on disruptive technologies.

Such new businesses typically offer (at least initially) low margins in small emerging markets where success is far from certain. Successful commercialization of disruptive technologies requires a culture that expects, accepts and even honors failure as a necessary part of exploring new markets, not a culture that only pursues low risk opportunities with near certain payoffs. This new culture should encourage a strategy of failing cheaply and often, rather than placing a few big bets. Without such a culture, the most talented people will avoid involvement in risky new business since the stigma of failure (which is likely) will damage their career prospects.

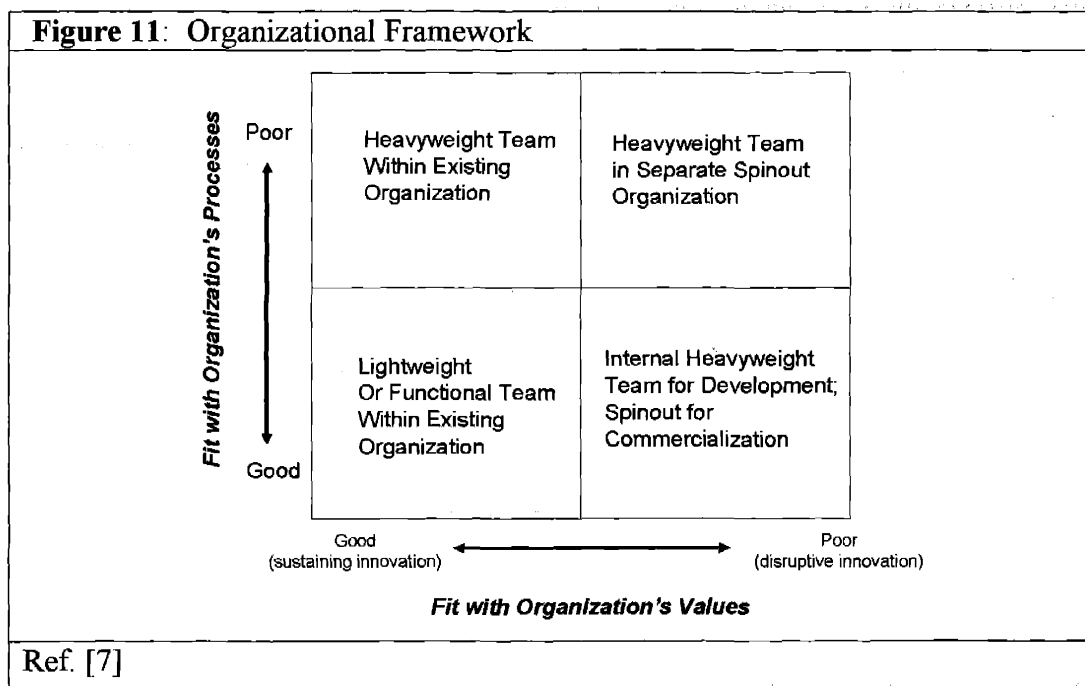
Leonard-Barton offers the theory of core rigidities to explain the challenges existing firms face in successfully commercializing disruptive technology.[33] She defines core rigidities as the values, skills, and managerial and technical systems that once served a firm well but are no longer appropriate. Her core rigidities are thus related to the resources, processes and values in Christensen's framework. A new idea in the core rigidity theory is that of dominant and nondominant disciplines. In engineering-driven firms, R&D is often the dominant discipline. The dominant discipline has high status, attracts the best talent, and tends to have strong influence in making strategic decisions. Nondominant disciplines such as marketing and manufacturing, have lower status and thus more difficulty in attracting top people. Members of nondominant disciplines typically have less input into major business decisions than members of the dominant discipline. The dynamics here are that of a self-fulfilling prophecy. The nondominant disciplines have smaller, less capable staffs which in turn reinforces their low status image and low strategic influence. Weakness in nondominant disciplines can become a particular problem when trying to launch new ventures where strong cross-functional participation and integration is important for success.

## ***4.2 Organizational Strategies***

The different processes and values needed for success in bringing disruptive technologies to markets clearly pose a problem for existing firms. Unless these processes and values can be modified, it is difficult for incumbent firms to make the necessary changes in strategy.

Christensen provides a useful framework which suggests organizational changes that can help incumbent firms with deploying disruptive technologies (see Figure 11).[7].

He suggests organizational approaches that differ depending upon how well an innovation fits with the organization's existing processes and values. If the innovation is a good fit with existing processes and values it is a sustaining innovation that can be handled with a conventional functional team or matrix-managed (lightweight) project team. On the other hand, innovations that are a poor fit with existing processes or values are best managed using heavyweight teams, a concept developed by Clark and Wheelwright.[34].



Heavyweight teams are small groups consisting of core members from each of the major functional areas (R&D, marketing, manufacturing, finance, human resources) who report directly to a senior manager. The core group is dedicated exclusively to commercializing the innovation and is devoted to delivering a system solution to meet customer needs. Each team member takes responsibility for the success of the entire project not just the contribution of his or her functional area. A contract book is used to

clearly define the team mission and expected outcomes. The heavyweight team can exist within the existing organization if the fit with organizational values is poor but overall values fit is good. The heavyweight team provides sufficient separation from the parent organization to permit new processes appropriate for commercializing the innovation to evolve. For disruptive innovations where the cultural fit with the parent organization is poor, Christensen suggests spinning out the heavyweight team into a separate organization. Heavyweight teams work well for commercializing disruptive technology since they are focused and agile and can get excited about the initially small payoffs from new businesses.

A great example of spinning out a heavyweight team in order to successfully bring a disruptive technology to market is HP's inkjet business.[7] At the time inkjet printing was invented HP's printing business was based on laser printers and was located in Boise, Idaho. Although the two marking technologies had a number of similarities, the business values were fundamentally different. Compared to laser printers, inkjet printers were lower cost, lower margin, lower performance products that were aimed more at home or personal printing rather than office or workgroup printing. This difference in values led HP to start up a brand new site, remote from Boise, in Vancouver, Washington, to focus on inkjet printer development and manufacturing. New divisions were also started up at existing sites in Corvallis, Oregon, and San Diego to support the inkjet work in Vancouver. This spinout strategy allowed evolution of new values and processes appropriate for the inkjet business.

One problem with the heavyweight team idea is that if done on a widespread basis there is a risk of corporate fragmentation and loss in knowledge sharing. In the extreme

case a corporation becomes a very loose collection of autonomous business units. Some of the advantages of belonging to a larger parent company are thus lost. Ghosal and Gratton suggest a horizontal integration approach that provides needed integration in four key areas without strangling entrepreneurial organizations with a vertical command and control structure.[35] This approach starts with a common IT infrastructure and knowledge database across all business units. Although this seems like common sense, autonomous business units will make different choices in these areas unless there is a corporate mandate for commonality. For example, prior to Carly Fiorina's reorganization of HP in 2001, each of its 83 product divisions had its own financial reporting system.[36] Ghosal and Gratton recommend that the common IT infrastructure and knowledge database, which provide operational and intellectual integration, be supplemented with social and emotional integration. Social integration is defined as active interactions between business unit managers and can be achieved through collective bonds of performance. For example, social integration at BP is accomplished through a peer challenge system in which business unit managers must gain approval of their annual performance goals not from top management but instead from a peer group consisting of managers of similar businesses within the company. Peer review helps eliminate sandbagging and insures that each business unit contributes its fair share to the overall performance of the company. In addition, managers at the top performing business units are required to help those at the bottom to improve. This system helps drive implementation of best practices across the company.

Finally, emotional integration is achieved by emphasizing important cultural values that are important in all business units across the company. Goldman Sachs has a

unifying value around client service while Johnson & Johnson has its Credo which summarizes strong commitment to customers, employees and community.[37] The HP Way expresses a similar set of company-wide cultural values at Hewlett-Packard. Emotional integration can be further enhanced through compensation or bonus schemes that are based on overall company performance, not that of a specific division.

To summarize, it is very difficult to successfully commercialize a disruptive technology within a large organization focused on an existing core business. The very management practices that led to the successful core business result in “active interia”, core rigidities, and processes and values inappropriate for the new business. A small, focused heavyweight team in a spinout organization, either inside or outside of the parent company, has the best chance of success.

### ***4.3 Commercialization Strategies***

Once a firm has chosen an appropriate organizational structure to avoid the “Innovator’s Dilemma”, the group responsible for commercializing a product based on the new technology must decide how best to get the product to market. The strategy that worked well for the parent organization may very well not be the right approach. A common pitfall is to attempt to enter a mainstream market right away. Mainstream markets are heavily defended by incumbents who have significant learning curve and economy of scale advantages. They will fight fiercely to defend their core business. Further, a strategy to attack a mainstream market right away often depends upon a major technological breakthrough, which adds additional risk. R&D investment to achieve significant breakthroughs should be done carefully with the customer needs and benefits

clearly in mind.[32] A better approach is to find a market which values the current attributes of the technology. This market is likely to be a niche market rather than a mainstream one. Profits from the niche market can help pay for investments to improve the technology over time so that other niche markets, and eventually larger mainstream markets can be successfully entered.[6] But which markets to target?

Christensen suggests going after the least-demanding tiers of an existing market where the prevailing product or process over serves at least part of the customer base.[3] The key to this “attack from the low-end” strategy is to find markets where the prevailing product is more than good enough. The litmus test is whether or not customers in a given market tier are willing to pay a price premium for further improvements in functionality, reliability or convenience. If so, then a disruption from the low-end is unlikely to be successful. Successful disruption from the low-end also requires a different business model from the mainstream competitors. This business model should support pricing that attracts low-end business while still offering attractive margins.

Another strategy is to create a new market of customers that are unable to use existing products or services due to their high cost or complexity.[3] The idea here is to compete against non-consumption rather than to try to steal customers from an established competitor. This approach is most likely to be successful if it results in a simple product that helps customers more easily and effectively do what they are already doing. A business model which requires customers to want to do something that had not been a priority before is likely to fail.

The original Netscape and Mosaic web browsers represent a great example of competing against non-consumption. They allowed non-experts to tap the power of the



internet for the first time. Another example is Southwest Airline's short hop direct flight service. This service made it possible for customers to conveniently travel moderate distances quickly, which was often not possible with a car or the larger airlines' hub systems.

When an existing firm attempts to enter a new business, the best approach may not be to do all the development internally. Roberts and Berry provide a very useful framework for selection of new business strategies based upon the organization's familiarity with the market and with the technologies embodied in the product or service.[38] See Figure 12. The suggested strategies range from internal development and acquisitions when the familiarity with both the market and technology is relatively high to licensing, joint ventures and venture capital investments when familiarity with both the market and technology is low. This framework suggests that internal development makes sense only when the firm is relatively familiar with

**Figure 12: Optimum Market Entry Strategies**

<b>Market Factors</b>	New, Unfamiliar	Joint Ventures	VC, Venture Nurturing, or Educational Acquisitions	VC, Venture Nurturing, or Educational Acquisitions
	New, Familiar	Internal Market Dev, Acquisitions, or Joint Ventures	Internal Ventures, Acquisitions, or Licensing	VC, Venture Nurturing, or Educational Acquisitions
	Base	Internal Base Development or Acquisitions	Internal Prod Dev, Acquisitions, or Licensing	Joint Ventures - Small Co/Big Co
		Base	New, Familiar	New, Unfamiliar
		<b>Technology/Service Embodied in Product</b>		

Ref. [38]

both the market and the technology. Outside the lower left-hand corner of Figure 12 new venture success is significantly higher if alternative strategies are employed. The Roberts and Berry framework shows that an existing firm can be successful with new ventures in unfamiliar areas if they are willing to work outside their own organization.

A second valuable framework of commercialization strategies for new businesses is provided by Gans and Stern.[39] This framework, which builds upon important earlier work by Teece, suggests strategies for dealing with incumbents.[40] Specifically, Gans and Stern suggest strategies based on excludability of the innovation and the value of the incumbent's complementary assets. See Figure 13. For each scenario, strategies are

**Figure 13: Commercialization Strategy Environments**

		<i>Importance of Incumbent's Complementary Assets</i>	
		Low	High
<i>Excludability</i>	Low	Attacker's Advantage	Reputation-Based Ideas Trading
	High	Greenfield Competition	Ideas Factories

Ref. [39]

provided for both a startup and incumbent and the expected competitive dynamics are discussed. The startup organization is in the strongest position (Greenfield Competition) when excludability is high (i.e., the incumbent cannot easily copy the

innovation due to patents or lack of key tacit knowledge) and the incumbent's complementary assets (manufacturing ability, distribution channels, brand, etc.) do not contribute significantly to the value proposition of the innovation. Here the startup can choose between contracting and product market entry; performance depends upon the strength of technological competition. The incumbent firm has the upper hand when excludability is low and its complementary assets are important for commercializing the innovation (Reputation-Based Ideas Trading). Here the incumbent can choose to either ignore the startup or engage in trust-based trading of ideas. In the other two scenarios, the startup either has a strong incentive to contract with incumbents (Ideas Factory) or to move quickly to exploit its technology advantage (Attacker's Advantage).

## **5. Conclusion**

This review has covered management literature related to disruptive technology, technology diffusion, and commercialization strategies for new technologies with the intention of providing insights on how inkjet might be successfully introduced as a disruptive process technology in a new industry such as circuits or displays. Important lessons can be distilled from the literature on how to identify a disruptive technology, find a promising market and create an effective introduction strategy, and manage the adoption (diffusion) process. Key lessons for this review that are directly relevant for successful introduction of inkjet as a disruptive process technology:

- First and foremost, the inkjet process innovation must offer real compelling benefits that produce significant cost reductions and/or productivity improvements.

- The innovation should target a well-defined niche market to induce networking effects and reduce learning costs. Ideally this market should be a new one where important, yet unmet needs can be addressed, or an existing market where disruption from below is possible.
- Target customers, which will be firms for a process innovation, should be chosen carefully with an eye towards whether the innovation is disruptive to that firm's existing business. If the process innovation is disruptive to a potential customer's existing technology a more effective strategy may be to compete against them rather than sell to them.
- Inkjet-based process technology must deliver a "whole product" including all service and support needed to insure that the customer realizes the full value proposition of the product; this will reduce uncertainty and speed diffusion. A whole product commitment is essential to "crossing the chasm" and insuring adoption of the innovation by pragmatic, mainstream firms.
- The right kind of information must be provided at each stage of the adoption process: mass media to generate awareness, followed by personal references and contact during the evaluation stage, and close support during the trial step. Making it easier for a potential adopter to try the technology on a limited basis can help speed diffusion (divisibility).
- Creating the right organizational structure is important for success. Commercialization of a disruptive technology within a large organization that is focused on a different core business is often difficult. Successful deployment of

inkjet as a disruptive technology by an existing inkjet player will likely require an internal or external spinout organization.

- Doing all development internally is often not the best or fastest way to get new technologies to market. Other strategies, such as licensing, joint ventures or acquisitions should be considered depending upon factors such as familiarity with the market and technology, excludability of the technology and the importance of incumbent's complementary assets.

Building a business strategy around these key ideas will maximize the chances of inkjet becoming a disruptive technology in new industries.

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## Chapter 3

### Inkjet Opportunities in the Flat Panel Display Industry

#### Table of Contents

<b>1. Introduction.....</b>	<b>67</b>
<b>2. Flat Panel Display Industry Value Chain.....</b>	<b>68</b>
<b>3. Display Technology.....</b>	<b>69</b>
<b>3.1 Liquid Crystal Displays.....</b>	<b>70</b>
<b>3.2 Plasma Displays.....</b>	<b>75</b>
<b>3.3 Organic Light Emitting Diodes (LEDs).....</b>	<b>76</b>
3.3.1 Competing OLED Technologies.....	77
3.3.2 OLED Technical Challenges.....	83
<b>3.4 Innovation Dynamics.....</b>	<b>84</b>
<b>3.5 Technology Summary.....</b>	<b>88</b>
<b>4. Customer Preferences.....</b>	<b>89</b>
4.1 Needs Hierarchies.....	89
4.2 Performance Comparison.....	92
<b>5. Industry &amp; Business Dynamics.....</b>	<b>93</b>
5.1 Industry Structure.....	93
5.2 Competitive Attributes.....	97
5.3 Industry Dynamics.....	98
5.4 Business Cycles.....	99
5.5 Corporate Strategy Dynamics.....	100
<b>6. Regulatory Policy Dynamics.....</b>	<b>103</b>
<b>7. Analysis &amp; Recommendations.....</b>	<b>105</b>
7.1 Inkjet Challenges.....	106
7.2 Adoption Accelerators.....	109
7.2.1 Casual Loop Diagram.....	109
7.2.2 Importance of New Products.....	110
7.3 Winners and Losers.....	114
7.4 Strategic Recommendations.....	116
7.5 Summary.....	117
<b>8. References.....</b>	<b>119</b>

This chapter explores the potential of inkjet printing to become a disruptive technology in the flat panel display industry. This exploration will begin with examination of key technology and business issues in the industry; this industry context is necessary to understand the opportunities for a disruptive technology. The technology and business discussion will be followed by an analysis of the potential for inkjet to become a disruptive technology in the display industry and strategic recommendations for how to best exploit this opportunity.

## **1. Introduction**

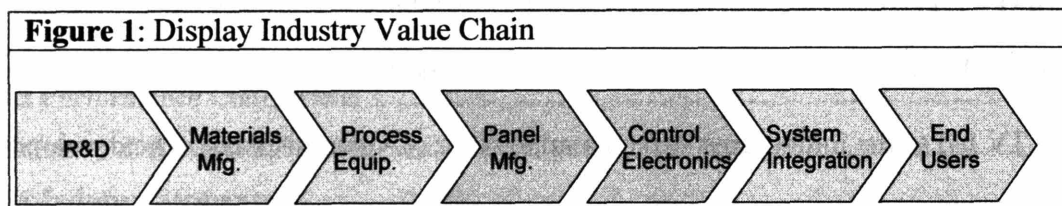
The display industry was born with the invention of the cathode ray tube (CRT) in 1897.[1] Applications were chiefly limited to scientific and military instruments until the home TV was successfully commercialized in the late 1940s.[2] The popularity of home TV led to the initial large scale manufacturing of video displays. The development of computing technology in the 1960s and 1970s led to additional demand for display terminals, initially for mainframe and minicomputers and, by the 1980s, for personal computers as well.[3] The 1990s saw the advent of large screen televisions as well as of portable computers and handheld computing appliances (PDAs, cell phones, GameBoys, digital cameras); these products represented entirely new markets for both large and small display devices.

These newer markets are not well served by CRT technology; the cathode ray tube itself cannot be made small enough for portable devices and becomes too bulky for large displays. CRT technology is very mature and is gradually being replaced by new, more advanced display technologies that can better meet the needs of both existing and

emerging markets.[4] This roadmap discussion will, therefore, focus on these new display technologies, which shall be collectively referred to as flat panel displays (FPDs) since one attribute the new technologies all have in common is dramatic reduction in the depth of the display device compared to a CRT. In particular, discussion will focus on today's dominant flat panel technology (Liquid Crystal Displays, LCDs) and the most promising technology of the future (displays based upon organic light-emitting diodes, OLEDs). It is in the emerging OLED display area where inkjet may become a critical enabling technology.

## 2. Flat Panel Display Industry Value Chain

The value chain for the flat panel display industry is shown in Figure 1.



At the left is R&D for new display technologies. Next comes manufacturing of all the inputs required to create flat panel displays. These inputs include liquid crystal or organic LED chemicals, glass or plastic substrates, filters, polarizing films, and backlights. The third stage in the chain is development of the process equipment required to manufacture the panels. This equipment is usually not produced by the display companies themselves but is procured from companies that specialize in tooling fabrication.

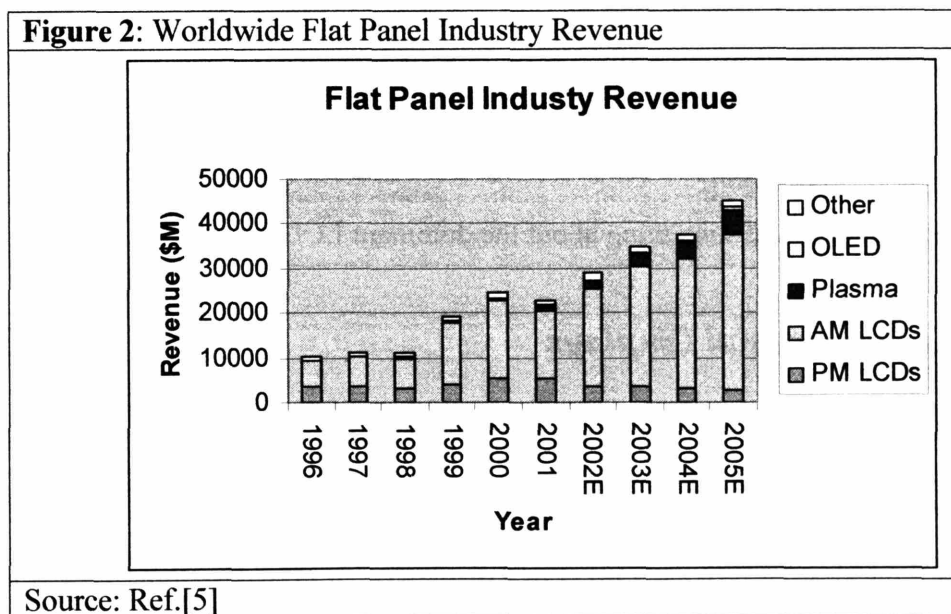
Since LCD technology is mature and a dominant design exists there is little product development activity in these first three stages of the value chain. OLED

display development, on the other hand, is still in the fluid phase. Firms are competing to establish the dominant design so there is significant development activity in R&D, materials manufacturing and process equipment.

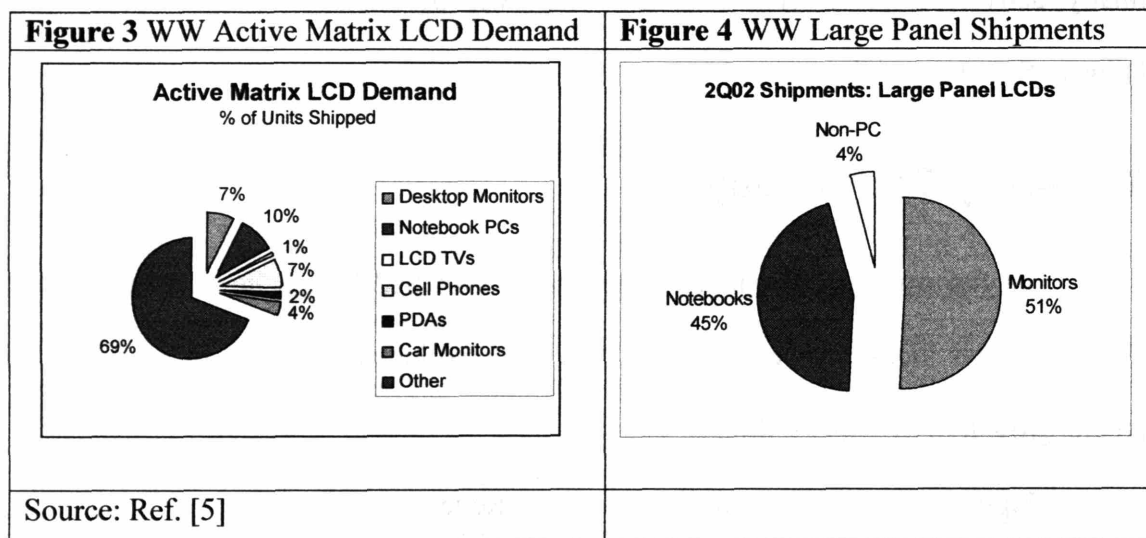
The next two steps (highlighted in yellow) are the core of the value chain and include the production of the display itself as well as the necessary control electronics (backplanes and display driver chips). Large capital investments are required for these stages. These steps are followed by integration of the displays into end products and, finally, delivery to customers. The value chain will be discussed in more detail in the Industry Structure section.

### 3. Display Technology

The flat panel display industry generated over \$22 billion in revenue in 2001. Figure 2 shows industry revenues since 1996 and also includes analyst forecasts, which predict growth to over \$40 billion by 2005.[5]



The great majority of industry revenue (89% in 2001) comes from displays based on LCD technology and the bulk of this revenue (66% in 2001) is from active matrix (AM) LCD displays. A breakdown of products using active matrix LCD displays is shown in Figure 3. The large “other“ category is testimony to the wide use of these displays in a broad variety of both consumer and industrial products. On a panel area basis, however, 90% of the demand comes from monitors, notebook PCs and televisions. A breakdown of demand for large flat panels is shown in Figure 4.



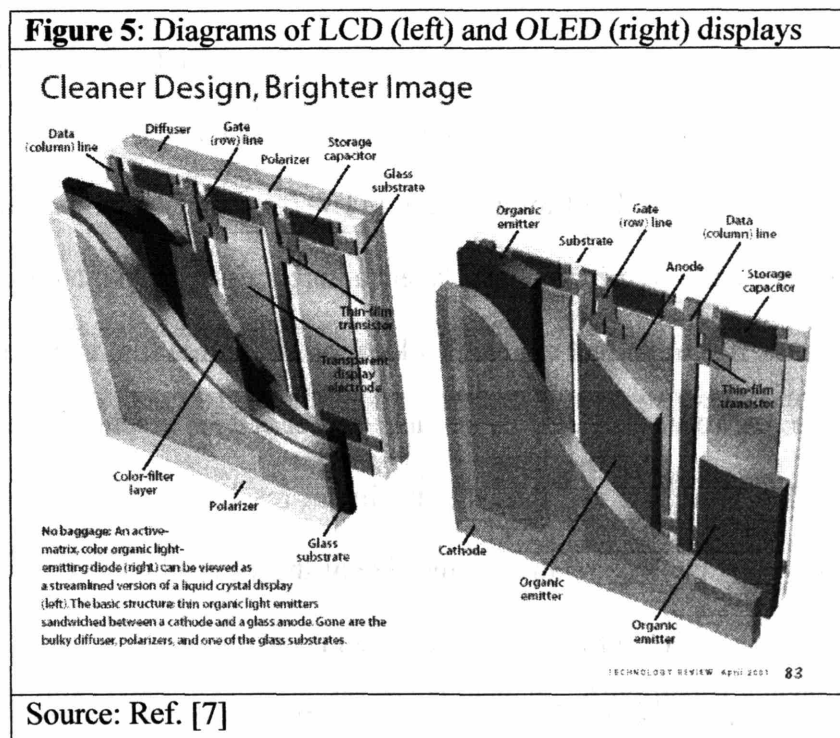
In order to understand the technology dynamics in the display industry it is important to understand something about the dominant LCD technology.

### 3.1 Liquid Crystal Displays

As the name implies, liquid crystal displays are based on liquid crystal polymers. This liquid crystal material itself does not emit light but rather serves as a shutter that regulates light in order turn each pixel in a display on or off. The light itself is provided by backlights (usually a mercury lamp) in the case of large format displays (laptops,

monitors, and TVs) and by ambient light in the case of small reflective displays such as those used for watches, calculators, and some PDAs. LCD physics is based on the ability of liquid crystals to polarize light. The polarity state of the liquid crystals can be altered by application of electric current. For a good introduction on how LCDs work see Ref.[6].

A critical technology dynamics factor for LCD displays is that they are complex devices, which are expensive to manufacture. Up to one-third of the cost of a laptop computer derives from the LCD display! [7]



A simplified LCD cross-section is shown in Figure 5. A single pixel monochrome LCD display requires two layers of glass, two polarizing filters, an indium-tin oxide electrode plane, a mirror or backlight, as well as a layer of the liquid crystal material itself. Color displays are created by dividing each pixel into three sub-pixels and

adding a color filter layer to make the subpixels red, green and blue. By varying voltage to the subpixels, 256 intensity levels can be achieved for each of the primary colors. Combining intensity levels among the subpixels enables a palette of over 16 million colors.

The complexity does not end here. A matrix backplane is required to permit control of each individual pixel. The matrix backplane consists of interconnects and transistors fabricated on a glass substrate located behind the stack of layers required to implement the LCD itself. The backplanes can either be passive or active.

Passive backplanes require a transistor for each row and column; this transistor can be located on an integrated circuit external to the display. Active matrix backplanes, on the other hand, require a thin film transistor (TFT) immediately behind each subpixel. The transistors are fabricated in a silicon layer (amorphous or polysilicon) deposited on the glass substrate. It is important to note that location of the thin film transistors in active matrix displays between the LCD layer and the backlight results in limits on the minimum possible pixel size and thus the maximum resolution of the display.[8] The size of the pixel must be large relative to the size of the TFT behind it in order to insure that sufficient light can pass through when the pixel is on.

Passive backplanes are cheaper to manufacture but cannot support high refresh rates or accurately control voltages at the pixel level, which is important for color accuracy. Passive matrix backplanes are most often used in handheld devices where these requirements are less important. Active matrix backplanes are the norm for most all large format applications, including laptops, desktop monitors and televisions. Here the expectation to deliver at least CRT-level performance has made this more costly



technology necessary. Figure 6 shows which products require passive or active matrix backplanes.

<b>Figure 6</b>	Passive Matrix	Active Matrix
Small Screen	Cell Phones Appliance Displays PDAs Calculators, Watches	Cell Phones (3G) Digital Camera Displays High-end PDAs DVD Players
Large Screen	Not Viable	Notebooks Monitors TVs

A typical laptop display with 1024x768 resolution requires three transistors per pixel, one for each subpixel, for a total of over 2.3 millions transistors! If more than a few of these pixels are bad, the display must be scrapped. Scrap rates as high as 40% are not uncommon and are an important contributor to the high cost of LCD displays since the price of the good displays must cover the cost of the scrapped ones. This yield problem only gets worse as display size is increased.

Most active matrix backplanes are fabricated in amorphous silicon; amorphous silicon has significantly lower carrier mobility than the single crystal silicon used for fabrication of integrated circuits so transistor performance is generally poor. It is good enough for switching LCD pixels off and on but not adequate for handling the logic and mixed signal processing required to drive the display. Amorphous silicon active matrix displays thus require external silicon chips to handle these functions.

There is, however, an industry trend, led by Toshiba, toward higher performance matrix backplanes.[5] These backplanes use a polysilicon instead of amorphous silicon substrate. Carrier mobilities are much higher, around 90% of that possible with single crystal silicon, thus permitting integration of much of the logic handled by external chips

in amorphous silicon displays. The polysilicon backplanes are more expensive to manufacture but this integration provides cost savings for devices with smaller displays where external display driver chips are a higher fraction of the total display cost. Elimination of external driver chips also reduces weight and enables thinner form factors. Over time, as yields improve and costs decrease polysilicon backplanes should migrate to larger display products such as notebook computers and monitors.

Polysilicon backplanes are very important for the technology dynamics for displays because, in addition to enabling cost savings for LCD displays they are absolutely necessary for larger OLED displays.

In addition to their high cost and complexity, LCD displays are rigid, fragile and suffer from image quality problems. These issues are directly related to their architecture. The many layers of glass and filters required to make an LCD display limit light transmission, thus reducing brightness and contrast, and constraining viewing angle. Power consumption is also high since a bright backlight must always be on regardless on how many pixels are lit.[9] Displays are the major power consumer in laptops and are largely responsible for short battery life. Further, even fast switching active matrix technology has trouble with high frame rate video applications.

The weaknesses of the dominant LCD technology, especially price and sub-par image attributes, are important for technology dynamics since emerging technologies must successfully address these weaknesses in order to gain market share. For example, LCD technology is currently not economical for screen sizes above 30" (diagonal).[5] The primary flat panel technology for larger screen sizes is plasma displays.[10]

### **3.2 Plasma Displays**

Plasma displays are very expensive; prices are around \$100 per diagonal inch. Prices start at \$3500 for a 32" unit and go up from there.[10] They can, however, be manufactured in sizes up to 50" and are currently used chiefly for niche business and commercial applications such as information displays for airports and high-end presentation displays for conference rooms. The consumer big screen TV market is, however, becoming an important growth driver.[5] Plasma displays provide a thin form factor alternative to bulky rear-projection systems for home theatres.

With plasma displays, each red, green and blue subpixel is individually lit; intensity is varied by adjusting the number and width of voltage pulses applied to each cell. The result is a nice bright image without the viewing angle problems common with LCDs. Image quality is not yet equal to that of top quality CRTs but the technology is improving. In spite of their advantages over LCDs, plasma display technology is likely to be competitive only in the market for very large displays. Plasma displays are not economical at sizes below 30" where there is tough competition from LCD and, especially, traditional CRT technology.

Note that LCD suppliers have not given up on the large screen market. The newest LCD fabs under construction will be able to produce panels using 1500mm x 1800 mm substrates. These fabs will be able to produce 40" and larger LCD televisions and displays that should be competitive with plasma displays. Sharp expects to begin volume production in such a fab next January and is so confident in their eventual success that they have decided to drop their entire plasma television product line.[11]

### **3.3 Organic Light Emitting Diodes (LEDs)**

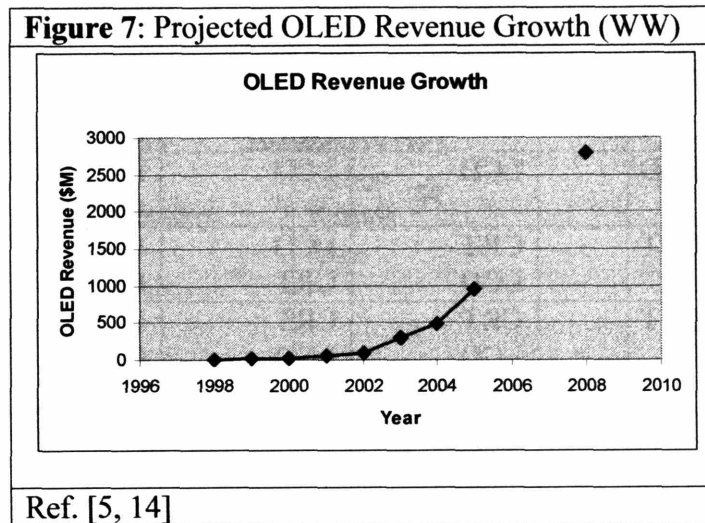
The technology more likely to threaten LCDs in the market for large and small format displays is that based on organic light-emitting diodes (OLEDs). OLEDs were discovered in 1979 by a Kodak researcher with scientific publication of the results coming eight years later.[12]

OLEDs are based on the phenomenon of organic electroluminescence. Certain organic molecules can efficiently convert electricity into light; the color of the emitted light can be tuned by adjusting the chemistry. Further, the light from the molecules can be switched off and on very rapidly. These features make OLEDs a very compelling display technology that could potentially disrupt the LCD hegemony.

The OLED display architecture is much simpler than that for LCDs (see Figure 5). Since the OLEDs emit light directly there is no need for the polarizers, backlights, color filters and diffusers required for LCDs. This simplicity makes OLED displays thinner and lighter than their LCD counterparts and could also translate into manufacturing costs that are 20-50% lower.[7][13] Further, OLEDs offer superior brightness (visible even in bright daylight), contrast, and image quality. OLEDs also have a big advantage in power efficiency since there is no backlight and only the pixels that are on consume energy. A laptop with an OLED display could have a 10 hour battery life vs. 2 or 3 hours with today's best LCD-equipped models.[9] In short, OLED displays are everything that LCD displays are not; they seem to offer both higher performance and lower cost.

The promise of OLED displays has attracted a large number of companies that hope to create and capture value in this emerging market. Over 80 companies worldwide

are involved in the OLED business.[7] The OLED market had only \$100M in revenues in 2002 but is projected to grow at a CAGR of 74% to reach \$2.8B by 2008 (see Figure 7).[14] There are currently four different OLED technologies competing to become the dominant design.



### 3.3.1 Competing OLED Technologies

The leading contender at present is Kodak's fluorescent small molecule OLED technology. This technology has been under development the longest and has already been commercialized in several products, including a car audio system and cell phone. See Figure 8. Kodak has also broadly licensed their technology, chiefly to Asian companies already in the flat panel display business. See Figure 9.

Kodak's technology lead stems from the fact that small molecule OLEDs were invented first and from the fact that the manufacturing approach leverages process technology used for LCDs. Small molecule OLED material is deposited using a vacuum vapor deposition process. The OLED material is vaporized in a vacuum system and then

<b>Figure 8</b> Matrix of Product and Display Technologies					
	☆ = OLED Milestone				
<b>Product</b>	<b>1995-1999</b>	<b>2000-2004</b>	<b>2005-2009</b>	<b>2010-2014</b>	<b>2015-2019</b>
<b>Sm. Appliance</b>	LCD ☆	LCD ☆	LCD <u>OLED</u>	<u>OLED</u> LCD	<u>OLED</u>
<b>Cell Phone</b>	LCD	LCD ☆ ☆	LCD <u>OLED</u> LCD	<u>OLED</u> LCD	<u>OLED</u>
<b>PDAs</b>	LCD	LCD	LCD <u>OLED</u>	<u>OLED</u> LCD	<u>OLED</u> LCD
<b>Notebooks</b>	LCD	LCD ☆	LCD	LCD <u>OLED</u>	<u>OLED</u> LCD
<b>Monitors</b>	CRT	CRT LCD	LCD CRT	LCD <u>OLED</u>	<u>OLED</u> LCD
<b>Televisions</b>	CRT	CRT LCD	CRT LCD	LCD CRT <u>OLED</u>	LCD <u>OLED</u> CRT
<b>Large Screen</b>	Projection	Projection Plasma	Plasma LCD Projection	Plasma LCD <u>OLED</u>	LCD <u>OLED</u> Plasma
<b>Flexible Displays</b>	N/A	N/A	N/A	Small <u>OLED</u>	Large <u>OLED</u>

Sources: [5, 15-17]

Note: Technologies in a given box listed in order of prevalence. Future prevalence orders are educated guesses.

**OLED Milestones (denoted by stars ☆ in table above)**

- 1979 – Discovery of small molecule OLEDs at Kodak
- 1989 – Discovery of light-emitting polymers at Cambridge Univ.
- 1999 – First small molecule OLED display introduced (Pioneer car audio display, monochrome, PM)
- 2000 – First cell phone introduced with OLED display (Motorola, 2 color, PM)
- 2002 – First polymer OLED product introduced (Philips shaver, monochrome, PM)
- 2002 – First cell introduced with full color OLED display (Samsung-NEC, PM)
- 2002 – Kodak introduces first full-color, AM OLED display, 5.48 cm (2.16 in)
- 2002 - Sony demos prototype of 13” AM-OLED display

condenses onto a cooled display substrate. A shadow mask is used to control location of each subpixel-sized spot of material.[7] Although this fabrication approach is relatively well understood, it is both costly and delicate. Another problem with small molecule

OLEDs is poor power efficiency, which may limit their use to small screen applications.[5]

**Figure 9: Alliances and Partnerships**

<b>Company</b>	<b>Kodak</b>	<b>Cambridge Display Technology</b>	<b>Universal Display Corp.</b>
<b>Material Type</b>	Fluorescent Small Molecule	Light Emitting Polymer & Dendrimer	Phosphorescent Small Molecule
<b>OEMs, Partners</b>	Denso Emagin Lite Array NEC Nippon Seiko Opsys Opto Tech Pioneer Ritek Rohm Samsung Sanyo (JV) SNMD Sumitomo TDK Teco Varitronix Optrex	Microemissive Displays Opsys (IP) Osram Philips Dow	Samsung Motorola Sony DuPont
<b>Chemicals</b>	Kodak	Covion DuPont Hoechst Dow	PPG
<b>Process Equip.</b>	Ulvac	Seiko Epson Litrex (acquisition)	Aixtron

A competing technology is being developed by Cambridge Display Technology (CDT) (Cambridge, U.K.) and its partners. The CDT OLED is based on light-emitting polymers (LEPs), which are much larger molecules than those used by Kodak.[7, 18] An important advantage of LEPs is that they can be readily dissolved in liquids. The solubility of the CDT's light-emitting polymers means that they can be applied to substrates by spraying or by using low cost printing technologies such as inkjet. [9] The

process technology required to print polymer OLED materials is immature but has the potential to be much cheaper than the more mature vacuum deposition process required for Kodak's small molecule materials and standard LCD processing. The big cost savings will be realized with the use of plastic substrates since they would allow deposition of display materials in a roll-to-roll process similar to that used for printing newspapers. If such plastic substrates can be used for both the display materials and the backplane electronics (see Chapter 4) then a truly flexible display could be produced. Applications might include a roll-up display for laptops or very thin, lightweight wall mounted displays for home and commercial use. The biggest obstacle to use of plastic substrates is their permeability to moisture and oxygen, which degrade the OLED material.[13]

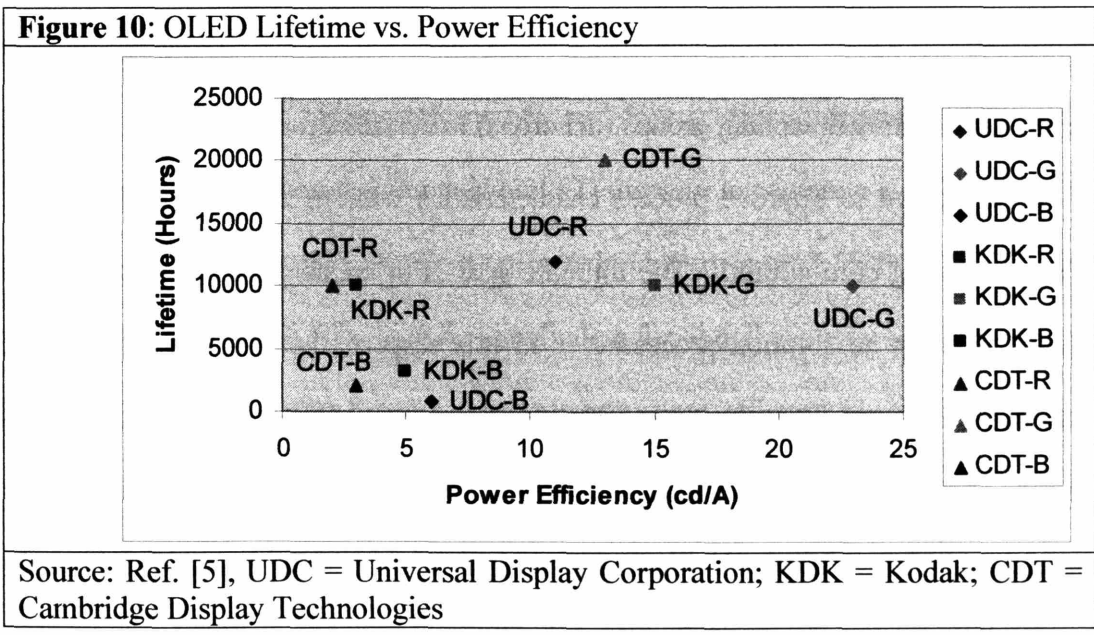
The development of printing technologies for LEPs is perhaps the best opportunity for existing inkjet companies to capture value in the OLED industry. Competencies in developing and driving printheads for traditional printing applications are directly relevant for deposition of OLED materials. Philips, CDT and others are already experimenting with inkjet deposition techniques.[13, 19] CDT recently acquired Litrex, a Fremont, California, startup that has developed a piezo inkjet-based machine tool for deposition of OLED materials.[20, 21] CDT is also partnering with Seiko Epson, the lone piezoelectric player in the mainstream inkjet printing market, as well as a manufacturer of active matrix backplanes.

There is, however, no guarantee that inkjet will become the printing method of choice for OLEDs. Toppan, a Japanese printing company, and world leader in production of color filters for LCD displays has recently announced acquisition of an



equity position in CDT and plans for joint development of OLED displays using light-emitting polymer technology.[22] CDT is clearly hedging their bets on which process technology will be best for creating LEP displays.

A third technology being developed for the OLED display market is phosphorescent OLEDs (PHOLEDs). This technology is being developed by Universal Display Corporation (UDC, New Jersey) and research partners at Princeton and the University of Southern California. Phosphorescent OLEDs offer the potential of near 100% efficiency as opposed to a maximum of around 25% for fluorescent OLEDs.[23] UDC has demonstrated better power efficiency (candelas/Amp) for all three primary colors (red, green blue) than is possible with either Kodak's small molecule or CDT's LEP technology.[5] See Figure 10. This higher power efficiency translates into longer



battery life for hand-held devices such as cell phone and PDAs. UDC recently announced a strategic alliance with DuPont to produce a printable phosphorescent OLED

material.[24] Such a material would combine the performance advantage of small molecule OLEDs with the printability of polymer OLEDs.

UDC has not lined up as many partners and licensees as Kodak or CDT but has forged key partnerships across the supply chain to allow them to take their technology to market. Although UDC has not yet commercialized a product based on their technology they recently demonstrated a working prototype of a cell phone (produced by partner Samsung) with a full-color active matrix display based on the PHOLED technology.[25]

The fourth OLED technology under development is based on dendrimer technology being developed by Opsys Displays in Oxford, U.K. Opsys was founded in 1997 and is a spin-out of Oxford University.[26] Dendrimer-based OLEDs have the potential to combine the best aspects of small molecule and polymer OLEDs. Dendrimers are large, sphere-shaped macromolecules with a light-emitting core. The core is connected by branching groups (dendrons) to surface groups. The surface groups can be engineered to improve process characteristics without affecting performance of the light emitting core within. The ultimate goal is to create a phosphorescent OLED material that can be solution processed. In this respect, the goals of the dendrimer technology are very similar to what UDC is trying to achieve with their alliance with DuPont. Although dendrimer OLED technology has yet to be commercialized, it is attracting significant interest in the industry. In fact, Cambridge Display Technology recently acquired Opsys' entire dendrimer business. This move was likely intended to diversify CDT's OLED investment risk.

### 3.3.2 OLED Technical Challenges

Despite the exciting promise of the four contending OLED display technologies, there are significant technical obstacles. One important issue is device lifetime and stability. Differential fading of the LEDs can occur in just one month of on time and LED lifetimes can be as short as 1000 hours.[7] These shortcomings must be resolved before OLED displays can be used in high “on time” applications such as monitors and TVs. Short OLED lifetimes are, however, not a major issue for low on-time, small screen applications such as cell phones, and audio and appliance displays. For example, cell phone screens typically see only about 200 hours of use before being replaced. It is in these markets where OLED is finding a commercial “beachhead”. See Figure 8.

The first significant commercial applications for OLED displays have been color displays for high-end cell phones. This application requires only a small screen and plays well to OLED’s strong video performance and low power consumption. Growth in demand for 3G cell phones should enable OLED displays to capture a significant share of the cell phone display market, which is estimated to grow to \$7.5B by 2005.[7] Other early opportunities for OLEDs include viewfinders for digital cameras and PDA displays. Ironically, OLEDs are also being investigated as more efficient backlight sources for traditional LCD displays. The biggest opportunity for OLEDs is to make sufficient improvements (lifetime, cost) to be able to take on LCDs in the market for the larger displays (>15”) used in laptops, monitors and TVs. Such improvements, however, are probably 5-10 years away. Figure 8 shows the predicted advance of OLED technology into various markets over time.

Another issue is that OLED displays, like LCDs, require matrix backplanes to enable their operation. Passive matrix backplanes for OLEDs can only drive small displays (160x120 pixels) before hitting voltage limits; active matrix backplanes are thus required for most applications. Active matrix backplanes for OLEDs require several transistors per pixel to achieve the needed current control and are thus even more complex and expensive than those required for LCDs.

Fortunately, the higher performance polysilicon backplane technology being developed for the LCD industry can support the additional logic required for OLED active matrix backplanes. The polysilicon backplanes are, however, more expensive than the amorphous silicon backplanes used in most LCD displays and offset some of the OLED cost advantage. OLEDs ability to leverage a key enabling technology for LCD displays make it a modular rather than a radical innovation and should help speed its adoption.

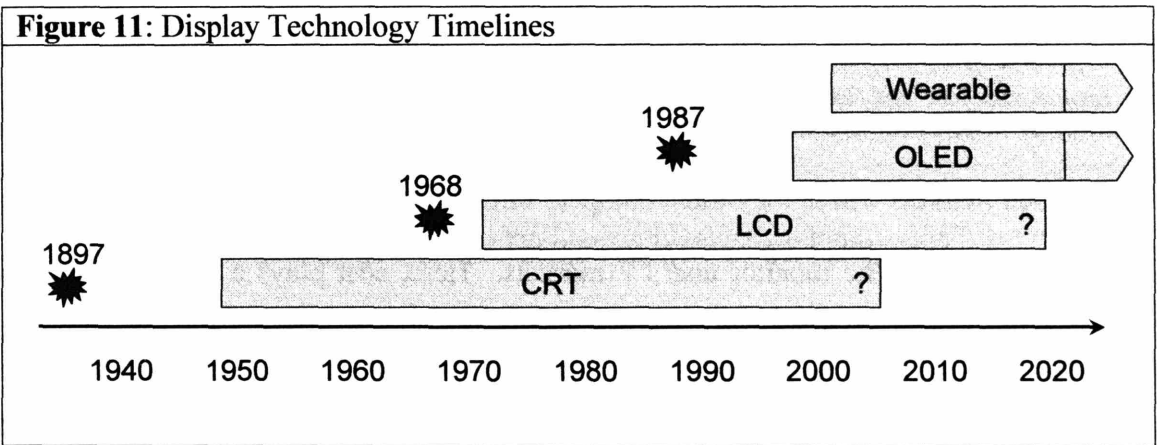
Fabrication costs also pose a challenge. Although OLED displays should have a cost advantage after several years of high volume production, the technology will probably be more expensive initially due to high startup costs and low yields. Major cost breakthroughs are possible if low cost roll-to-roll processing can be realized.[13] Roll-to-roll processing not only requires deposition of OLED materials on plastic but also development of better packaging and encapsulation methods to protect sensitive OLED materials from light and oxygen.

### ***3.4 Innovation Dynamics***

The display industry is a slow clockspeed industry.[27] It takes a long time for display innovations to be commercialized and to displace the dominant design. Over the

last century there have only been a few major display innovations, such as the transition from black-and-white to color CRTs and introduction of LCD flat panel displays.[9] The displacement of LCD displays by OLED displays may be the next major transition.

Evidence of this slow clockspeed is provided in Figure 11. For example, the CRT was invented in 1897, first commercialized in the late 1940s and is still the dominant large display technology today. LCD technology, invented in 1968, is just beginning to displace CRTs in markets where the two technologies compete. Similarly OLEDs, discovered in 1979 and first announced in the scientific literature in 1987, are just beginning to be commercialized in one or two narrow market segments.[12]



Innovations in display technology do not always come from within the mainstream industry. For example, the major OLED technologies were either developed by a firm outside the industry (Kodak) or in university research labs (Cambridge, Princeton, Oxford) that later spun out startup companies.

LCD display technology, on the other hand, did have its origins within the mainstream industry. It was initially developed in the 1960s by scientists at RCA, a major player in the television manufacturing industry at the time.[28, 29] This research

was motivated by RCA's chief executive David Sarnoff, who had the vision of a wall-mounted television. Although RCA invented LCD displays, they decided not to pursue their commercialization, perhaps because these displays did not satisfy needs of existing customers. RCA engineers then left the company and founded LCD startups such as Optel and Microma. Sarnoff's dream of a thin wall-mounted television was finally realized in 1988 when Sharp demonstrated a 14-inch color LCD display. RCA's failure to successfully commercialize disruptive LCD technology is very similar to dynamics of the disk drive industry, studied by Christensen, where leading companies consistently failed to recognize disruptive technologies until it was too late.[30]

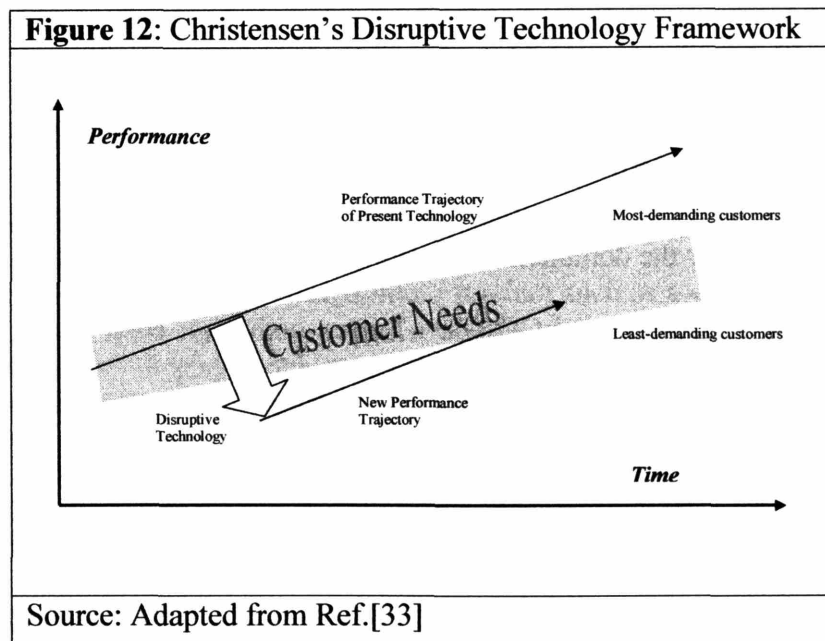
The diffusion of new display technologies is strongly influenced by the type of market in which they are introduced. Diffusion of new display technologies is slower in established markets where they must compete directly with the dominant technology as LCDs are doing in the monitor and TV markets. Here, cost plays a dominant role in driving display transitions.[14] Diffusion is faster when the dominant technology is not well suited to a new market; the rapid adoption of LCDs for laptop displays is a case in point.

The latter is a good example of the "compete against non-consumption" strategy suggested by Clay Christensen.[31] LCD displays helped to create a whole new portable computer market that had not existed before. Early portable computers, based on CRT displays, such as the Osborne, were just too big and clumsy for most people to use.[32]

LCD displays followed the "disrupt from below" trajectory into the mainstream display market; Christensen suggests that this pattern is typical of disruptive

technologies. See Figure 12. LCD displays were first adopted in niche markets such as calculators and watches where ancillary factors such as power requirements and form factor were more important than the primary CRT performance factors of price and image quality. LCD displays then appeared in laptop computers and are now attacking the mainstream CRT markets for televisions and desktop monitors.

LCD displays followed the disrupt from below trajectory into the mainstream market without ever being cheaper than the mainstream CRT technology (which Christensen suggests is usually the case). Christensen's contention that the mainstream technology will continue to improve until it exceeds what the mainstream market requires is also not borne out in the case of LCD and CRT displays. In this case, the dominant CRT technology reached a performance plateau years ago and has not continued to improve to levels that exceed what customers require.



OLED displays do not fit Christensen's definition of a disruptive technology as one that has lower performance and lower cost and initially penetrates a niche market on

the strength of ancillary attributes. Instead, OLED displays have higher performance and higher cost than the dominant LCD technology and are being introduced into mainstream markets where LCD displays are well entrenched. So far no major applications have been identified where OLED displays will not be competing with more mature technologies.

The major players in the dominant LCD technology are also not behaving according to the *Innovator's Dilemma* model. They are, as Christensen predicts, improving performance and going after higher margin customers (e.g., 30" and larger displays) but are also simultaneously aggressively reducing cost to increase market share in the desktop monitor and smaller screen television (< 30") markets. The fact that OLED displays do not fit with Christensen's framework certainly does not mean that they will not be successful in eventually displacing LCDs; it is indication, however, that this transition is unlikely to happen quickly and easily.

### **3.5 Technology Summary**

LCDs are by far the dominant flat panel display technology and will not easily be unseated in most applications. LCDs have issues with high cost, image quality, and power consumption but the major players have strong incentives to make improvements in these areas. Newer flat panel display technologies, plasma and OLED, are attacking LCDs at the extremes of the display size spectrum. For displays between 15" and 30" in size LCDs compete chiefly with traditional CRT technology. OLED displays have many compelling attributes and may eventually make LCDs obsolete but the technology is still immature and such a displacement is still some years away. Inkjet printing may become an important enabling technology for manufacturing of OLED displays. Unlike



Christensen's disk drives, OLEDs have higher price and higher performance than the dominant LCD technology and are attempting to compete in mainstream instead of niche markets.

## **4. Customer Preferences**

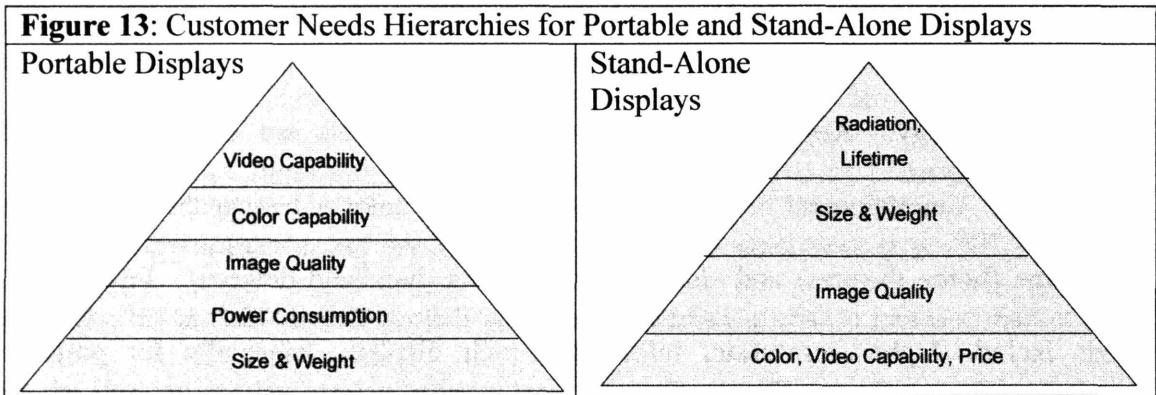
Customer preferences are an important driver for development of flat panel display technology. Key high level customer needs drivers are entertainment and information. Entertainment needs include high quality, color video-capable displays in both large (home theatres) and small screen formats (handheld devices). Information needs include higher resolution, information rich displays, especially for portable handheld devices, that can improve productivity. The growth in markets for products with very large and very small displays, where CRT technology is either not suitable or less desirable, has definitely fueled demand for flat panel displays.

### **4.1 Needs Hierarchies**

Figure 13 shows customer needs hierarchies for displays for both portable devices, where the display is integrated into a product such as a cell phone or PDA, and for large stand-alone displays such as computer monitors and large-screen televisions. Needs hierarchies are somewhat specific to the actual products that the displays are used in but this division provides a good sense of the differences between these major market segments.

For portable devices small size and weight are at the bottom level of the needs hierarchy; displays without these attributes cannot be integrated into handheld or portable devices. Flat panel displays for portable devices are thus not competing with mature

CRT technology. Just above size and weight in the needs hierarchy for portable displays comes power consumption. Handheld computing appliances run chiefly on batteries and the display is typically a major consumer of power. More power efficient displays can significantly extend battery life.



When these needs are met customers focus on image quality, which includes attributes such as brightness, contrast and resolution. The early Palm Pilot products were weak here but still saw high adoption rates. High resolution is particularly important for applications where the display is held close to the eye.

After image quality comes color capability, and finally video capability. Video capability refers to the ability to display high frame rate video feeds or movies. The advent of 2.5G and 3G wireless technology is expected to increase demand for displays that provide color and video capability in mobile environments.[5] Note that for some portable appliances such as digital cameras or 3G cell phones, color and video capability is a must, rather than a want attribute.

Stand-alone flat panel displays are used chiefly for desktop monitors and televisions. In much of this market FPDs, which are currently all LCD based, are displacing CRTs so the expectations for color and video are based on CRT performance;

these attributes therefore occupy the lowest level in the needs pyramid. Another low-level need for large FPDs is affordability; the major factor slowing diffusion of FPDs into large screen markets is price. For example, 17" CRT monitors are available for less than \$100 while 17" LCD monitors start at about \$400.[34] Similarly, a 20" CRT television retails for about \$200 vs \$2000 and up for an LCD TV.[34] Demand is proving to be strongly price elastic so demand is expected to ramp up as prices fall.[5] There is lots of room for growth since market penetration of FPDs is still quite low, 18 % for desktop monitors and just 2% for televisions. [5]

Next on the needs hierarchy for large format FPDs are image-related attributes. This is an area where today's dominant LCD technology is not particularly strong. LCD brightness, contrast and viewing angle are customer dissatisfiers. Emerging FPD technologies, such as OLEDs, address many of these shortcomings.

Further up the needs hierarchy for large FPDs are size and weight. The smaller size and weight of FPDs compared to CRTs is a major factor driving their adoption. Computer users appreciate the significant gain in desktop area achieved by switching to smaller form factor FPDs. Some office users are taking advantage of the smaller FPD form factor to add a second monitor to their desktops to boost productivity. Television buyers also appreciate the form factor advantages of FPDs. They are more space efficient and can even be wall mounted. Further, FPD technology (especially plasma) scales to screen sizes (>50") otherwise achievable only with bulky rear-projection systems.

At the top of the pyramid are attributes like radiation emissions, display lifetime, resolution and cost of ownership. These are areas where FPDs have advantages over

CRTs but are unlikely to become important competitive attributes until most of the lower-level needs are met. High resolution (200 dpi) is particularly important for handheld and portable devices where viewing distances are less than 12 inches. As discussed earlier, LCD display architecture limits maximum possible resolution.

## 4.2 Performance Comparison

Figure 14 compares OLED and LCD performance in areas important to customers. OLED performance is superior on almost every attribute. This performance dominance is the key reason that OLED displays are likely to eventually displace LCDs in both small and large screen applications. Price will be an important factor governing this displacement rate; development of manufacturing processes capable of producing OLED displays cost effectively is critical. The history of LCD displays shows the strong effect high prices have in slowing adoption in markets where the new technology is a substitute for an existing one. Also, OLED display lifetimes must be improved to 20,000 hours or better to allow the technology to break out of its current low display on-time product niche.

**Figure 14: Comparison of LCD and OLED Displays**

Attribute	LCD	OLED
Size		✓
Weight		✓
Brightness		✓
Bright Light		✓
Power Usage		✓
Radiation	✓	✓
Life Span	✓	
Resolution		✓
Response Rate		✓
Viewing Angle		✓
Price	✓	

Source: Ref. [35]

It is an important to note that the government, especially the military, is an important customer for flat panel display technology. Government needs are typically well ahead of those of other consumers and help drive development of emerging display technologies, such as wearable and “heads up” displays. Further discussion of the effect of government on display technology appears in the Regulatory Policy Dynamics section.

## **5. Industry & Business Dynamics**

### ***5.1 Industry Structure***

Like the memory chip industry, the LCD display industry is heavily concentrated in Asia, specifically in Japan, Korea, and Taiwan. Flat panel display manufacturing is capital and labor intensive and can only be profitably accomplished by large firms with significant expertise in high tech manufacturing and access to cheap labor. Both memory chips and LCD flat panel displays are commodity products which require huge capital investments (a new LCD fab costs \$1B) and offer only thin profit margins. The world’s #1 supplier is Samsung. Other major Korean players are LG Phillips<sup>4</sup> and Hydis. In Japan the major firms are Sharp, Hitachi and Toshiba. The major Taiwanese companies are AU Optronics, Chie Mei Opto and Chungwa Picture. [5]

The structure of the LCD display industry is quite fragmented across the value chain. See Figure 2. There is no one vertically integrated company that is active in all segments. Most firms in this industry participate in just one or two stages of the value chain. Since this industry is quite mature the major players in the R&D stage are chiefly the R&D departments of large display manufacturers such as Samsung and Sharp.

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<sup>4</sup> A joint venture between Phillips N. V. of the Netherlands and LG Electronics of South Korea.

Materials suppliers tend to specialize in one key input to the flat panel display such as glass substrates (Corning, Nippon Sheet Glass), liquid crystal polymer (Merck, Hitachi), or color filters (Toppan, Dai Nippon) and are rarely the same companies that actually make the flat panels. Process equipment for the LCD industry is supplied chiefly by companies such as Applied Materials that make similar equipment for the semiconductor industry.

The flat panel companies themselves tend to specialize in the complex panel manufacturing process. Some of them also make their own passive or active matrix backplanes while others outsource this step. Off-panel display driver chips are typically supplied by semiconductor companies. Some of the large, diversified Japanese companies (Hitachi, NEC) have this capability in house. Integration of the displays into final products is often done by OEMs; however, many of the large Asian companies also make their own monitors and TVs (Sharp, Hitachi, Samsung). Some companies such as Three-Five Systems specialize in integration of flat panel displays into specialty products.

Like the LCD display industry, the OLED industry structure is also quite fragmented across the value chain. The major differences between the two industries are in the R&D, materials development and process equipment stages. Participants in the R&D stage are the firms responsible for invention of one of the four major OLED technologies (CDT, UDC, and Kodak). With the exception of Kodak, which also has materials manufacturing capability, these firms license their technology to other firms in the value chain in order to create products. Firms in the materials stage are all chemical companies that have arrangements with the OLED technology companies to scale up manufacturing of OLED materials (e.g., Covion, Dow, DuPont) With the exception of

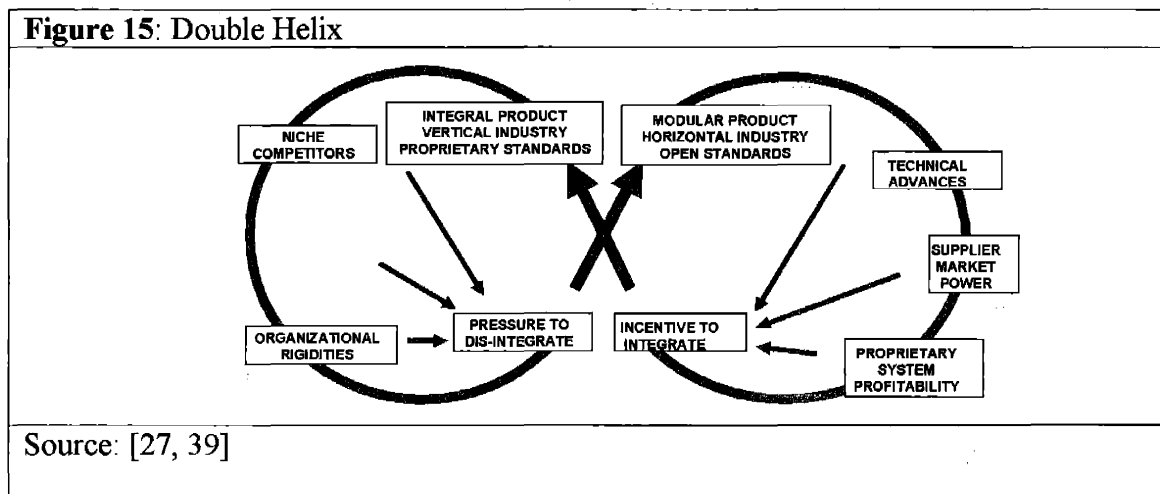
DuPont these chemical companies are not attempting to participate in other stages of the value chain.

DuPont sees high strategic value in OLEDs and is also making investments in both R&D and display module manufacturing. R&D investments include acquisition in 2000 of UniAx, a California-based company working in the LEP area.[36] DuPont has created an Olight brand for their OLED display products and began shipping evaluation kits to customers in December 2002. [37, 38] DuPont is definitely a company to watch as the OLED industry evolves.

A significant weakness in the OLED value chain is in the process equipment stage. Technology development is particularly immature for polymer OLEDs. There is considerable excitement over the potential of inkjet technology to evolve into a low cost manufacturing method but a product based on this approach has yet to be successfully commercialized. With the exception of Seiko Epson, the companies that are trying to develop inkjet into an OLED manufacturing technology have little previous experience with the technology. There appears to be a significant opportunity for major inkjet players such as HP and Canon to apply their years of inkjet expertise to development of OLED machine tools.

A key question is whether thermal inkjet, the dominant inkjet technology used for traditional printing, is well-suited to deposition of OLED materials. All of the OLED inkjet development so far is based on piezoelectric inkjet. Piezo inkjet seems to have some advantages in that it does not require vaporization of OLED material in order to drive drop ejection.

The rest of the value chain for OLED displays looks very similar to that for LCD displays. Companies that have licenses to build display panels based on OLED technology are largely firms that are in the LCD industry (e.g, Samsung, Philips). These firms have competencies in high volume display manufacturing and can leverage their knowledge of display control electronics. Finally, integration of the displays into final products and product distribution will be accomplished in the same way as for LCD displays. The fact that both LCD and OLED displays use similar matrix backplane technology makes this task easier.



Professor Charles Fine of MIT's Sloan School of Management has developed a double-helix framework which attempts to explain the evolution of industry structure over time.[27] See Figure 15. The OLED and LCD display industries are quite disintegrated and are on the right-hand side of the helix. Industry forces do not seem to be driving things back towards a vertically integrated structure very quickly. The last time the industry was strongly vertically integrated was in the early days of the TV industry in the 1950s, more than fifty years ago. This very slow transition from integration to dis-



integration is characteristic of a slow clockspeed industry. As discussed earlier, some consolidation is expected in the OLED industry once a dominant design emerges.

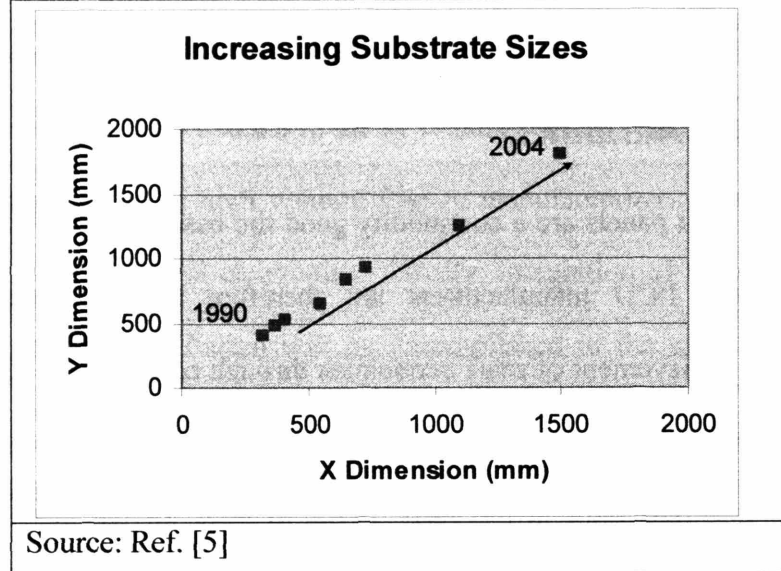
## **5.2 Competitive Attributes**

Since LCD flat panels are a commodity good the basis for competition is chiefly price. The major LCD manufacturers are therefore heavily focused on yield improvement and achievement of scale economies through construction of new fabs that can handle larger glass substrate sizes. Yields have improved from 60-70% for Generation 1 and 2 fabs built in the early 1990s to 90% for the latest Generation 5 factories.

Larger substrate sizes allow more flat panel displays to be produced from the same piece of glass and thus offer the same advantages that larger wafer sizes offer to semiconductor companies. The difference is that the LCD substrates are much larger than wafers. The latest Generation 5 substrates are 1.1 x 1.25 meters and yield a dozen 15" display panels each. Figure 16 shows the aggressive increase in substrate sizes over time. Substrate areas have doubled every 3.6 years since LCD fabs came on line in 1990. This compares to a doubling every 7.5 years for silicon substrates.

In the immature OLED display industry the basis of competition is chiefly on the performance attributes of the competing technologies. This type of competition is expected for an industry that has not yet produced a dominant design. Once a dominant design emerges the competitive dynamics should become more similar to that for the mature LCD industry with increased focus on scale economies and process improvements to reduce cost.

**Figure 16: LCD Substrate Sizes**



### **5.3 Industry Dynamics**

The dynamics in the LCD industry are consistent with Utterback's framework on industry structure.[40] The LCD display industry is a mature industry, characterized by a relatively small number of firms and heavy focus on process as opposed to product innovation. The dominant design for LCD displays is well established so the primary basis of competition is process innovations to reduce manufacturing cost and to improve image quality attributes. One opportunity for further efficiencies in the LCD industry would be standardization of substrate sizes. Within each size generation there are as many as five slightly different substrate sizes across different companies.[5] These size differences increase manufacturing costs because process tooling must be customized for each unique size.

The dynamics in the OLED display industry are quite different but also fit with Utterback's framework. This industry is immature and very much in the fluid phase.

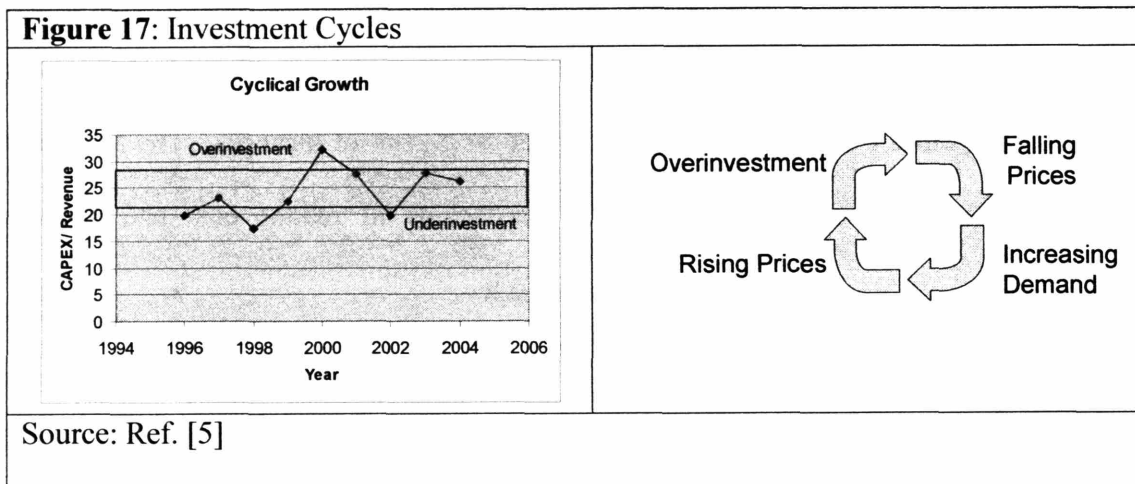
This phase is characterized by a large number of firms competing to establish a dominant design. At present there are over 80 firms participating in the OLED industry and four different technologies vying to become the dominant design. Utterback's framework suggests that a dominant OLED technology will eventually emerge. Once the dominant design is determined there will be a significant reduction in the number of participating firms as companies exit the market, are acquired or go out of business. The remaining firms will focus increasingly on process innovations to reduce cost and improve performance.

#### **5.4 Business Cycles**

The flat panel display industry is characterized by a strong supply-demand balance and is strongly cyclical. This cyclical nature is illustrated in Figure 17, which shows the ratio of capital investment to revenue over time. This metric signals overinvestment when above 30% and underinvestment when below 20%.<sup>[5]</sup> This cyclical trend is driven by the large capacity of new LCD fabs, which introduce additional supply in large chunks, and the strong price elasticity of demand for LCD displays in markets where they are substitutes for CRTs. Excess capacity leads to falling prices; the lower prices fuel demand eventually leading to increasing prices, which finally leads to another round of overinvestment. This cycle seems to have a period of about three years based on recent data. The LCD industry is quickly developing the moody boom-bust dynamics of other electronics commodities such as DRAM.<sup>[14]</sup>

The OLED display industry is too immature to have developed a characteristic business cycle. The technology is just beginning to be commercialized and some of the major players (e.g., UDC, CDT) are still chiefly focused on R&D and process

development. As the OLED display industry matures the bullwhip effect may impact the supply chain with companies further upstream seeing stronger cyclicity than those closer to the end product.

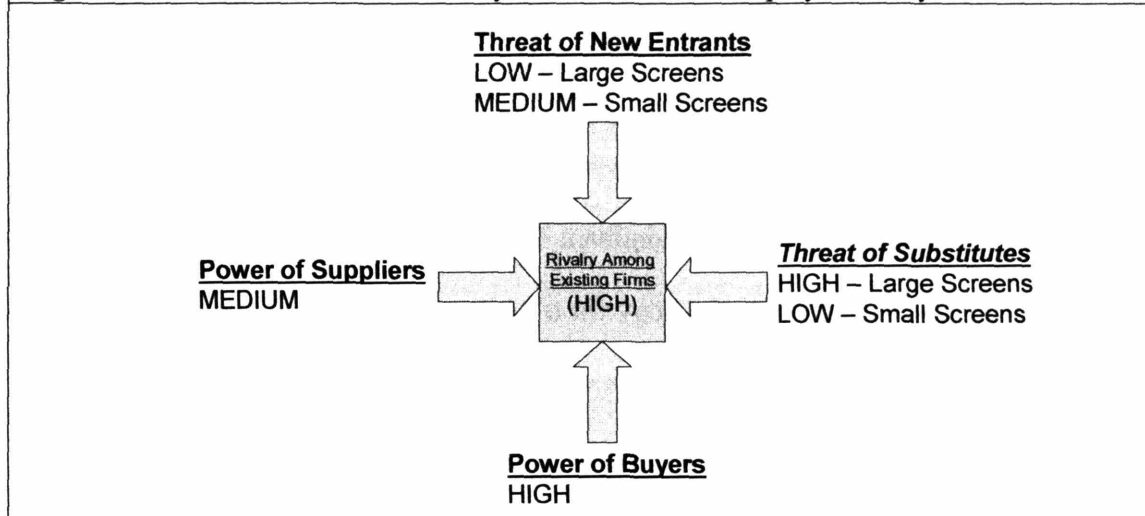


## 5.5 Corporate Strategy Dynamics

Porter's Five Forces framework is a useful tool for understanding the strategies that different firms are pursuing in the flat panel display industry.[41] A Five Forces model for this industry appears in Figure 18. For the mainstream flat panel display market, which is chiefly LCD displays for notebooks and monitors, rivalry among existing firms is high. As discussed above, LCDs have become a high-tech commodity product and the many firms in the business compete chiefly on price. For these same reasons, power of buyers is also high. Companies building laptops or monitors have many flat panel suppliers to choose from. They can switch suppliers relatively easily due to industry standards for displays.

The threat level of substitutes is high for larger LCD panels that go into desktop monitors and televisions; here CRTs are well-established and much cheaper. Threat of

**Figure 18:** Porter's Five Forces Analysis of Flat Panel Display Industry



substitutes is also high for the large display screen (>30") where plasma displays are well-established and rear-projection display systems are also an alternative. For smaller panels used in notebook computers and handheld devices, the threat of substitutes is low. CRTs aren't an option here and new technologies such as OLEDs are not yet well established. However, as OLED technology begins to penetrate the small screen market, there will be increased cost pressure on LCD manufacturers. Since, LCD display performance is largely inferior to that of OLEDs, LCD firms will have little choice but to compete with OLEDs on the basis of cost.

Threat of new entrants is relatively low for mainstream LCD displays. There are many players already and the high capital costs and low margins are likely to discourage new players. Further, new entrants are unlikely to enter this market with OLED technology before the end of the decade. On the other hand, threat of new entrants is somewhat higher for small screens, where LCD technology is ubiquitous. OLED technology looks like a credible threat to disrupt this market but significant disruption is probably 5-10 years out. Finally, power of suppliers to major LCD manufactures is

moderate. There are several large suppliers for important LCD materials such as liquid crystal polymer, glass substrates, backlights, and color filters. Suppliers of OLED material and technology will have high supplier power as this technology becomes more prevalent. Patent protection of the dominant OLED design should limit the number of competing firms offering this technology for a while. However, key early patents begin to expire as early as 2004 for small molecule OLED technology and 2007 for polymer OLEDs so this supplier power advantage may be short-lived.

The high levels of three of these forces (Rivalry, Buyer Power, and Substitutes) help explain the fierce competition in the mainstream market and concentration of manufacturing in Asia where high-tech manufacturing know-how and favorable cost structures co-exist. These high forces also explain why other firms are not rushing into the mainstream business and why non-Asian firms are focused on other parts of the display value chain, such as R&D and customization of displays for specific non-mainstream markets.

A key driver of corporate strategy for OLEDs is technology uncertainty. A dominant design has yet to emerge and it is still unclear as to which technology will win in the marketplace. Companies are trying to reduce risk by betting on more than one technology or limiting their commitment to just a portion of the value chain. Even larger players like Kodak and Philips are not pursuing a high investment, vertical integration strategy. The result is a complex web of licensing, joint development agreements, alliances and acquisitions. See Figure 9. Asian firms that are heavily invested in LCD displays are chiefly backing Kodak's more mature small molecule OLED technology. The small molecule technology, though probably not the least expensive in the long run,

allows them to get OLED display products to market sooner to defend their business as customer awareness of and preference for superior OLED displays develops. European and US companies that do not have a major LCD business to defend are chiefly backing the less mature but potentially less expensive polymer or other OLED technologies that can be solution-processed.

## **6. Regulatory Policy Dynamics**

Significant government support for the U.S. display industry comes from the military, specifically the Defense Advanced Research Projects Agency (DARPA). The military views displays as windows into the world of information. Information is an increasingly important part of modern warfare so advanced display technology is seen as having high strategic value. DARPA is interested in both rugged, low power, lightweight, portable displays that can be carried or even worn by individual soldiers and very large, high information content displays for use in command posts. DARPA is also very interested in the benefits of flat panel display technology for military aircraft. Their impact is particularly important for surveillance aircraft such as JWACS and JSTARS which have many displays. DARPA estimates that replacing CRT displays in these planes with flat panel displays would improve mean time between failures (MTBF) from 500 hours to 3300 hours and save over 1000 pounds of weight.[42] DARPA funds display-related R&D at both companies and universities. Projects are selected which promise to provide the military with display technology that has a clear advantage over what is commercially available.

Past DARPA-supported successes include development of the world's highest resolution active matrix LCD (3072x2048) by Xerox.[43] This technology is intended to

be used in the target acquisition and pilot night vision systems in the Apache attack helicopter. Another DARPA funded innovation was a reflective LCD display that can maintain static images after power is turned off. This display is intended for mobile applications where power consumption is a critical factor. Although DARPA has had success with LCD-based display innovations, they have also supported research on OLED-based displays. The potential of OLED technology to enable very lightweight, flexible displays as well as wearable displays has been of particular interest. DARPA grants may be a good source of early, external research money for development of the manufacturing technology, such as inkjet printing, required to enable these OLED display innovations.

Although DARPA sponsorship of various R&D projects has been important for driving innovation in flat panel displays, perhaps the most visible DARPA activity in support of the U.S. display industry has been its role in creation of the U.S. Display Consortium (USDC) in 1993. The USDC is an industry/government partnership devoted to maintaining a competitive flat panel industry in the United States.[44] According the USDC web site, "USDC's technical mission is to develop the supply chain required to enable the manufacturing of most flat panel display technology options. R&D projects are supported for the development and commercialization of innovative new equipment & process technology for front-end and back-end manufacturing process steps; of new materials required to produce displays; of procured components required for display fabrication; and for software, hardware and design analysis for factory automation and CIM operation." USDC's scope is thus very similar to the original scope of Sematech, an industry/government consortium formed in the early 1980s to help maintain a healthy,



competitive semiconductor industry in the U.S. USDC is focused not on helping companies get specific products to market but rather upon insuring that the U.S. maintains a competitive domestic manufacturing infrastructure in display technology. To date USDC has spent \$100M on projects toward this goal.

The USDC would be an ideal partner to work with on development of an inkjet-based manufacturing tool for OLED displays. The need to improve manufacturing capabilities for OLED displays is an excellent match with USDC's mission to improve domestic manufacturing infrastructure for display technology.

## **7. Analysis & Recommendations**

This chapter has reviewed the key technology and business issues related to evolution of the flat panel display industry. This review has brought to light interesting opportunities for players in the traditional inkjet printing industry to capture value in the fast growing flat panel display industry. Specifically, the promise of inexpensive, lightweight, flexible displays based on printable OLED materials can only be fulfilled if a reliable, low cost process technology can be developed to apply the OLED materials to plastic substrates. Inkjet printing seems ideally suited to this task given that it is a mature technology that has evolved to perform a similar job with traditional ink on paper.

Inkjet can generate a pattern directly from digital data and requires no pattern-specific tooling. Further inkjet is non-contact, which eliminates risk of contamination of the OLED "ink" by the substrate. Finally, inkjet is a purely additive process with no chemical waste. In spite of its maturity for traditional printing, several issues must be addressed for inkjet to successfully evolve into a display manufacturing technology.

## **7.1 Inkjet Challenges**

A key question that must be answered is the degree to which inkjet can be scaled up from a low cost, relatively low performance printing technology to a high performance manufacturing technology. The design criteria for these two applications are quite different. For consumer printing, dominant design criteria are print quality, cost and ease of use. For a manufacturing application the important design criteria are likely to be speed, quality and reliability. Cost of the tool and supplies will be less important since the printing machine tool and its supplies would be part of a high value-added manufacturing process and would not be sold through highly competitive retail channels. Reliability and quality will be critical to keep scrap costs low.

An early test of how well inkjet technology can scale to commercial applications is Phogenix, a Kodak-HP joint venture. Phogenix is a commercial photofinishing system that generates color prints from traditional film or digital sources using inkjet rather than silver halide technology.[10, 45] It is, however, too early to tell whether inkjet will prove to be disruptive to traditional photofinishing technology.

Another issue which needs to be addressed is identification of the inkjet technology, piezoelectric or thermal inkjet, best suited to a display manufacturing application. Most all work to date on inkjet printing of polymer OLEDs has focused on use of piezoelectric inkjet, not thermal inkjet, which is the dominant inkjet technology for consumer printing. Litrex, a subsidiary of CDT, and Seiko Epson are actively exploring the piezo approach. Piezoelectric heads are more costly to manufacture but afford greater flexibility in the type of fluids which can be dispensed.

Thermal inkjet printheads are less expensive to manufacture and support higher nozzle densities. Thermal inkjet technology is thus very well suited to consumer printing needs but its suitability for display printing is largely unknown. In thermal inkjet printing the material to be jetted must be capable of being boiled on the surface of a thin film resistor. Expansion of the bubble that forms on the resistor provides the driving force for drop ejection. This mechanism works very well for aqueous-based inks but little is known about its performance in other solvents that may be required to dissolve polymer OLED materials. Thermal inkjet obviously involves some heating of the fluid. Although only a very thin film of liquid is boiled, bulk fluid temperatures can reach 50-60C. The ability of OLED materials to withstand this kind of heating is not understood. Further, some fluids also leave a thin film of deposits on the resistor surface as a result of the repeated heating. These deposits, called kogation in the industry, can result in degraded printing performance.

Exploration of the merits of thermal inkjet for display printing would require establishment of a partnership with one or more companies currently developing soluble OLEDs (CDT, UDC, Dow, DuPont). These firms would likely welcome interest from a major inkjet player in strengthening the weak manufacturing stage in the value chain. Additional funds for pursuing this research might be available in the form of a DARPA grant; DARPA has a keen interest in the success of technologies that could enable flexible displays. Further support might be available through USDC if the investigation progresses towards development of an inkjet machine tool for display manufacturing.

A key business question related to the development of inkjet-based process tools for OLED display manufacturing is one of value capture and profitability. It is well

known that most of the profit in consumer inkjet printing comes from selling the supplies not the printers. In turn, most of the profit from the supplies comes from the ink itself and not the cartridge. In the case of OLED supplies the inkjet companies would not be developing and providing the OLED “ink”, which is being developed by companies such as CDT and DuPont. If the consumer inkjet business model holds, much of the profit stream from inkjet manufacturing of displays may flow to the companies developing the OLED materials and not to the companies making the process tools. The inkjet companies could thus end up being chiefly equipment vendors and be denied much of the profitable supplies business. The process equipment business is highly cyclical and considerably less attractive than a supplies-driven business which derives steady revenues from an installed base. Inkjet companies venturing into the display manufacturing business will need to structure their alliance agreements with OLED suppliers very carefully in order to insure capture of a fair share of the profits. As key OLED patents expire toward the end of the decade inkjet companies may be able to begin formulating their own OLED materials and thus increase their supplies profits.

Even if the technical and business challenges discussed above can be overcome, it is not a given that inkjet will become the dominant process technology for display manufacturing. The flexibility of inkjet printing with respect to pattern generation has somewhat limited value for display manufacturing where the pattern of OLED material on the substrate is consistently the same (repeating spots of red, green and blue). Given this consistent pattern, a significant threat to inkjet as the deposition method of choice for polymer OLEDs is the more traditional printing technology used by Toppan and Dai Nippon to create the color filters for LCD displays. If this technology can be successfully

adapted to print OLED materials, it, and not inkjet, could become the method for choice for OLED display manufacture.

## **7.2 Adoption Accelerators**

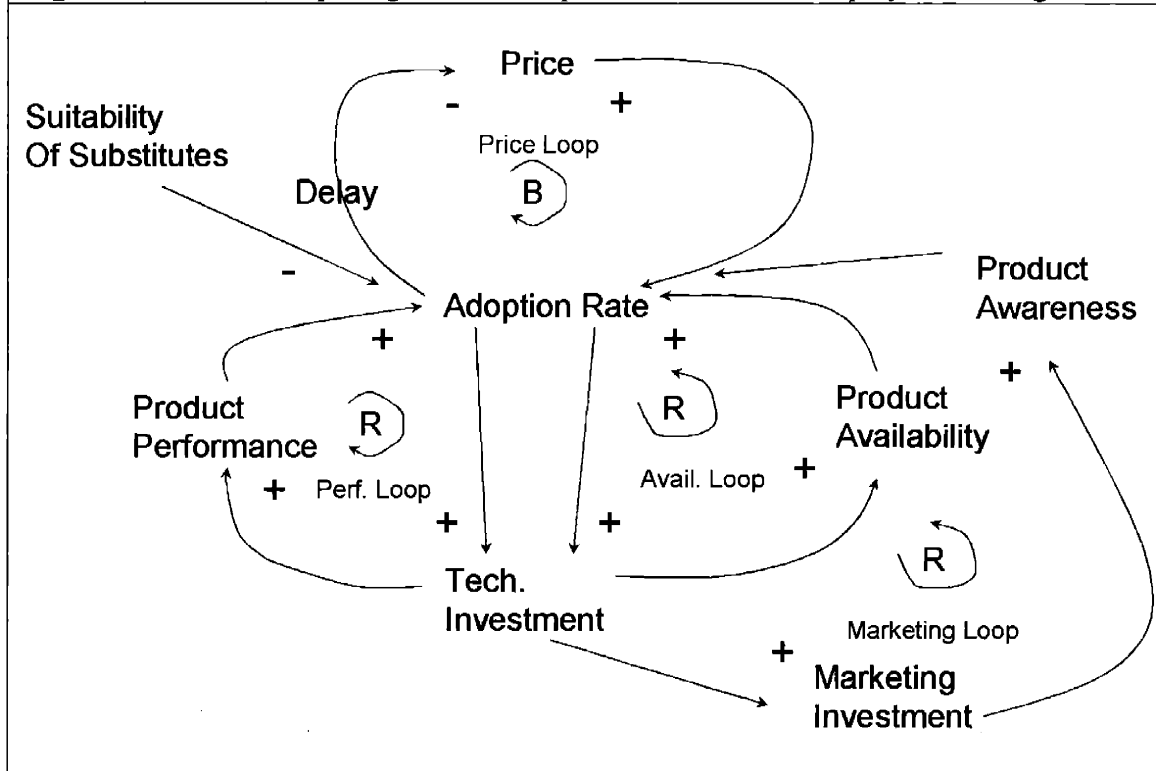
### **7.2.1 Casual Loop Diagram**

Historical data reviewed in this chapter shows that the display industry has been characterized by slow clockspeed or slow adoption of new technologies. The casual loop diagram in Figure 19 shows key factors driving adoption rate of new products in the display industry.

Key factors include product availability, product performance, product awareness, suitability of substitutes, and price. The “chicken and egg” problem is that up-front technology and marketing investments are required to “jump start” the Price Loop which becomes important as adoption rate climbs and economies of scale drive cost and price reductions. Note that there is a delay before adoption rate impacts prices; firms cannot, therefore, wait for demand to materialize before making investments in technology and marketing.

The casual loop diagram helps explain the importance of technology investment by government (e.g., DARPA, US Display Consortium) in helping drive adoption rate. The government does not require a quick or certain payback to justify its investment. The emergence of a dominant design will also boost technology investment by focusing investment, now spread across four competing technologies, on the one that the market really wants.

**Figure 19: Casual Loop Diagram for Adoption Rate of New Display Technologies**



The existence and suitability of substitutes is a very important factor. Adoption of LCDs in large screen markets (monitors and TVs) has been slowed by the existence of a strong substitute product (CRTs) as well as by low performance and high prices. Adoption of LCD displays in small screen markets was much faster due to the lack of a substitute technology. Without a substitute technology, significant adoption rate can be realized even with higher prices and lower performance.

### 7.2.2 Importance of New Products

A key to accelerating the clockspeed for OLED displays will be creation of new products where LCD displays are not good substitutes. These markets will be ones where the OLED display attributes of brightness, video capability and low power consumption are important and can command a price premium; recall that these are all

areas of weakness for LCD displays. Small screen markets should be attacked first since performance requirements (especially display lifetime) are lower and manufacturing is easier. Adoption and acceptance of the technology in these markets will help spur adoption of larger form factor OLED displays as the technology matures.

Figure 20 shows the production figures for products which require small flat panel displays for 2001 and the forecast for 2004.[46] The cell phone market represents the biggest opportunity with 80% of the demand and ten times higher volume than the next biggest market.

<b>Figure 20</b> <b>Small Screen Product</b>	<b>Units (thousands)</b>	
	<b>2001</b>	<b>2004E</b>
DVD Players	20,200	34,300
Digital Still Cameras	14,754	18,430
Camcorders	11,847	12500
Car Navigation	4100	6000
Hand-held games	12,000	16,500
PDAs	9165	13,780
Cell Phones	346,400	464,199
Ref. [46]		

The first such small screen market where OLEDs displays are likely to see high adoption rates is likely to be that for 3G cell phones. Cell phones with 3G technology not only provide wireless phone service but also allow users to surf the web and download games as well as music and video clips. Some phones have built-in cameras that allow users to send still photos as well as digital video. These phones require bright, color video-capable screens with low power requirements and are thus a very good fit for OLED technology. At present, only Japan has significant 3G infrastructure but Europe and the U.S. should begin to see availability over the next several years. Pricing for 3G services is likely to be a key factor in acceptance of this new wireless technology.

The portable DVD player market is also well suited for disruption by OLED display technology. Much of the value proposition of these products is related to display quality and battery life. The brightness and fast refresh rate of OLED displays are particularly important features for this market. Further, portable DVD players with OLED displays will almost certainly be able to command a significant price premium. Handheld game products have similar display requirements to DVD players and are another opportunity for early market entry for OLED screens. The high CPU power consumption of handheld games makes the power efficient OLED display particularly attractive.

In addition to cell phones, DVD players, and handheld games, entirely new products are being developed that could take good advantage of OLED displays. One such example is the Lyra Audio/Video jukebox made by RCA.[47] This handheld product, currently priced at \$399, features a 3.5 inch color screen. It not only handles music downloads but can also record up to 80 hours of programs directly from your television. Such innovative new products will help drive adoption of OLED displays.

Penetration of OLED displays into other small screen markets such as camera and camcorder displays and mainstream PDAs is likely to take longer. In these markets, the display is a less important part of the product's value proposition and consumers are less likely to be willing to pay a significant price premium for OLED displays. Displacement of LCD displays in these markets will probably require the price of OLED displays to decrease significantly.

OLED penetration of the markets for larger (>10") displays is unlikely to occur until late in the decade because the technology will simply not be ready before then. At



present only a few prototypes of large OLED displays have been built and volume production is some years out. Further, OLED display lifetimes must improve significantly before they can be deployed in these markets. When laptop-size OLED displays do become available, their adoption will depend strongly on awareness and market acceptance of the displays in the small screen markets discussed above. If OLED displays are successful in the small screen markets, they should be able to gain an early foothold at the high-end of the laptop market.

For example, an OLED display would enable a super light-weight notebook with a brilliant display and superior battery life. The new machine would dominate competing LCD-equipped models on the important attributes of weight, display performance and power consumption and should be able to command a significant premium. Another OLED-equipped high-end model might include a large screen and built in DVD player and be tailored for multimedia and entertainment applications. As with small screen products, adoption will depend on finding markets that value the attributes of OLED displays and are willing to pay a premium to get them.

OLED displays are likely to eventually penetrate the market for large screen displays (> 30"). This penetration will occur after OLED displays have a significant presence in the medium size display market (10"-30"). In addition to price, a key adoption driver for large OLED displays will be wide availability of broadband to the home. Video-on-demand services, in particular, are likely to encourage purchase of large screen displays for home theatres. The super-thin form factor of OLED displays will allow them to be easily wall-mounted almost anywhere.

### **7.3 Winners and Losers**

As discussed earlier in the chapter, a dominant design for OLED displays has yet to emerge. Which of the competing technologies is likely to emerge as the winner in the marketplace? According to Utterback, it is doubtful that the dominant design can be recognized except in retrospect.[40] He claims, however, that simplicity and technological elegance are characteristic of many dominant designs. Although it is impossible to be certain as to how the future of the display industry will unfold, it is interesting to speculate on what might happen.

The small molecule OLED technology pioneered by Kodak clearly has the first-mover advantage. Kodak has broadly licensed its technology, mostly to Asian firms already in the display business, and products with small molecule color OLED displays have already been introduced. This technology does, however, require complex and costly vacuum processing and does not scale readily to low cost manufacturing using flexible substrates and roll-to-roll processing. This shortcoming may very well prove fatal in the highly cost-competitive display industry. Further, Kodak's partner list, though long, does not include many highly innovative firms that could help Kodak find a market for their technology where it does not have to compete directly with LCDs.

Low cost manufacturing is much better supported with polymer, or perhaps dendrimer OLED materials that can be solution processed. Although these technologies are less mature, they seem better suited to fulfilling the long-term potential of OLED technology to provide very lightweight, low-cost, flexible displays. Cambridge Displays is the leader in this area and has strong partners such as Philips and DuPont to help get its technology to market. CDT is also partnering with both inkjet and traditional printing

companies in efforts to quickly identify the best manufacturing approach. CDT's recent acquisition of Opsys' intellectual property puts them in an excellent position to capitalize on emerging dendrimer technology, which may have some advantages over CDT's own polymer OLED technology. Although CDT is a small company, their history shows that they are very agile and business savvy. They have chosen partners carefully and attempted to diversify their risk throughout the value chain by investing in more than one partner or technology.

The only company likely to challenge CDT for dominance in solution-processed OLED materials is Universal Displays. Although UDC's more mature phosphorescent OLED technology requires a complex vapor phase deposition process, the company has recently announced a joint development agreement with DuPont to develop new phosphorescent OLED materials that can be solution processed. If this work is successful, UDC will have a very compelling product offering, especially since the UDC technology is the most power efficient available. UDC's success here might also provide an excellent partnering opportunity for a major inkjet player. UDC currently lacks a partner with the printing expertise required to take advantage of solution-processed OLEDs.

It is worth noting that UDC has a small but very capable team of partners, including Samsung, Motorola and Sony. The latter two are particular well known for product innovation and could help UDC deploy their technology in exciting new communication and entertainment products.

In conclusion, one can only guess at which OLED technology is likely to emerge as the dominant design. However, the OLED technologies that can be solution

processed are better suited to fulfilling the long-term promise of the technology and seem to better meet the criteria of simplicity and technological elegance that often characterize dominant designs. CDT is clearly the leader here but UDC could pose a strong challenge.

## **7.4 Strategic Recommendations**

The Roberts and Berry framework discussed in Chapter 2 provides valuable guidance to an inkjet company interested in the display manufacturing business. See Chapter 2, Figure 12. Here the inkjet company is quite familiar with the technology but unfamiliar with the display market. For this situation the framework suggests that a joint venture, venture capital investment or perhaps an educational acquisition would be appropriate strategies. Key partners for such activities would include CDT or UDC, and perhaps, one or more of their material development partners (DuPont, Covion, Dow). UDC is a particularly attractive partner since they are just now getting involved with printable OLED materials and do not yet have a relationship with a major player in the printing industry.

In these development partnerships inkjet companies will need to leverage the strength of their complementary assets, which are chiefly their ability to develop and manufacture inkjet printing devices. Process equipment is the Achilles heel in the value chain for OLED displays. Companies developing and manufacturing polymer OLED materials cannot capture value unless this material can be efficiently applied to substrates. Although their intellectual property around the OLED material may provide excludability, OLED companies have strong incentives to cooperate with major inkjet players in order to get their technology to market.

For major inkjet players to successfully exploit opportunities in display manufacturing, they must organize for success. Christensen's framework provides valuable guidance in this area.[48] As discussed earlier, development of an inkjet machine tool for display manufacturing is a poor fit with organizational values based on development of consumer inkjet printers; the important product attributes are quite different. Such a project may, however, be a good fit with organizational processes designed to get new products to market. In this case Christensen's framework suggests that a heavyweight team in a separate spinout organization offers the best chance for success. See Chapter 2, Figure 11.

## **7.5 Summary**

The flat panel display industry is a critically important industry; its products fundamentally impact how people work and play. Displays take data, whether for information or for entertainment, and make it useful and accessible. Displays are thus a critical enabling technology for a huge variety of technology products ranging from tiny handheld devices such as PDAs, cell phones and digital cameras, up to large area monitors, TVs, commercial displays and home theatre systems.

The display industry has historically been characterized by slow clockspeed; innovations are slow to be commercialized and can take decades to become dominant. Fifty-year old CRT technology still has the lion's share of the market for monitors and TVs. CRT technology is, however, increasingly unable to meet customers' evolving display needs. LCD displays are ubiquitous in handheld and portable devices where CRTs simply cannot be used and are beginning to penetrate the markets where they compete directly with CRTs. Despite its advantages, LCD technology is vulnerable due

to its high price, poor image quality attributes in several areas, and challenges in scaling to very large screen sizes.

Display technology based on OLEDs appears the most likely to displace LCDs. OLEDs offer the promise of lower cost, lower power consumption, and better image quality, especially for video applications. Even flexible displays appear possible. OLED technology is, however, immature and significant technical and production issues must be overcome before it will be competitive. Further, LCD manufacturers have huge investments in manufacturing assets and are thus highly motivated to lower costs and take advantage of strong price elasticity of demand. LCD manufacturers are fierce competitors and will not give up easily. OLED-based displays are likely to displace LCDs eventually but this transition could take a decade or longer.

Adoption of OLEDs can be accelerated by increased technology investment by firms and governments as well as by introduction of new products, such as 3G cell phones and portable DVD players, that exploit OLED's advantages over LCD displays. Adoption of OLED displays will increase if new markets emerge in which OLEDs do not have to compete directly with LCDs.

There is a significant opportunity for major inkjet players to capture value in the emerging OLED display industry. The promise of polymer or other solution-processed OLEDs to deliver cheap, lightweight and, perhaps, flexible displays depends upon development of a robust, low cost process technology to spray or print the material onto substrates. A first step for inkjet firms is establishment of a working partnership with a developer of solution-processed OLED materials. Such a partnership is critical to get access to materials for initial R&D, which include evaluation of which inkjet technology,

inkjet or piezo, is best suited for deposition of OLED materials. Once this decision has been made development of a process tool can begin. This development should be pursued by a heavyweight team in a separate spinout organization. This team must pay careful attention to crafting the business agreement with the OLED partner to insure fair sharing of supplies profits. Inkjet players must move quickly to capitalize on this opportunity. CDT is already partnering with Epson on inkjet development and has recently signed an agreement with Toppan to explore use of other printing technologies for OLED display fabrication.

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## Chapter 4

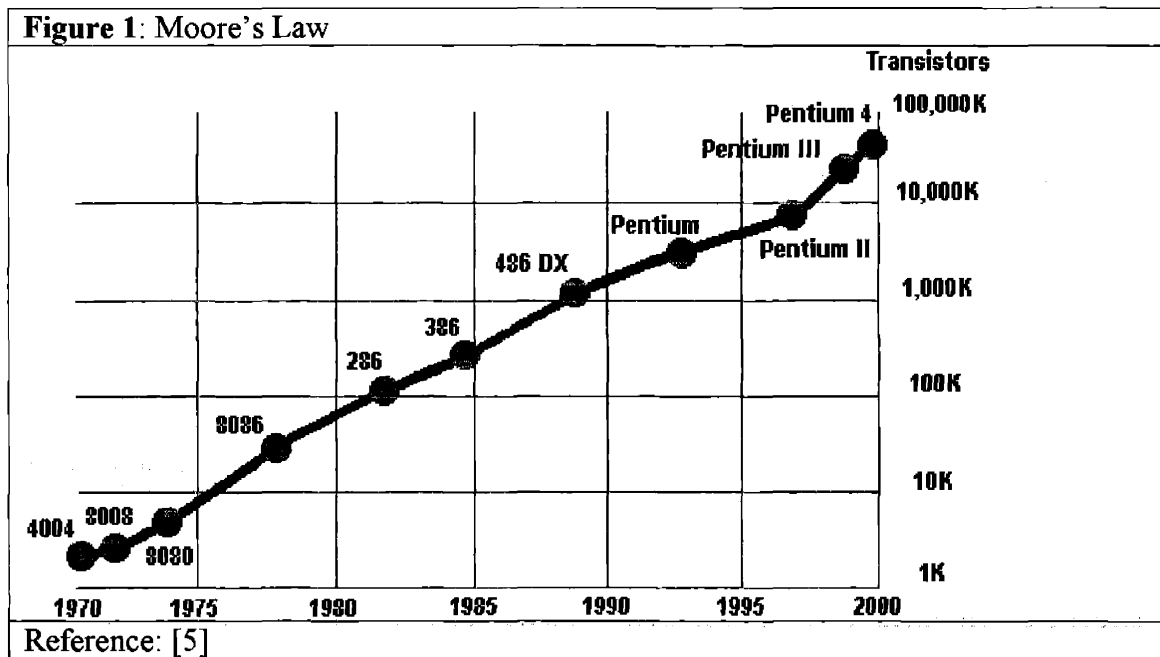
# Inkjet Opportunities in the Low Cost Electronics Industry

### Table of Contents

<b>1. Introduction</b> .....	<b>125</b>
<b>2. Product &amp; Markets</b> .....	<b>127</b>
2.1 Radio-Frequency ID Tags .....	127
2.2 Smart Cards.....	128
2.3 Flexible Display Backplanes.....	129
2.4 Solar Cells .....	130
2.5 Low Cost, Non-volatile Memory .....	131
<b>3. Technology</b> .....	<b>133</b>
3.1 Embedded Silicon .....	133
3.2 Polysilicon TFT on Plastic .....	136
3.3 Organic Thin Film Transistors (OTFTs).....	138
3.4 All Inorganic Transistors .....	144
3.5 Memory and Solar Cells.....	145
3.6 Technology Dynamics.....	148
<b>4. Industry Structure</b> .....	<b>149</b>
4.1 Value Chain & Industry Structure .....	149
4.2 Alliance & Partnerships .....	153
4.3 Competitive Attributes .....	154
<b>5. Analysis and Recommendations</b> .....	<b>155</b>
5.1 Winners and Losers.....	155
5.2 InkJet Challenges .....	157
5.3 Inkjet Recommendations.....	159
<b>6. Bibliography</b> .....	<b>161</b>

# 1.Introduction

The amazing progress in the field of microelectronics has been well chronicled.[1] For decades this industry has driven dramatic improvements in computing power and enabled an enormous variety of products and services that rely on digital technology. In 1965, Intel founder Gordon Moore predicted that the number of transistors per unit area would double every year or so.[2] This prediction, known as Moore's Law, has been borne out. For almost thirty years the number of transistors per unit area has doubled every 18 months (see Figure Figure 1).[3] The latest Pentium 4 processor from Intel has over 42 million transistors.[4] This exponential rate of improvement in transistor density and thus



chip performance has come at the price of high manufacturing cost and complexity. Today's semiconductor fab costs over \$1B and requires 2 weeks or more of round-the-clock processing to complete a single circuit.[6] This heavy investment of money and

engineering effort has lead to a wide variety of digital products, such as cell phones, laptops and video games that pervade many aspects of our lives. This relentless march towards ever higher circuit complexity and performance has, however, bypassed important emerging markets for low cost electronics. These markets value cheap, even disposable, circuits in which attributes such as large area coverage or flexible substrates are more important than gigahertz speeds or megabyte storage densities. Products that can take advantage of such low cost electronics include active matrix backplanes for displays (mentioned in Chapter 3), radio-frequency identification (RFID) tags, smart cards, solar cells, sensors, and memory.[7-10]

The key to achieving low cost electronics is development of new circuit manufacturing technologies that do not require expensive wafer fabs with their complex and costly lithography, implantation, and vacuum processing steps. These new circuit manufacturing technologies have more in common with the way newspapers are made than with traditional silicon processing. Companies are leveraging techniques such as roll-to-roll processing and printing methods, including stamping, embossing and inkjet, to create ultra-cheap circuits.

This chapter explores the emerging low cost electronics industry, with particular attention paid to the potential role of inkjet as a disruptive technology. The scope of this discussion will include review of new products and markets enabled by low cost electronics, examination of competing technologies, a look at industry and business dynamics, and conclude with analysis and recommendations with respect to the role of inkjet in this industry.

## **2. Product & Markets**

### **2.1 Radio-Frequency ID Tags**

RFID tags are perhaps one of the most exciting opportunities enabled by low cost electronics. RFID tags are tiny computer chips that function as electronic barcodes. They store information (up to 1MB but usually much less) that can be transmitted wirelessly to a reader that can be up to 90 feet away. Applications for RFID tags include access, security, tracking, logistics, anti-counterfeiting, and ticketing.[11] They are widely used for automatic toll pay on highways and tracking high-value items such as copiers, motorcycle parts and pets.[11, 12] RFID tags are very useful for creating unprecedented supply chain visibility. Companies can easily track parts throughout their supply chain; a pallet or box of RFID-labeled parts must only pass within range of a reader and each individual part will broadcast its unique ID to the tracking system.[13]

RFID tags are not new technology; they have existed in one form or another since the 1930s. There are hundreds of millions already in circulation and over 500 vendors selling RFID technology.[14] The RFID market is expected to grow to \$7.5B by 2006.[14] Despite the popularity of RFID tags, their adoption in less expensive consumer goods has been prevented by their cost. Today's silicon-based RFID tags cost from 30 to 40 cents up to a dollar, which is too expensive for use in products such as groceries and drug store items. Prices must drop to just a cent or two for RFID tags to begin to replace bar codes on inexpensive products.[15] Low cost electronics is expected to enable such price points and could eventually lead to near-universal adoption of RFID tags on all kinds of products. The flexible, plastic substrates used for low cost electronics will even permit their use in non-rigid products such as clothes and paper.

Such widespread adoption of RFID tags could significantly change the way that we buy and use products.

For example, grocery store checkout could be accomplished by simply pushing the loaded cart by a reader; there would be no need for handling and scanning each item. The RFID-equipped products could also communicate with appliances in the home. A shirt could tell the washing machine what settings to use and the pizza could broadcast the correct cooking settings to the oven. [15]

The ultimate vision is to create an “internet of things” where most all products incorporate RFID tags and a common standard allows any reader to read any tag.[13] Such a system would allow companies to track parts and products throughout their lifecycle and share information over the Internet. Realizing this vision depends upon establishment of communication standards, and, more critically, upon low cost electronics enabling penny price points

## **2.2 Smart Cards**

Smart cards are another market where low cost electronics could have a major impact. Smart cards are a natural extension of the RFID tag idea. While RFID tags only contain “hard coded” identification data, smart cards include read-write memory and even a microprocessor.[16] Smart cards can transmit their data to a reader wirelessly (like RFID tags) or through direct physical contact. They are used as smart credit cards which are charged up with prepaid dollars. Each time the card is used, the smart card is debited and the balance is written to the card’s memory. Such a system with wireless smart cards is currently in use on Washington D.C.’s subway system and will soon be implemented on transit systems in other cities.[16] Another smart card application is to



provide a more secure identification system for employees. The smart card can store biometric data such as fingerprint characteristics to be used for more secure building entry and computer access. In Europe smart cards are used to pay for phone calls. The cards store not only balance information but also phone numbers and other personal information that is instantly available on any card-equipped phone. Even in normal credit card applications, smart cards offer much better data security than magnetic strips.

Merchant's favor smart card adoption as a means to reduce the \$4B in annual losses due to credit card fraud.[16] Widespread adoption of smart cards in credit card applications is limited by the large \$11B cost of implementing smart cards, this cost includes the cost of the smart cards themselves as well as the necessary readers and data networks. A good chunk of this cost are the actual cards; today's smart cards cost \$4 or more vs. a few cents for a magnetic strip credit card.[16] Low cost electronics could enable significantly cheaper cards and thus hasten their adoption beyond the current niche markets of ID cards and subway passes.

### ***2.3 Flexible Display Backplanes***

As discussed in Chapter 3, display technology is evolving in the direction of cheaper, thinner, and perhaps, flexible displays. New display technologies such as organic LEDs and electronic ink permit the display material itself to be deposited on a flexible substrate.[17] However, these new display technologies still require a matrix backplane to drive the display.<sup>5</sup> Therefore, in order to achieve, an ultralight and flexible display the matrix backplane as well as the display material itself must be deposited on a flexible substrate. This need for flexible backplanes with thin film transistors capable of

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<sup>5</sup> Backplanes are discussed in some depth in Chapter 3 so the discussion here will be brief.

controlling display pixels is a significant opportunity for low cost electronics that can be built on plastic substrates.

## **2.4 Solar Cells**

Another exciting opportunity for low cost electronics is fabrication of cheap, flexible arrays of solar cells. Current energy consumption based on fossil fuels is not sustainable in the long run and it will become increasingly important to find renewable, nonpolluting power sources for the future. Solar power looks like a very promising alternative; every minute of every day the amount of solar energy that hits the earth exceeds the world's entire annual power needs.[18] Capture of even a tiny fraction of this energy could go a long way towards providing a steady supply of environmentally clean energy. A major obstacle to wider use of solar power, however, is the cost of the solar cells.

Most solar cells available today are built on expensive silicon wafers and cost per watt is three to four times that of electricity off the grid.[18] However, it is possible to build solar cells using much less expensive thin films of amorphous silicon or organic semiconductors that can be coated onto flexible substrates. Further, solar cells are relatively simple devices and do not require sophisticated circuitry. These two factors make solar cell arrays well suited to manufacture on flexible substrates using roll-to-roll processes.

Two startup companies, Iowa Thin Films and Konarka, have developed flexible solar cell arrays using such processes and are competing for leadership in this emerging market. [19-21] Their low cost and flexibility should allow photovoltaic cells to be used in many applications where they were not previously practical. For example, cheap solar

cells could eliminate the need for batteries in portable consumer electronics as well as camping and marine gear. In fact, Iowa Thin Films already offers a solar powered stereo headset.[21] Cheap, flexible solar cells could also be integrated into roofing tiles and clothing to provide environmentally friendly power at home or on the go.[20] Military applications of solar power are particularly compelling since they could help reduce the heavy load of batteries that the modern soldier must currently carry to power computers and communication equipment.[21] Perhaps the most exciting emerging application of cheap solar arrays is their potential as a clean, affordable energy source in off-grid locations in developing countries. SELCO, a pioneering solar electric power service company, is already working to implement such a solution in South Asia using conventional solar cells.[22] Low cost electronics could enable much less expensive solar cells and hasten their adoption as an energy solution in both developing and industrialized countries.

## ***2.5 Low Cost, Non-volatile Memory***

A fifth market for low cost electronics is that for cheap, non-volatile memory. Polymer memory is a low cost electronics technology that could become important in this market. Polymer memory devices are not yet available but are being aggressively developed as a cheaper alternative to non-volatile flash memory. Polymer memory cells have a much simpler architecture than their silicon counterparts and are thus expected to be both smaller and cheaper.[8] Unlike silicon-based memory, polymer memory can be stacked vertically to create three dimensional arrays.[23] This extra dimension could allow polymer memory to offer several times the storage density of silicon chips. Although prototype polymer memory chips are currently being produced in conventional

wafer fabs, their materials and design may eventually lend themselves to less costly manufacturing methods, such as inkjet printing.[8]

Early markets for polymer memory are expected to be non-volatile storage for portable digital devices, such as cell phones, PDAs, and MP3 players. Memory demand for such appliances is expected to increase with the wider availability of broadband internet capability which will encourage download and storage of large files (e.g., video). [24] When polymer technology is more mature it may be able to replace hard disk drives as the mass storage media of choice for personal computers and laptops. This application of polymer memory would provide significant user benefit by eliminating the time delay associated with boot up, thus enabling an “instant on” computer.

Successful penetration of the market for non-volatile memory is unlikely to be quick or easy. The market for “new” memory technology is expected to develop slowly, reaching only \$250M by 2006; which is just 1% of the overall memory market.[24] Even today’s dominant flash memory technology took a decade to become established. Further, there are several competing technologies which offer similar value propositions. Among them are magnetic RAM, ferroelectric RAM, and ovonic memory.[25] Newer technologies based on carbon nanotubes and molecular electronics are also targeting this market.[26, 27]

Low cost electronics technology is poised to disrupt a variety of markets. In general, these markets value low cost and a flexible form factor rather than speed and performance. These compelling attributes of low cost electronics stem directly from a radically different manufacturing approach that has more in common with printing than with traditional silicon circuit manufacturing. This approach allows circuits to be used

in new ways that are simply not practical with traditional silicon technology. The next section examines the different technologies being developed to take advantage of the significant opportunities in low cost electronics.

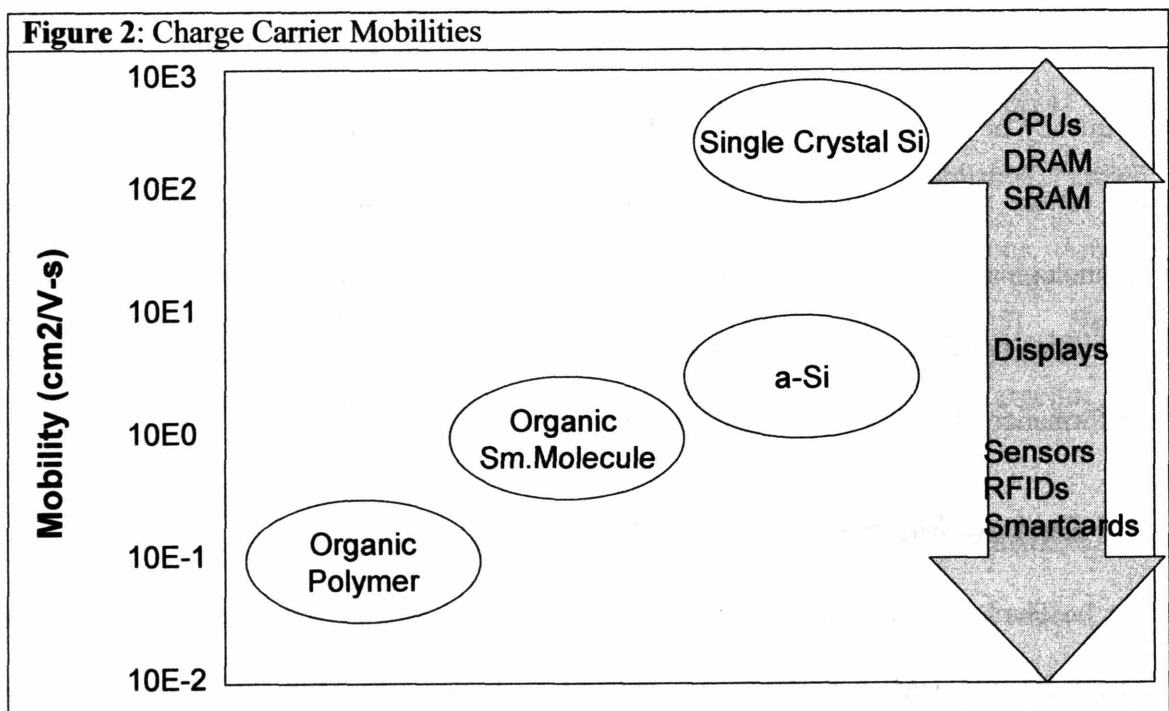
### **3. Technology**

Several different technologies are being developed to create circuits for low cost electronics markets. These range from those that leverage silicon chip technology, either by embedding traditional silicon chips in plastic substrates or applying silicon processing steps on plastic films, to those that use printing technologies to create organic or inorganic thin film transistors. A key factor in evaluating and understanding these technologies is the carrier (either electrons or holes) mobility that can be achieved. Carrier mobility is the speed that an electron or hole moves through a material in the presence of an electric field and is directly related to the maximum possible operating frequency of a transistor. Units for electron mobility are  $\text{cm}^2/\text{V}\cdot\text{s}$ . Figure 2 compares the carrier mobility of single crystal silicon to that for several low cost electronics technologies. Note that low cost electronics technologies do not enable the high electron mobilities possible with single crystal silicon and thus are not suitable for building high performance chips, CPUs or high-speed memory.

#### **3.1 Embedded Silicon**

The low cost electronics technology that is most similar to that used for traditional silicon circuits is Alien Technologies embedded silicon process.[28, 29] Alien is initially targeting the RFID tag market, but the technology can be used in other applications such as display backplanes. Alien's approach involves fabricating tiny chips, called

Nanoblocks, in a traditional silicon wafer fab. These chips range in size from tens to hundreds of microns across. Once the wafer processing has been completed the individual chips are separated from the wafer by wet chemical etching rather than precision sawing. This wet etch approach creates smooth beveled edges on the chips, which makes the dice look like tiny pyramids. The separated dice are then suspended in a liquid which is flowed over plastic webbing, which is handled with reel-to-reel equipment. The plastic webbing is pre-notched with holes that are the same shape as the tiny chips; the chips drop into these holes in the correct orientation as the liquid flows over the webbing. This approach, which Alien terms Fluidic Self-Assembly (FSA), allows accurate placement of thousands of Nanoblocks per second. Any unused chips are simply recycled and used to flow over another substrate



Once a substrate is fully-populated with chips, a polymer film is laminated onto the chip-embedded substrate to hold the Nanoblocks in place. Via holes etched through

this top layer and screen printed conductor traces are added to provide electrical connections to chips.

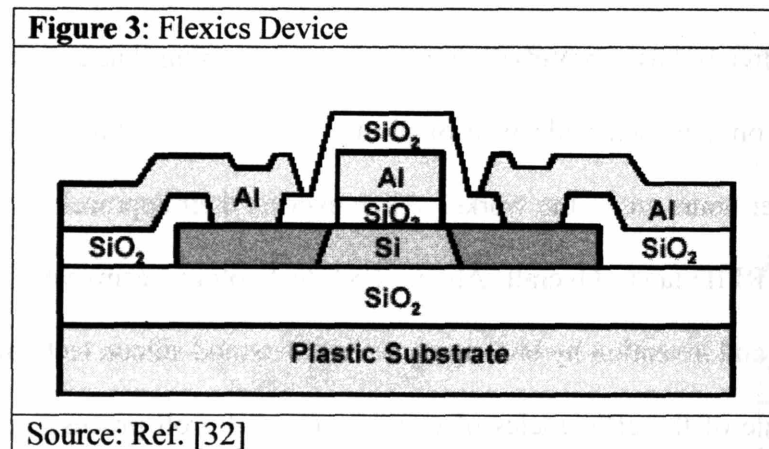
Alien's approach has the important advantage of separating fabrication of the circuit from that of the substrate. This approach avoids the significant challenge of trying to fabricate circuits directly onto flexible substrates. Instead, Alien's chips are generated in foundry fabs with well-characterized CMOS processes. The chips are very small and relatively simple (a few thousand transistors); yields and die per wafer are thus high and die costs low. Use of standard CMOS processing on silicon wafers also means that applications of FSA technology are not limited by carrier mobility (see Figure 2). Further, the chips can be tested prior to separation from the wafer so post-assembly yield loss is minimized. Since the circuits are not fabricated directly on the plastic substrates the reel processing is relatively simple; e.g., the plastic substrate is not exposed to vacuum or high temperature conditions.

Alien already has a prototype process up and running that can produce 250,000 parts per hour on a 6 inch wide web of plastic. Plans for a line that can produce 2 million units per hours are in the works. Alien expects their approach to enable a 5 cent price point for RFID tags. Overall, Alien's FSA technology seems very compelling. It minimizes risk and invention by leveraging well-understood silicon technology while still taking advantage of the efficiencies of continuous roll-to-roll processing. Reliance of silicon technology, however, rules out the possibility of quick and easy design changes or the possibility of desktop or very small-scale fabrication.

### 3.2 Polysilicon TFT on Plastic

Two companies, Flexics and Rolltronics, are pursuing low cost electronics technology that involves fabrication of polysilicon thin film transistors (TFTs) directly onto plastic substrates.[30-32] Polysilicon mobilities are around  $60 \text{ cm}^2/\text{V}\cdot\text{s}$ , enabling fabrication of all but the highest performance solid state circuits.[31] The technology used by both companies is licensed from Lawrence Livermore National Laboratories.[33] Flexics founders include scientists who developed the technology while at Lawrence Livermore.[34]

Like Alien's embedded silicon process, the polysilicon TFT technology leverages well-understood wafer fab processes. Figure 3 shows the Flexics device, which is based on standard CMOS processes. The key difference is that the polysilicon TFT approach



involves fabrication of active devices directly on a plastic substrate. A key challenge here is forming the high mobility polysilicon material while keeping the plastic substrate at a temperature of less than  $100^\circ\text{C}$ .[32] Low temperature polysilicon processes developed for use on silicon wafers involve process steps with temperatures of  $300\text{-}400^\circ\text{C}$



and are thus not suitable for use with plastic substrates. The polysilicon on plastic process involves several process changes to avoid exposing the plastic substrate to high temperature. A key process difference is the use of a laser to form the polysilicon film required for the devices. The laser results in local heating of the silicon film to over 1500C for about 1 microsecond, which is sufficient for it to melt and recrystallize to form higher mobility polysilicon. The short laser pulse and insulating silicon oxide film between the silicon film and substrate prevent damage to the plastic.

Flexics initial target market for their polysilicon on plastic technology is flexible backplanes for displays. They aim to develop a plug-compatible flexible backplane that display manufacturers can easily use instead of the standard glass backplanes.[34] Such plastic backplanes will make current LCD displays cheaper, lighter, thinner, and more rugged and will also be suitable for use with electronic ink or organic LED display materials to create flexible displays. Later markets for Flexics may include memory modules and optical component integration. [34]

Flexics plans to manufacture their products using roll-to-roll processing. Process development to enable this approach is currently underway. Meanwhile plastic substrate prototypes are being built on wafer-shaped substrates using standard batch-based fab equipment.[33]

Rolltronics, on the other hand, has already demonstrated the ability to manufacture transistors on plastic using roll-to-roll processing.[30, 35] This feat was accomplished in partnership with Iowa Thin Films, which has significant expertise in reel processing of flexible electronics from their core solar cell array business.[36] Rolltronics is planning to invest \$100M in a fab capable of generating 10 feet of plastic

circuits per minute. They are hoping to begin mass production of plastic components as soon as next year. Like Flexics, Rolltronics is targeting the display backplane market and expects to capture market share based on costs that are 5 to 10 times lower than those for glass backplanes.[36] Rolltronics also has their eye on opportunities in the RFID and sensor markets, where they expect demand for low-cost, moderate-speed, flexible logic circuits.

Overall, the polysilicon TFT on plastic technology looks promising. Many of the process steps are very similar to those used in fabrication of CMOS devices in a wafer fab. Further, process innovations that permit low temperature processing on plastic have been demonstrated. The lower mobility of polysilicon versus single crystal single silicon means that the polysilicon device performance will not be as good as that possible with Alien's embedded silicon process. It is, however, much better than that possible with organic or amorphous silicon transistors and is good enough for a wide variety of applications. See Figure 2. Since the polysilicon process still relies on traditional lithography methods to pattern films, design changes require fabrication of new photomasks and thus cannot be done quickly.

### ***3.3 Organic Thin Film Transistors (OTFTs)***

Several companies are working to develop transistors using organic semiconductor materials. This approach is a more significant departure from standard silicon processing than either the embedded silicon or the polysilicon TFT technologies. Rather than taking advantage of the well-understood semiconducting properties of silicon, organic thin film transistors (OTFTs) rely on semiconducting organic material. The advantage of this approach is that the tricky problem of figuring out how to combine

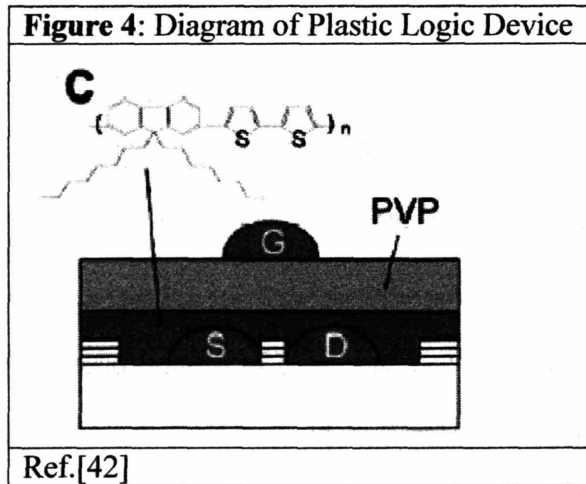
silicon with plastic is entirely avoided. The organic semiconductor material can be applied directly to the substrate with simple methods such as inkjet printing or stamping. Organic TFT technology is very well suited to applications where low cost and large area coverage are important.[10] Further, OTFT fabrication can be accomplished at low temperature and is thus compatible with plastic substrates. A drawback of OTFTs is their relatively low performance. This low performance results from low charge carrier mobilities, which typically range from 0.01 to 1 cm<sup>2</sup>/V-s (see Figure 2), and relatively coarse device geometries. Typical gate lengths for OTFTs are 5-10 microns, 40 or more times larger than gate lengths possible with silicon processing.[37]

Most all organic semiconducting materials are p-type and the charge carriers are holes, rather than electrons. [38] From an applications perspective it would be desirable to also have n-type organic semiconductors. Use of the both n-type and p-type organic semiconductors would enable fabrication of p-n junctions, inverters and more power-efficient CMOS circuits. Research into n-type organic semiconductors has shown them to be unstable and very susceptible to reaction with air and water. These problems will probably eventually be solved but initial products based on OTFTs will almost certainly be based on p-type devices. One way around the problem of building organic CMOS circuits is to combine organic and inorganic (e.g, amorphous silicon) transistors. [39] However, this approach adds process complexity.

Like organic LEDs, organic semiconductor materials are of two basic types, small molecule and polymer.[17] Small molecule materials such as pentacene exhibit higher mobilities (as high as 1-2 cm<sup>2</sup> /V-s, see Figure 2) but can only be applied to substrates using vacuum deposition processes. Polymer semiconductors can be solution processed;

that is they can dissolved in liquids such as xylene or toluene and applied to substrates using printing methods such as stamping or inkjet.[40] Mobilities of the polymer materials are, however, only one-tenth or less of those possible with small molecule materials.

One of the major players in development of polymer-based OTFTs is Plastic Logic, based in Cambridge, U. K. [41] Plastic Logic is developing all polymer transistors that can be built almost entirely by inkjet printing.[42] Inkjet is used to deposit conducting, insulating and semiconducting polymers as well as to create via hole connections. The only step that relies on traditional lithography is patterning of a thin hydrophobic polyimide film that sits on the plastic substrate. This film is needed to limit spreading of the drops of conductive polymer used to create the source and drain. A diagram of Plastic Logic's all-polymer transistor is shown in Figure 4.



There are two key advantages to this entirely printed device structure. First of all, most of the expensive equipment required in a wafer fab for patterning and etching thin films is not necessary. The capital cost for a manufacturing facility for polymer-based circuits are expected to be only 30-35% of that for a silicon wafer fab.[10, 43] Operating

costs are also expected to be lower. This cost structure should allow Plastic Logic products to compete at very low price points. The second important advantage of entirely printed devices is design flexibility. Since there are no photomasks to modify, circuit designs can be modified simply by changing the data file used to generate the printing pattern. The economical build quantity for a unique circuit is thus very small, perhaps even one. The ability to easily make design changes is advantageous for quick prototyping as well for mass customization of products.

The major drawback to Plastic Logic's all-polymer transistor technology is the inherently low performance of polymer semiconductor materials. Polymer transistors are competition only for amorphous silicon, not crystalline silicon technology. Plastic Logic's first target applications are RFID tags and backplanes for niche LCD displays and electronic paper.[43] A small active matrix backplane prototype with 4800 gates has been demonstrated but real product revenue is not expected until 2005. Further in the future Plastic Logic plans to deploy their technology in markets for sensors, memory and smart cards. Long term aspirations are ASICs and backplanes for high performance OLED displays; success in these markets will likely require a different technology.

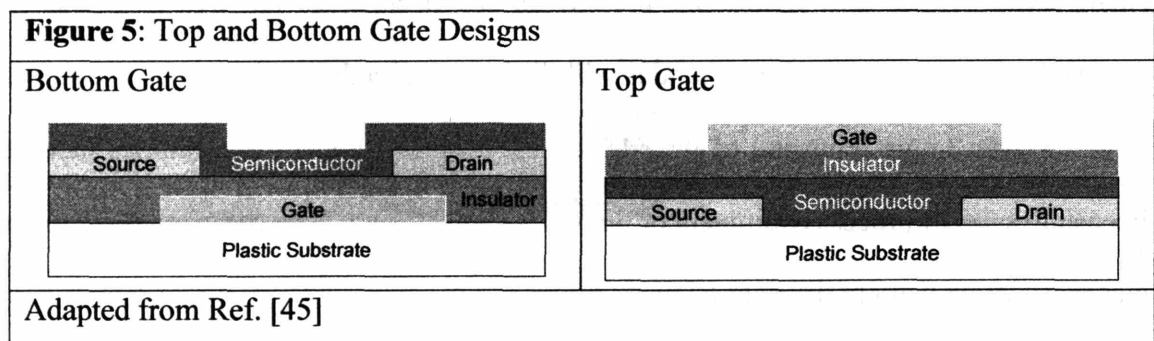
Plastic Logic is unsure of their long-term business model. Possibilities include licensing, sales of process equipment or limited manufacturing. The company plans to let customers drive them to the right business model.

Philips is also working on development of all-polymer transistors. Their devices are built using spin coating and lithography rather than inkjet printing.[44, 45] Although lithography is undesirable from a cost perspective, only three photomasks are required to make a transistor. Philips has experimented with both top and bottom gate designs (see

Figure 5). The top gate designs were used with a polymer semiconductor and resulted in mobilities of about  $0.001 \text{ cm}^2 / \text{V}\cdot\text{s}$ . [44] The bottom gate designs were compatible with higher mobility pentacene (small molecule) material which improved mobilities by a factor of 10.

An unusual aspect of both designs is the use of conductive polyaniline films for the gate and source/drain layers. This material's resistance increases dramatically (11 orders of magnitude) upon UV light exposure. Philips exposes the entire circuit except the gate or source/drain regions, which remain conductive. There is no need to remove material after the UV exposure step. Philips calls this technique for generating conductive and insulating areas in the same film photochemical patterning.

Philips has demonstrated functional integrated circuits on plastic with over 300 gates using both their top and bottom gate approaches. [44, 45] The Philips work on OTFTs has been within the central research lab; the company's plans for commercializing this technology are not clear.



Another major player in OTFTs is Bell Labs, now part of Lucent. Scientists at Bell Labs are using microcontact printing, rather than inkjet or lithography to build their devices. Microcontact printing, first developed at Harvard, relies on a rubber stamp that is made by first creating a master by patterning and etching a silicon wafer with the

required pattern using high resolution lithography. [46] Silicone rubber is then poured over the master to create a high resolution stamp. Although lithography is required to make the master, the resulting stamp can be reused many times to create thousands of circuits. [37]

The Bell Labs devices use a bottom gate configuration (see Figure 5). A low resolution stamp is used to pattern a gate layer of indium tin oxide which sits on the plastic substrate. An insulating layer is then deposited to cover the gate. The next step, patterning of the source and drain electrodes, is a critical step and requires a high resolution stamp. The separation of these electrodes must be 15 microns or less to guarantee adequate device performance. The source and drain electrodes are made of gold, which must be deposited in a vacuum system. Gold was chosen because it can be stamped with a special chemical ink (hexadecanethiol), which forms a protective monolayer on the gold surface where the source and drain electrodes will be. The unstamped areas are then etched away to complete formation of the electrodes. Finally a layer of semiconducting polymer is spin cast on top. Bell Labs has demonstrated mobilities of  $0.1-0.5 \text{ cm}^2/\text{V-s}$  with this approach.

Bell Labs is targeting active matrix backplanes for electronic paper as an initial application of their technology. [47] They are partnering with electronic paper display maker E-Ink in this effort. [48] The two companies have demonstrated a 1 mm thick, 6 inch square display (256 pixels) using the Bell Labs OTFT technology. This display is  $\frac{1}{4}$  the size and weight of an LCD display of comparable size.[49] Electronic paper is a good early application for OTFTs since it does not require high refresh rates and does not need fast-switching transistors to control the pixels.

IBM, Xerox and Siemens are also conducting research in OTFTs, but have not yet demonstrated prototype circuits or announced plans for commercialization. This research is focused chiefly on engineering of the organic semiconductor layer to achieve better stability and higher performance (mobility). There is also significant university research in OTFT development. Universities with active research programs in this area include UCLA, Penn State, and the University of Arizona.

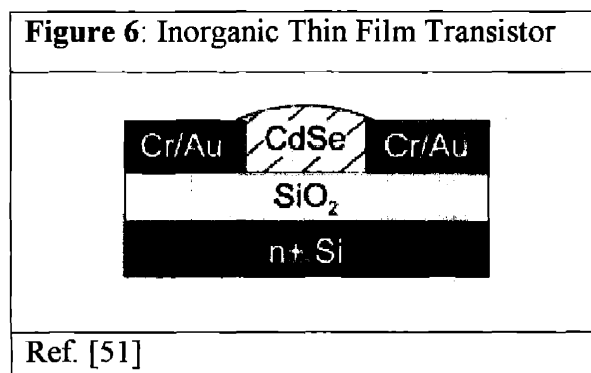
### ***3.4 All Inorganic Transistors***

Organic TFTs are clearly an important low cost electronics technology and have been the focus of work at several companies. One startup company, Kovio, is exploring an alternative low cost electronics approach based on all-inorganic printable materials. Kovio is a Silicon Valley startup employing nanoparticle ink technology developed at MIT's Media Lab. [50] The chief advantage of Kovio's printed electronics technology is the higher mobilities possible with inorganic semiconductor materials. Research at MIT has demonstrated mobilities for printed inorganic devices of up to  $1 \text{ cm}^2/\text{V}\cdot\text{s}$ , an order of magnitude higher than mobilities possible with printable (polymer) organic semiconductors. [51] Inorganic semiconductors (Si, Ge, GaAs) are the basis for most all high performance microelectronics and have intrinsic mobilities of  $1000 \text{ cm}^2/\text{V}\cdot\text{s}$ . Kovio's approach thus offers the possibility of printable electronics with sufficient performance for applications such as microprocessors. Printable inorganics may make the vision of a desktop fab where you can download and print your own circuits a reality. [6, 52]

Inorganic materials are typically not soluble in liquids suitable for printing. The MIT innovation that makes printing inorganic materials possible is based on solutions of



cadmium selenide nanocrystals. The nanocrystals are suspended in a solvent and printed onto a substrate. Nanocrystals have the unusual property of melting points that are as much as 1000C lower than bulk material. Thus a short sintering period at 350C is sufficient to turn the nanocrystals into a robust polycrystalline film. A diagram of the MIT device is shown in Figure 6. Although the initial nanocrystal work has been done with cadmium selenide, the general approach should be applicable to a wide variety of other semiconductor materials (Si, Ge, GaAs, etc.).

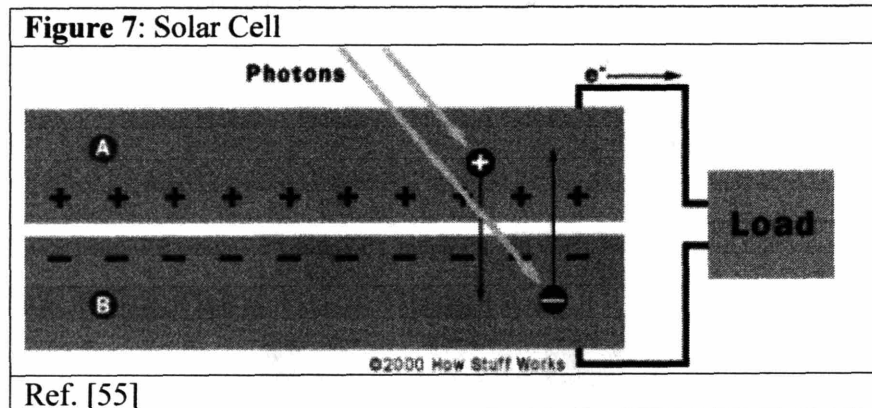


There is little public information available on Kovio. They have thus far raised over \$10M and count Vinod Khosla, a well-known venture capitalist, among their investors. [53, 54] Early markets are likely to include RFID tags and display backplanes.

### **3.5 Memory and Solar Cells**

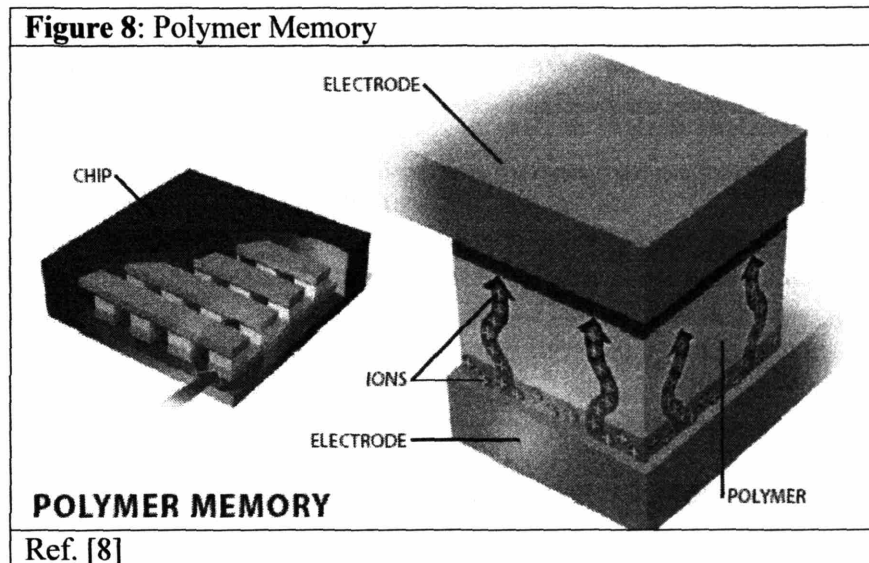
Polymer memory and solar cells are both simple types of devices and do not require fabrication of transistors. Solar cells are basically diodes, built with layers of p-type and n-type semiconductor material, that are sandwiched in-between a pair of electrodes [55] See Figure 7. Incoming photons strike the n-type material and create electron-hole pairs. The electrons and holes move under the electric field provided by the diode to create

current flow. Iowa Thin Films uses doped amorphous silicon layers deposited on plastic films to create their solar cell products. Konarka, meanwhile, uses semiconducting titanium dioxide nanoparticles coated with a light-sensitive dye. Although these approaches do lend themselves to use with flexible substrates, these materials are not well-suited to printing-based manufacturing.



One emerging approach which may enable such low cost production is use of organic materials to make solar cells. [18] Organic LED and organic semiconductor materials can both be used to create solar cells. Some of these materials can be solution processed and could be applied with printing methods. The simple architecture of solar cells makes printing a particularly compelling manufacturing approach. Development of organic solar cell materials is, however, in the early stages. Efficiencies are only a few percent versus 15% or better with inorganic materials and there are significant issues with material degradation in the presence of oxygen. [18] Companies working on development of organic LED displays (e.g., Cambridge Display Technologies, DuPont) are beginning to explore the possibilities of organic solar cells. Konarka is also moving into this area with their recent acquisition of an Austrian company developing organic photovoltaics.[56]

Like solar cells, polymer memory cells are simple devices that do not require fabrication of transistors. Polymer memory simply consists of pillars of polymer material sandwiched in between perpendicular arrays of conductor lines (see Figure 8). [8, 24] Polymer memory has the potential to be 10-15 times cheaper than conventional silicon due to its simpler architecture.



The secret to polymer memory lies in the bistable nature of the polymer itself. Polymers used in memory applications can be switched between two stable states by application of an electric field. These two states permit storage of binary data; their stability means that either state persists even after electrical power is removed. Polymer memory is thus non-volatile like today's flash memory.

A polymer memory concept being developed by Coatue, a Boston-based startup with backing from Advanced Micro Devices, relies on a change in the electrical resistance of the polymer. In the Coatue device, the configuration of the polymer changes upon application of an electric field to a polymer pillar memory cell, resulting in a decrease in its electrical resistance. When an opposite field is applied the polymer

switches back to its higher resistance configuration. The polymer is thus bistable and data can be stored based on these two different conductivity states.

Another polymer memory approach, being pursued by Thin Film Electronics, a Swedish R&D firm entirely owned by Intel and Opticom ASA, is based on ferroelectric polymers.[24] Here the polarity of the polymer rather than its resistance changes with application of an electric field. Again the polarity states are stable, permitting non-volatile storage of binary data.

Polymer memory is not yet on the market and current development relies on conventional wafer fab technology. However, the simple device architecture and use of a polymer film as the memory material offers the future possibility of lower cost solution-based processing for a least part of the fabrication process.[8] Another exciting possibility is the potential for three dimensional memory arrays. [8] The cross-bar structure is quite simple and very thin so it may be possible to create multi-level arrays with very high storage capacities.

The potential of polymer memory has attracted the attention of major integrated circuit companies. As noted earlier, both Intel and AMD are investing in small firms developing polymer memory. [24] The interest of these major semiconductor players is a significant vote of confidence in this emerging technology.

### ***3.6 Technology Dynamics***

Low cost electronics seems to fit Christensen's definition of a disruptive technology. It has lower cost and lower performance than the mainstream silicon technology and is targeting markets that are not accessible to silicon technology. Silicon technology is simply not economical for very low cost or large area applications. In

several markets, such as penny RFID tags or flexible display backplanes, low cost electronics is competing against non-consumption. Addressing latent needs in unserved markets is often a successful strategy for disruptive technologies. Christensen predicts that a disruptive technology will gain a beachhead in low cost and low performance applications and then move up market to displace the incumbent technology in mainstream applications. In the case of low cost electronics, this part of Christensen's model seems unlikely to be fulfilled. With the possible exception of printable inorganic transistors, low cost electronics technologies will never have the capability to compete with silicon in high performance integrated circuit applications. These technologies will co-exist with and complement rather than displace silicon technology by enabling use of circuits in low cost or even disposable products. Low cost electronics is a disruptive technology that is likely to be successful due to its ability to create new, previously unaddressed markets rather than its ability to outperform the incumbent technology in existing applications.

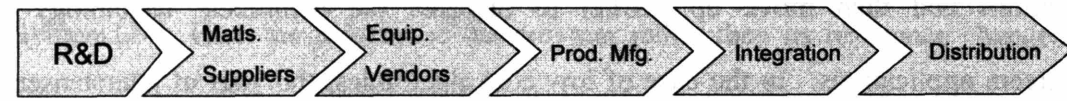
## **4. Industry Structure**

### ***4.1 Value Chain & Industry Structure***

The value chain for the low cost electronics industry is shown in Figure 9. The participation of firms across this value chain is summarized in Figure 10. The industry structure is an interesting mix of startups and large, high-tech companies. The large companies are mostly focused on R&D related to development of novel transistor structures that can be cheaply manufactured on flexible substrates. Some small companies (Kovio, Plastic Logic) are also focused in this area. These efforts are

unlikely to result in products for several years. Other small companies (Alien, Rolltronics, Flexics) are working to get products to market sooner by adapting well-understood silicon technology for use in low cost roll-to-roll manufacturing.

**Figure 9: Low Cost Electronics Industry Value Chain**



**Figure 10**

Company	Type	R&D	Materials Suppliers	Equipment Vendors	Product Mfg.	Integration	Distribution
PlasticLogic	Startup						
Alien Technology	Startup		Foundries				
Flexics	Startup		Si Fab				
Rolltronics	Startup		Si Fab				
Iowa Thin Films	Startup		Si Fab				
Konarka	Startup						
IBM	Large						
Lucent	Large						
Siemens	Large						
Kovio	Startup						
Dow	Large						
Philips	Large						
Coatue	Startup						
Thin Film Elec.	Medium						
Xerox	Large						
Seiko-Epson	Large						

A clear sign of the immaturity of this industry is the heavy concentration of firms in the R&D stage of the value chain and the relatively low participation in other stages. Of all the players, only Iowa Thin Films, with its flexible solar cell arrays, currently has a true low cost electronics product on the market.

Dow appears to be the only major chemical company currently working on low cost electronics materials. It is likely that other chemical companies will get involved as R&D efforts come to fruition and companies seek partners to help them scale up for mass production. Companies, such as Alien, Flexics and Rolltronics, which are leveraging wafer fab processes, can get the materials they need for manufacturing from the same sources as the semiconductor industry.

There are two significant players in the equipment vendor stage of the value chain. Iowa Thin Films has emerged as a leader in the development of roll-to-roll processing equipment for low cost electronics. They are using this equipment to produce their low cost solar arrays and are also partnering with Rolltronics to provide them with equipment for manufacture of polysilicon transistors on plastic. Seiko Epson, a major manufacturer of piezoelectric-based ink jet printers, is working with Plastic Logic. [57] This partnership should give Epson a head start in developing inkjet-based machine tools for printing circuits. Another potential equipment player is Litrex, a subsidiary of Cambridge Display Technologies, which makes inkjet-based machine tools for manufacture of OLED displays. Presumably their equipment, which is capable of jetting solutions of OLED polymers, could also handle organic electronic materials for circuit manufacturing.

Companies that have already commercialized their low cost electronics technology (Iowa Thin Films) or will soon do so (Flexics, Rolltronics, Alien) are choosing to do their own manufacturing. They evidently believe that their tacit knowledge of manufacturing processes is an important source of competitive advantage. Further, since reel processing of electronics is entirely new there are few if any existing

companies capable of handle this manufacturing on an outsource basis. The production strategy for the most of the companies that are currently involved only in R&D activities related to low cost electronics is unclear. Smaller companies such as Plastic Logic or Konarka may choose to license their technology, or at least outsource manufacturing, to bigger companies able to make large infrastructure investments. Larger companies such as IBM or Siemens could afford a vertically integrated approach to entering low cost electronics markets; at this point, however, it is not clear how they plan to try to capitalize on their R&D investments. One exception is Lucent's Bell Labs, which is partnering with EInk, to create flexible displays based on electronic ink technology.

The integration stage of the value chain is probably only important for display backplanes. In this case the backplane is a component of a complex display product and, with the exception of Philips, firms in the low cost electronics industry are not in the display business. Firms targeting this market will almost certainly sell their backplanes to display companies who will build display modules for use in cell phones, PDAs, laptops and desktop monitors. So far, only Lucent has announced a display partner. Other low cost electronics products, such as RFID tags, smart cards, and solar cells, do not require significant further manufacturing before they can be sold to customers. For these products it is likely that the company doing the product manufacturing will also do the necessary integration to create a final, saleable product.

The final stage of the value chain is distribution. Since most low cost electronics products have yet to reach the market, distribution channels have yet to be developed. Display backplanes, which must be integrated into displays to have value, will certainly be sold through existing display distribution channels. Iowa Thin Films is distributing its



solar cell products through a small number of vendors that specialize in solar and other environmentally friendly products.

## 4.2 Alliance & Partnerships

The low cost electronics industry is characterized by a relatively small number of alliances. See Figure 11. This situation is in sharp contrast to the OLED industry discussed in Chapter 3 where there is a complex web of inter-company relationships. This lack of partnerships is somewhat surprising given the complexity of developing new electronics technologies, especially those that involve invention of new organic or inorganic transistors. This development work requires expertise in several diverse areas including chemical synthesis, device physics and novel manufacturing methods; few companies, especially smaller ones, have strong competencies in all of these areas. The small number of partnerships to date is perhaps another sign of the industry's immaturity. With most companies still focused on R&D the pressure to form partnerships is somewhat limited. As new cost electronics technologies mature, look for an increase in the number of partnerships as the players seek the means to bring the products to market and to begin to recover their substantial development investment.

**Figure 11: Industry Partnerships**

<b>Company</b>	<b>Partners</b>	
Plastic Logic	Epson	Dow
Bell Labs	Eink	
Rolltronics	Iowa TF	
Coatue	AMD	
Thin Film Electronics	Intel	
Xerox	Dow	Motorola

### 4.3 Competitive Attributes

The primary adoption drivers for low cost electronics are expected to be flexible form factor, and, of course, cost. In some applications, such as flexible displays and penny RFID tags, the new technologies are creating entirely new markets. These products are simply not possible with existing technologies. In other markets, such as solar cells and memory, the new low cost technologies must compete with existing products on the basis of price and performance. The grid in Figure 12 shows predicted market entry dynamics for low cost electronics technologies based on the cost and performance versus amorphous silicon technology.

New low cost electronics technologies are expected to displace amorphous silicon in cases where they deliver the same or higher performance at lower cost or higher performance at the same cost. In these cases low cost electronics would be expected to displace incumbent amorphous silicon technology even in products such as desktop monitors, where the flexible form factor is not highly valued.

**Figure 12**

		Performance vs. a-Si		
		High	Same	Low
Cost versus a-Si	High			
	Same	Displace	New App.	
	Low	Displace	Displace	New App.

In cases where the flexible form factor of low cost electronics technologies is valued the new technologies may be adopted even if cost and performance are the same. Adoption is also possible when performance and cost are lower than amorphous silicon, provided that performance is still good enough to get the job done.

## **5. Analysis and Recommendations**

### **5.1 *Winners and Losers***

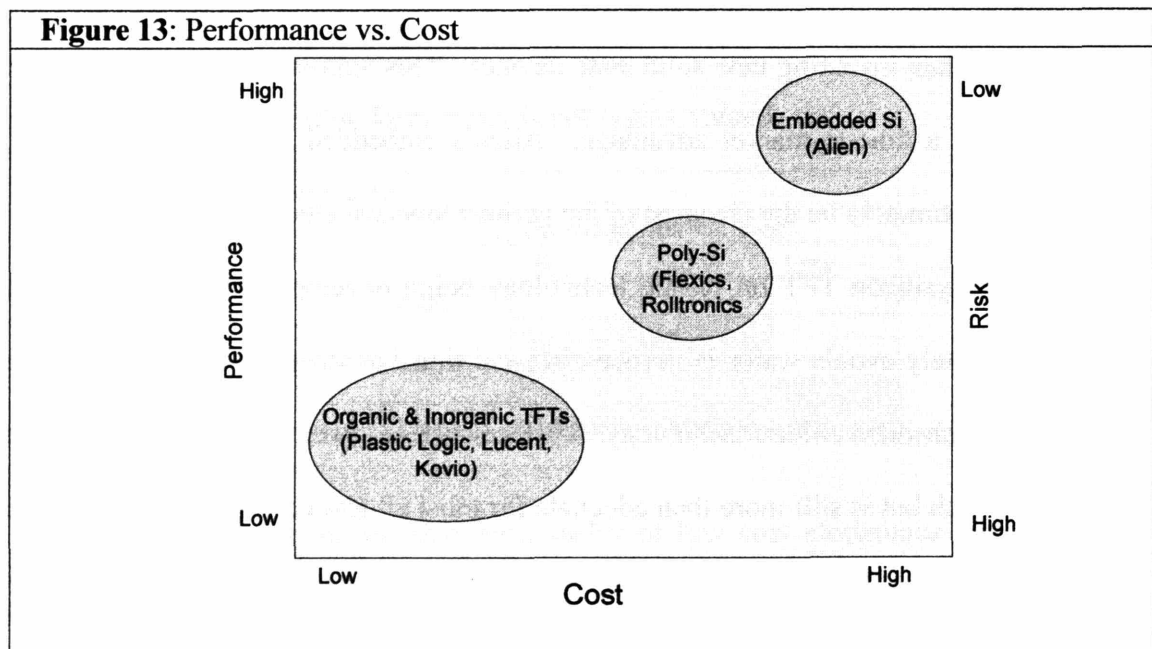
It is rather early to make high confidence predictions as to which firms and technologies will prevail in the emerging markets for low cost electronics. Since success in these markets is largely cost-driven the dominant design may not be the first one to market but instead the one with lowest price. It is also unclear as to which of the various potential markets for the technologies will become the most important.

In this high uncertainty environment, Alien Technology's approach looks compelling. Heavily leveraging existing silicon circuit technology allows them to address a wide range of product applications from higher performance display backplanes and smart cards to lower performance RFID tags. Further this strategy allows them to focus their resources on developing the new roll-to-roll processes for manufacturing circuits rather than inventing new solid state devices. This approach minimizes risk and should provide a time-to-market advantage. Alien's embedded silicon approach may, however, not ultimately be the cheapest of the various low cost electronics technologies.

The polysilicon TFT on plastic technology being developed by Rolltronics and Flexics completely avoids wafer fab processing and thus has the potential to be cheaper than Alien's embedded silicon technology. Performance is lower than that possible with Alien's approach but is still more than adequate for most all low cost applications. There is also more risk with the polysilicon approach since significant process innovation is required to build transistors on flexible substrates using fab-like processes.

The organic and inorganic transistor technologies are higher risk still. These technologies require invention and characterization of entirely new transistors built from

unconventional materials; much R&D work remains to be done before these technologies can be commercialized. Standards for these new devices do not yet exist, although the IEEE has begun work in this area for organic TFTs. [17] New high yield, high capacity manufacturing processes must also be developed that can apply these materials to substrates. Further, the partnerships and channels required to bring these new products to market have also yet to be created. An additional risk for the organic TFT technologies, especially those based on semiconducting polymers, is that performance currently falls short of amorphous silicon and they may thus only be suitable for the lowest performance applications. This risk does not seem to exist for Kovio's printable inorganic transistor technology, which appears capable of least amorphous silicon performance. [51] Kovio could be a clear winner if their technology can deliver performance equivalent to or better than polysilicon FETs.



In spite of these challenges, the new transistor technologies should offer the lowest cost means for production of active circuits. A manufacturing approach based on

printing, rather than lithography, also offers the flexibility to make quick design changes and, perhaps, mass customize products.

Figure 13 summarizes the risk, performance and cost characteristics of the competing low cost electronics technologies.

## **5.2 InkJet Challenges**

Inkjet clearly has the potential to be an important enabling technology for low cost applications. There are, however, a number of challenges related to using inkjet to print circuit materials. For example, inkjet can only be used for organic and inorganic materials that can solution-processed. In the case of organic materials, only the polymer materials meet this requirement. These materials have lower mobilities than amorphous silicon so product application may be limited to the least demanding applications such as RFID tags and electronic ink displays. This may not be an issue as long as these markets are sufficiently large and profitable. The ability to move up market is, however, limited.

Another issue for inkjet is that solutions of organic polymers can be difficult to dispense. Solvents such as xylene and toluene are often required to dissolve the organic semiconducting polymers. [40] These solvents may attack polymer materials used to build the inkjet printheads. Also such organic solvents are quite volatile and can evaporate in the inkjet nozzles leading to clogging problems.[40] Difficulties jetting circuit materials led a Xerox team to investigate inkjet as a means of creating resist patterns instead. [40] This approach requires conventional means for deposition and etching of thin films but still avoids use of photomasks.

Much of the R&D work on use of inkjet to dispense circuit materials has been based on use of just a single nozzle. Although this approach is simpler for experimental

purposes it is not practical from a manufacturing perspective. Reasonable manufacturing throughput can only be achieved with use of multiple nozzles. Once nozzle arrays are employed, however, it is necessary to take additional care to minimize nozzle variability and to make sure all nozzles are functioning properly. An additional throughput challenge is that optimal deposition conditions may require considerable delays between subsequent drops. If adjacent drops are printed too quickly, surface tension may cause a string of unconnected dots, rather than a line, to be formed on the substrate.[40] A delay between drops provides time for solvent evaporation and helps to guarantee formation of a continuous line of material; there is, however, an obvious throughput impact.

Accurate control of the position and size of circuit features is another challenge for inkjet printed electronics. Due to the low mobilities of printable semiconductor materials it is important to achieve channel lengths of 10 microns or less in order to realize reasonable device performance. Such dimensions are challenging for inkjet since factors such as angular misalignment of the printhead, thermal expansion of the printhead and drop velocity variation all contribute to dot placement error. [40] Once the droplet hits the substrate liquid spreading contributes to further variation. Local alignment of the printhead to circuit features can help minimize dot placement error. Control of liquid spreading, on the other hand, typically requires additional features on the substrate to contain the liquid. An example of this approach is the patterned polyimide layer employed by Plastic Logic. [42, 43] Laser machining of trenches for the ink might be another approach.

It is important to note that all the published work to date on inkjet printing of circuit materials has utilized piezoelectric, not thermal, inkjet printheads. Piezoelectric

heads rely on physical movement of a membrane to achieve drop ejection rather than expansion of a bubble created by boiling a thin film of liquid with a tiny resistor. Piezo technology is believed to be able to jet a wider range of material than is possible with thermal inkjet due to the lack of thermal effects. There is however, no published data to establish that thermal inkjet is not suitable for printing circuit materials.

### ***5.3 Inkjet Recommendations***

Established inkjet players, such as Epson, Canon and Hewlett-Packard, have specialized knowledge and assets that are relevant to development of inkjet as a circuit printing technology. There is clearly opportunity in the value chain for development of robust circuit printing machinery. These companies should, however, think and plan carefully before attempting to participate in this industry.

As discussed in the previous section, significant challenges must be overcome for inkjet to become a robust manufacturing technology for fabrication of low cost circuits. These firms must be prepared to invest for the long run in order to have any chance of success. A limited, short run investment is very unlikely to bear fruit.

Even if development efforts are successful there is no guarantee that inkjet printed circuits will become the dominant low cost electronics technology. Limited material performance, particular for organic semiconductors, may limit the ability of inkjet printed circuits to participate in evolving high growth markets such as flexible displays. Development of higher mobility printable semiconductor materials would avoid this limitation while preserving the significant advantages of printing.

Another issue is that the expertise of established inkjet firms is in designing cheap, reliable printheads for mass production not designing printheads capable of mass

production of cheap, reliable circuits. Application of inkjet printing to construction of low cost circuits is an entirely different design challenge than building a low cost consumer printer. The product requirements for a circuit printer are those of a high precision machine tool not a \$99 consumer electronics product. It is not important that the circuit printer itself be inexpensive but rather that it be engineered to produce inexpensive circuits.

This strong difference in product requirements between consumer printers and circuit printers suggests that development work should proceed within a focused heavyweight team that is somewhat separated from core business activities. [58] A heavy weight team alone, however, is probably insufficient for success. Even though inkjet companies are familiar with the technology they are not familiar with low cost electronics markets. A joint venture, alliance or acquisition may be necessary to acquire the needed market understanding. [59] Additional licensing efforts may also be required to obtain the rights to use promising, patented processes or materials.

The best chance for existing inkjet companies to capture value in the emerging low cost electronics industries may be to think more broadly about their competencies. Inkjet companies excel at mass production and testing of cheap, reliable yet complex electronic components (inkjet printheads). Hewlett-Packard, which integrates printheads into its ink supplies, is already in the disposable electronics business. Inkjet companies may not need to figure out how to inkjet print circuits in order to become important players in low cost electronics. They may be better off applying their strong skills in designing low cost printheads to develop new and better technologies for creating low cost electronics.



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# Chapter 5

## Summary & Conclusions

### Table of Contents

<b>1. Summary</b> .....	<b>167</b>
<b>2. Opportunities for Disruption</b> .....	<b>168</b>
<b>2.1 Will OLED Displays Be Disruptive?</b> .....	<b>169</b>
<b>2.2 Will Low Cost Electronics Be Disruptive?</b> .....	<b>170</b>
<b>3. Will Inkjet Be a Key Enabling Technology?</b> .....	<b>172</b>
<b>3.1 OLED Displays</b> .....	<b>173</b>
<b>3.2 Low Cost Electronics</b> .....	<b>174</b>
<b>4. References</b> .....	<b>178</b>

# 1. Summary

Inkjet has clearly been a disruptive technology for traditional printing. This thesis has endeavored to examine the potential of inkjet technology to become a disruptive technology in other industries, specifically displays and low cost electronics. The very attributes of inkjet that have made it such an important printing technology also make it compelling in other applications. Inkjet excels at depositing picoliter quantities of liquid on a substrate with very high precision and at very low cost.

Traditionally the ink has been aqueous solutions of dye or pigment, the substrate has been paper, and the result has been black and white and color documents or even photographs. However, when the “ink” becomes electronics materials such as light-emitting polymers or semiconducting organic compounds and the substrate becomes plastic the result can be low cost, flexible displays and circuits. Inkjet is a purely additive technology and thus avoids the need for the expensive lithography and vacuum processing steps usually required to pattern thin films. Further, since inkjet directly writes the desired pattern for the display or circuit, there is no need for expensive photomasks. Economic build quantities are thus small and design changes can be made easily. The simplicity of printing circuits or displays versus the complexity of traditional manufacturing means that capital costs for an inkjet-based manufacturing facility could be as little as 1/3 of the \$1-2B cost of today’s wafer and flat panel display fabs.

The promise of inkjet as an electronics manufacturing technology is great. It seems to drive all the important business factors in the right direction; i.e., lower capital cost, lower variable cost, lower cycle times, and increased design flexibility. But will inkjet really prove to be a disruptive technology in these new applications? To answer

this question we must first assess whether the products that are enabled by inkjet manufacturing are themselves disruptive. If so, then we must consider whether they are uniquely or best enabled by inkjet. If inkjet is the only or best way to make a disruptive product then it would be safe to conclude that inkjet itself is a disruptive technology.

## 2. Opportunities for Disruption

Christensen provides a useful framework to address the question as to whether the opportunities that inkjet enables in displays and electronics are truly disruptive; that is, will they result in new markets or new business models with high potential for growth and success? [1] Christensen suggests that disruptive new businesses are created through one of two main strategies: creation of a new market as a base for disruption or disruption of the incumbent business model from the low end. Litmus test questions are proposed to determine whether a new business opportunity is consistent with either of these strategies. See Figure 1. Application of this framework suggests that both the displays and low cost electronics products enabled by inkjet technology are likely to be disruptive innovations, chiefly through creation of new markets.

<b>Figure 1, Ref. [1]</b>	
<b>Strategy</b>	<b>Tests</b>
Create a New Market as a Base for Disruption	Does the innovation target customers who haven't been able to do it themselves due to lack of money or skill?
	Is the innovation aimed at customers who will welcome a simple product?
	Will the innovation help customers do more easily and effectively what they are already trying to do?
Disrupt From Below	Are prevailing products more than good enough?
	Can you create a different business model?



## **2.1 Will OLED Displays Be Disruptive?**

OLED displays have the potential, in the long run, to create new markets for both large and small displays. OLEDs should enable low cost, light-weight, wall-mountable displays for home theatre and commercial markets. Today's technology for these markets costs thousands of dollars and is out of reach for most consumers. OLED technology should enable large screens at sub-\$1000 price points and help drive these products into the mass market. On the other end of the size spectrum, OLEDs should enable portable, roll-up displays that can provide big screen convenience for hand-held devices, a capability that is not available today. In both large and small screen formats, OLED displays will create new markets and achieve growth by competing against non-consumption.

Note that early applications of OLED displays (cell phone, PDAs, laptops) do not have this virtue and must instead compete with existing flat panel technology. In these applications the OLED display is a higher performance, lower cost replacement for color LCD displays. In these applications OLED displays are more a sustaining rather than a disruptive innovation. OLED displays thus pass Christensen's first test for creation of new markets, but only in the long run (10 years or so) when it will be able to move into new markets not accessible with LCD technology.

OLED technology also seems to pass the second "simple product" test. OLED displays will be bright and easy for users to view and will enable better battery life in portable applications. Users will welcome the ability to view their displays easily both indoors and out and will appreciate not have to hassle with annoying power saver features that dim or turn off the display to save batteries.

For these same reasons, OLED displays also pass Christensen's third test for creation of a new market as a base for disruption. There is no doubt that OLED displays will help customers more easily and effectively do what are already trying to do. A better, cheaper display technology does not require customers to want to do something that is not currently a priority. On the contrary, displays are the "last mile" between information and the brain and play a fundamental role in the way that we work and play. OLED displays should create a better overall viewing experience in any application.

OLED displays convincingly pass the tests for a technology that will be disruptive based on its ability to create new markets. These new markets will not materialize immediately; OLED displays will initially be a sustaining innovation by providing better display capability in existing products. As the technology evolves and matures it will become disruptive by enabling new products with price points or capabilities unattainable with other technologies.

## ***2.2 Will Low Cost Electronics Be Disruptive?***

Application of Christensen's framework to low cost electronics technologies suggests that they too will prove to be disruptive. Low cost electronics innovations will create new markets chiefly by making existing capabilities available at much lower price points rather than by creating entirely new product categories. Dramatically lower price points for products such as RFID tags, smart cards and solar cells will enable entirely new classes of customers to take advantage of these products. These customers do not use these products today due to their cost; products based on low cost electronics

technologies will thus be able to compete against non-consumption, a powerful growth driver for new businesses.

Low cost electronics technologies will also enable simple products that customers will want to use. For example, RFID tags on consumer products will simplify the checkout task at the supermarket and will eventually simplify the everyday chores of cooking and laundry by allowing food or clothing items to communicate with appliances. Smart cards will simplify use of both mass transit and tollways and provide easy, yet more secure, means for credit payment and personal identification. In other applications, such as nonvolatile memory and solar cells, low cost electronics takes already simple products and makes them more affordable.

Adoption of products based on low cost electronics does not require customers to want to do something that is not currently a priority. Instead, low cost electronics technologies will allow customers to more easily accomplish daily tasks such as shopping and commuting. Low cost electronics will also allow consumers to make better use of existing handheld digital products by enabling integrated solar arrays to extend battery life and much cheaper nonvolatile memory for storing information.

Like OLED displays, low cost electronics technologies pass Christensen's three litmus tests and thus appear likely to become a disruptive innovation. The next critical question is whether inkjet technology is likely to be a key enabling technology for making these new products and whether existing inkjet players should invest in evolving today's traditional printing technology into tomorrow's electronics manufacturing technology. Key factors are the inkjet technology fit, the strength of competing

technologies and the size of the opportunity. A framework based on these factors will be introduced to compare the opportunities for inkjet in displays and low cost electronics.

### **3. Will Inkjet Be a Key Enabling Technology?**

Inkjet printing applied to manufacturing of displays and low cost electronics is fundamentally a process innovation which may enable a variety of new products. Utterback suggests that the level of process innovation increases once a dominant product design becomes established and firms begin to compete to develop the process technology that allows the product to be developed at the lowest cost. [2] According to this framework a dominant product design emerges first followed later by development of a process technology for producing that product most efficiently. Evidence suggests that this pattern has been followed in several industries; new display and low cost electronics products enabled by inkjet process technology, however, may depart from this pattern.

Here dominant product and process innovations may not emerge serially but rather together...or not at all. The value proposition of products such as large, flexible displays or penny RFID tags is based largely on the capabilities of the process technology used to produce them. The emergence of such new product categories hinges on successful process innovation to deliver key product attributes. Inkjet has strong potential but must demonstrate that it can make the transition from a consumer printing technology to a robust, reliable, high yield manufacturing method. This step seems a large one but inkjet has already proven once to be a disruptive technology and should not be counted out. In the following sections the potential of inkjet as an enabling process

technology for OLED displays and low cost electronics is examined in terms of technology fit, strength of competing technologies, and size of opportunity.

### **3.1 OLED Displays**

In the case of OLED displays, the inkjet technology fit appears very good. The task of precisely positioning circular drops on media is well-aligned with existing inkjet capabilities. The feature sizes and required tolerances are similar to what inkjet can already do. Cambridge Display Technology and its subsidiary Litrex have already demonstrated that piezo-based inkjet technology is well-suited to deposition of OLED polymer solutions. [3] Further work, however, is required to assess whether thermal inkjet is suitable for this application.

The primary competition for OLED displays based on polymer materials that can be applied with inkjet, is OLED displays based on small molecule materials. Small molecule OLEDs can only be applied in a vacuum system using shadow masks. Although small molecule OLED technology is more mature than that based on jettable polymers, the need for expensive and complex vacuum processing is a significant disadvantage. As discussed in Chapter 3, printable OLED materials will only improve over time and are likely to become the dominant OLED technology in the end due to their significantly lower manufacturing cost. This cost advantage becomes more important as display sizes increase and the higher cost of small molecule OLED manufacturing is allocated to fewer displays per unit area. Inkjet's emergence as the dominant process technology for OLED displays may occur gradually as these displays are adopted in larger area applications.

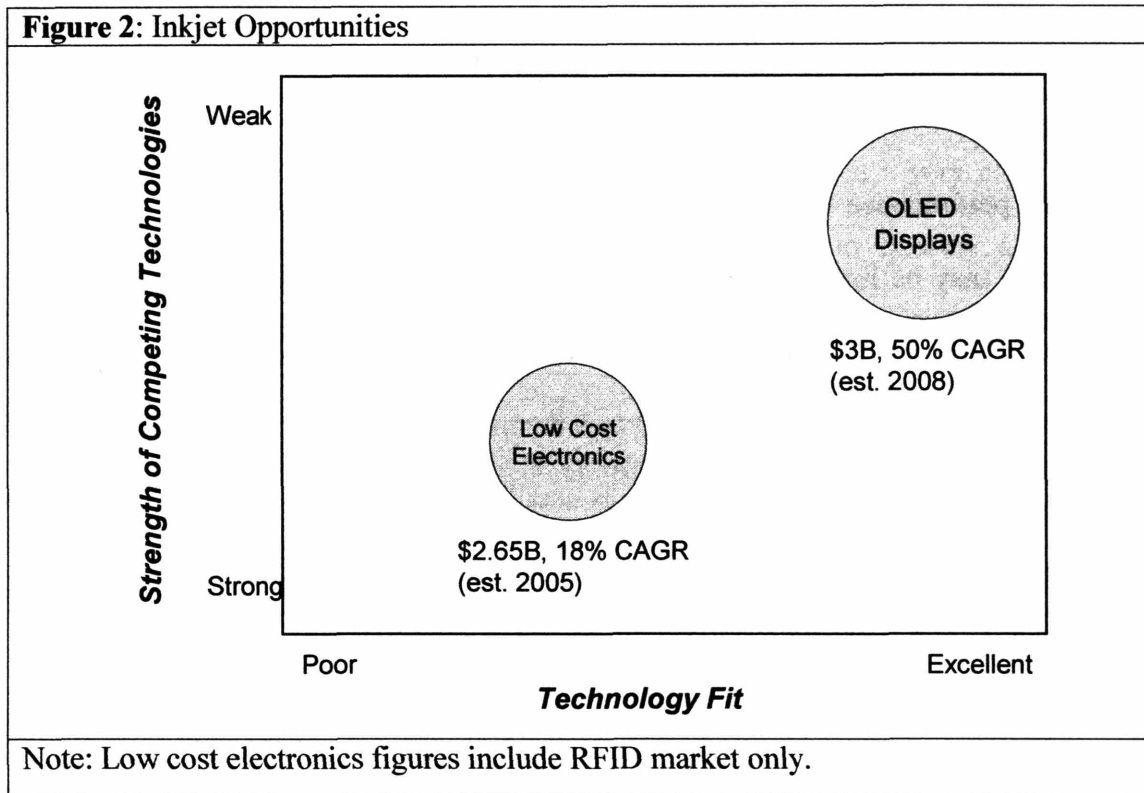
It is not yet known whether printing technologies other than inkjet could be used to manufacture displays based on polymer OLEDs. Toppan, the world's largest manufacturer of color filters for LCD displays, has entered into a partnership with Cambridge Display, presumably to investigate the suitability of their technology for printing OLEDs.[4] Toppan has significant competencies in display-specific printing and could become a major player in OLEDs. Inkjet, however, has an advantage over Toppan's more traditional printing technology in that it is a non-contact printing method. The importance of this advantage for manufacturing OLED displays has yet to be determined.

Finally the size of the opportunity in OLED displays is expected to be quite large, approaching \$3B in 2008 with an annual growth rate of over 50%.[5] New products, such as large display screens and roll-up displays, will help sustain this growth into the next decade. Figure 2 summarizes the inkjet opportunity for OLEDs in terms of the factors of technology fit, strength of competing technologies, and size of opportunity.

### ***3.2 Low Cost Electronics***

For low cost electronics, the technology fit for inkjet is not as good as for displays. The types of semiconducting organic materials that can be printed with inkjet have rather low carrier mobilities and are suitable only for undemanding product applications such as RFID tags or solar cells. More demanding low cost electronics applications such as smart cards and active matrix displays may not be accessible with an inkjet manufacturing approach. The approach of jetting inorganic nanocrystals may

provide a path towards higher performance but this approach is still very early in its development.



Another issue with use of inkjet for printing circuits is that the feature sizes and tolerances are beyond current inkjet capabilities. Required gate lengths of 5-10 microns cannot be achieved with inkjet printing only and require additional measures such as patterned hydrophobic layers to confine the ink droplets.[6] Further, printing the smooth-edged, straight lines required for circuits can be difficult with inkjet since the jetted material naturally tends to form a hemispherical dot on the substrate. [7]

Limited technology fit is not the only challenge for inkjet as a manufacturing technology for low cost electronics. Competing technologies include tiny silicon chips embedded in plastic (Alien Technologies) and polysilicon-based circuits built on plastic (Flexics, Rolltronics). Both of these technologies leverage well-understood silicon

technology and offer higher performance than is currently possible with inkjet printed circuits. Other printing technologies such as embossing or stamping may also emerge as competitors; early data shows that these approaches can pattern smaller features than inkjet. [8]

If performance of inkjet-printed circuits cannot be improved, the market opportunity may be limited to RFID tags and solar cells. The RFID market size was \$1.6B in 2002 and is expected to grow to reach \$2.65B by 2005 (CAGR of 18.3%). [9, 10] This market size includes the RFID tags themselves as well as readers, software and services. The market opportunity here is smaller than that for OLED displays and is growing at a lower rate. The solar cell market is expected to reach \$1B by 2005 but only a small fraction of these will be made with printable materials. [11]

The market for low cost RF identification tags is developing quickly. Companies are anxious to realize the significant supply chain efficiencies possible by replacing bar codes with rf-readable labels. There is a limited window of opportunity for inkjet-printed circuits to become established in this market. Developers of this technology must soon demonstrate that it can deliver on the promise of ultra cheap RFID tags. Inkjet printed circuits have lower performance than competing technologies and therefore must win on cost. If inkjet printed circuits take too long to develop a competing technology may become established and achieve significant scale economies to offset a more complex manufacturing process. Early entrants should also be able to influence adoption of standards that are favorable to their technology and perhaps disadvantageous to competitors. A key factor will be which technology can first hit the one or two cent price point required to make RFID tags economical in the huge consumer products markets.



The overall opportunity for inkjet technology in low cost electronics is compared to that in displays in Figure 2. The opportunity in OLED displays seems more attractive. OLED display applications represent a large and growing market where manufacturing requirements are a good fit with inkjet capabilities. Further, competing technologies either have a significant cost disadvantage or are at a very early stage of development. Inkjet technology thus seems more likely to become a disruptive manufacturing technology in the OLED display industry than in the low cost electronics industry.

Existing inkjet players should therefore invest first in trying to evolve their technology to create a high yield, high throughput system for manufacture of polymer OLED displays. Significant development effort will be required to turn inkjet into a robust manufacturing technology. If these efforts meet with success, learnings can be leveraged to extend the technology to circuit printing for low cost electronics applications.

In either case the inkjet firms should strive to control as much of the value chain as possible. This strategy will allow them to capture the maximum value from their technology investment. If the inkjet firms only provide a manufacturing tool or a component, most of the value is likely to be captured by the firms selling the end products; inkjet firms could end up with only “cost plus” returns. If the current inkjet printing industry is any indication, control of the supplies piece of the value chain will be particularly important for sustained profitability.

Inkjet technology has revolutionized the printing industry and provided handsome returns for the major players. This industry is, however, maturing and firms must

consider how they how they can leverage their knowledge and assets to sustain future growth. The unique aspects of inkjet technology make it well suited as a low cost electronics manufacturing technology for displays and low cost circuits. These are opportunities for a second inkjet revolution where this remarkable technology could prove to be disruptive yet again.

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