Commercial Assessment of Roll to Roll Manufacturing of Electronic Displays

By

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ABSTRACT

The cost of manufacturing electronic displays currently limits the range of applications and markets into which it is currently economically feasible to adopt displays. Roll-to-roll manufacturing has been identified by the display industry as a new and fundamentally different manufacturing paradigm that has the potential to significantly reduce the manufacturing cost of a display relative to the conventional approaches used in the industry. This manufacturing cost reduction could have a profound impact on the display industry by not only transforming the display manufacturing infrastructure, but also by permitting electronic displays to penetrate new markets. The purpose of this thesis is to determine how roll-to-roll manufacturing technology could develop and to assess what impact the technology could have on the electronic display manufacturing industry.

This work first identifies the material, patterning, and equipment technologies that need to come together in order for roll-to-roll manufacturing to be industrially feasible, and then determines how and if the technology will offer a cost reduction over conventional manufacturing techniques. Next, the markets for displays are segmented and analyzed to discern whether niche initial markets exist where roll-to-roll could have a distinctive advantage and gain traction. Competitive technologies such as LCD and modular LED are discussed and it is determined that roll-to-roll displays must compete with LCD technology on the basis of price in the markets in which LCD has incumbency in order to achieve widespread adoption. The display industry structure is analyzed by means of an assessment of the supply chain, intellectual property landscape, financing mechanisms, and business models to understand how partnerships and financial investment risk are salient aspects of the commercialization process. It is concluded that materials cost advantages over current manufacturing approaches and the timing of roll-to-roll technology integration developments relative to the incremental manufacturing cost decreases in competing technologies will ultimately dictate the success of roll-to-roll manufacturing.

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I must also express grave appreciation to Professor Eugene Fitzgerald for providing the conceptual and analytical tools that are needed to understand how technologies move from the lab bench into industry. The vision and insight that he offered was monumental in enabling me to see through the clouds of information that I had gathered and put structure to ambiguity in order to get down to the core issues that are driving the development of roll-to-roll technology.

Additionally, I must extend multiple thanks to Gerry Chen for his time and the in-depth knowledge that he imparted to me on this subject. Thanks to Greg Moeller and the QD Vision team, Liz Ziepniewski of I.T. Strategies, and all of the people I met at conferences, trade shows, and seminars who provided the countless conversations that truly allowed me to see the big picture. I would like to thank the MIT Center for Integrated Photonic Systems (CIPS) for providing the funding for this work.

Finally, I would like to thank my family and friends for giving me the intangible things that made me smile throughout the entire experience.

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1 Introduction to Roll-to-Roll

1.1 Background

Roll-to-roll (R2R) processing has been identified by the display industry as a technology that could significantly reduce the costs associated with manufacturing displays. Roll-to-roll manufacturing can be most easily conceptualized as the process by which low cost products such as labels and newspapers are currently produced, where thousands of square feet of printed material can be printed for just a few cents. Although electronic display materials are much more expensive than newspaper materials, the R2R printing process itself is inherently low cost and extremely scalable. Industry efforts to achieve R2R manufacturing aspire to implement more arcane materials and controls into this fundamentally mundane process in order to realize order of magnitude reductions in the display manufacturing cost structure. If each layer of a display could be patterned onto a roll of substrate in a continuous deposition process, then it could be possible to realize a profound decrease in the cost of manufacturing an electronic display relative to the conventional approaches used in the industry.

The basic concept of R2R can be illustrated by Figure 1-1, where a functional layer is transferred onto a substrate by contacting the surface to a patterned roll that contains the layer material in an ink form. Although this direct contact printing is one approach to achieve a R2R compatible deposition, there are other additive approaches that are compatible with roll-to-roll processing such as ink jet printing or laser patterning.

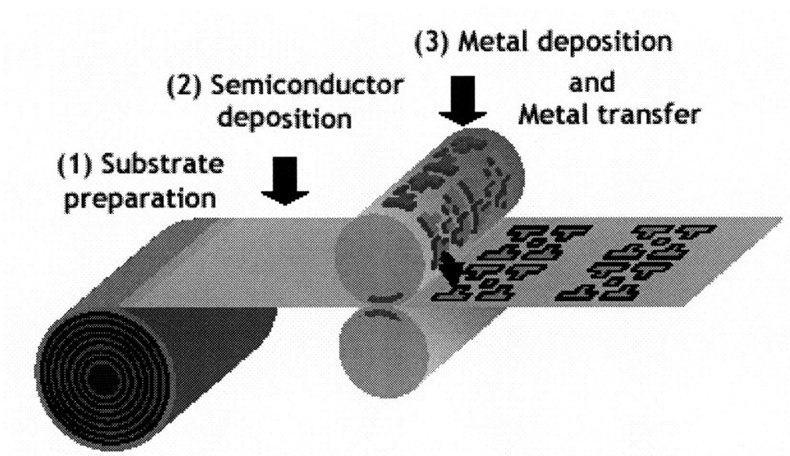


Figure 1-1 R2R Manufacturing Concept

The fundamental difference between roll-to-roll manufacturing and the manufacturing approaches currently used in the display industry is that R2R is a web process whereas the conventional display manufacturing techniques utilize batch processes. This allows the layers and processing operations to be applied to the display continuously as it is moved through the manufacturing facility. The cost reductions are expected to be derived primarily from a reduction in the material handling cost of moving the work-in-progress inventory from process to process within a plant. Additionally, if additive patterning techniques can be used in the R2R process then it is conceivable that a reduction in the cost of materials could also be achieved.

1.2 Thesis Scope

The scope of this work is to assess the commercial potential of roll-to-roll manufacturing in the context of its application to the display industry. This work offers insights on the commercialization process and how roll-to-roll manufacturing could develop from the lab bench to a full scale manufacturing facility. Firstly, this entails the identification of the technology pieces that need to come together in order for R2R to be implemented into a manufacturing facility, and how and if these can coalesce to realize a reduction in manufacturing costs compared to conventional approaches in the industry (Chapter 2). Second, the display market is segmented and applications for the technology are identified, including an assessment of initial markets where R2R could have a distinctive advantage (Chapter 3). Next, the thesis builds on this understanding of the marketplace by evaluating the competitive technologies that R2R will encounter in the markets, and also identifies technologies that will complement the development of R2R (Chapter 4). The display industry structure is then analyzed, including an assessment of the supply chain, intellectual property landscape, financing mechanisms, and business models, to draw inferences about successful strategies for commercialization of R2R technologies (Chapter 5). Finally, based on a broad understanding of the technology and industry, conclusions are made about the commercial potential of roll-to-roll manufacturing (Chapter 6).

CHAPTER

2 Research and Technology Assessment

The three areas of research that are critical to the development of roll-to-roll manufacturing are advancements in materials, patterning techniques, and equipment. These are the three technology pieces that must be in place in order for roll-to-roll fabrication of displays to be utilized by industry. It should also be noted that much of the research that is critical to the commercial enabling of R2R is not explicitly labeled as R2R research. For example, a large component of the research related to flexible substrates is carried out for mobile applications. Although the development of flexible substrates is considered to be essential to the advancement of R2R, many of the endeavors in this area are focused only on its application to mobile devices. Similarly, many other areas of research that are fundamental to the commercial success of R2R may be disguised or categorized in terms of a more narrowly defined application or device structure.

2.1 Materials

There are two main types of materials that are used in the manufacturing of a display: the supporting materials and the functional materials. The supporting materials are static layers that do not directly contribute to the image generation process within the display; these materials include the substrate (which is traditionally glass) and the barrier layers. On the other hand, the functional materials in the display play a dynamic role in generating the image that the display produces; these materials include the emissive or light modulating layers and the TFT backplanes. Figure 2-1 illustrates how these layers fit into the overall structure of an active matrix LCD (AM-LCD) and an active matrix organic LED (AM-OLED) display.

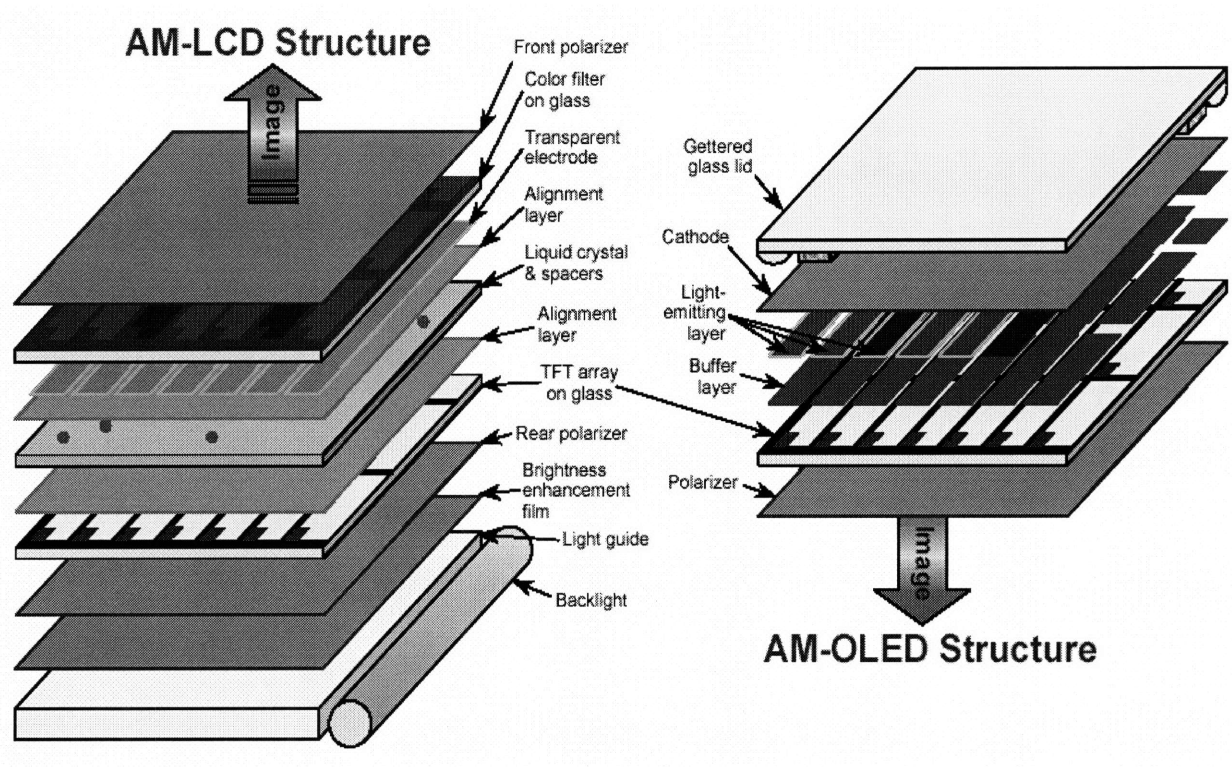


Figure 2-1 Layers Comprising an Active Matrix LCD (AM-LCD) and Active Matrix Organic LED (AM-OLED) display [1]

2.1.1 Supporting Materials

Nearly all displays currently use Corning glass as the substrate upon which the other layers are processed. A flexible substrate is almost imperative if roll-to-roll manufacturing of displays is expected to be realized by industry [2]. The parameter that characterizes the flexibility of the substrate is called the safe bending radius, and the smaller this number is then the more the substrate can be bent without failure. Roll-to-roll processing requires some level of flexibility in the substrate so that the substrate can conform to the rolls that print material onto the substrate or guide it through the process. Much research that is relevant to R2R has been focused on identifying substrates that are compatible with a R2R process. The two substrate materials that have been identified as having the potential to be R2R compatible are stainless steel and plastics (PEN, PI). Figure 2-2 below compares some important properties of stainless steel and plastic substrates to the traditional 1737 Corning glass substrate.

Property	Stainless-Steel	Plastics (PEN, PI)	Glass
Thickness (μm)	100	100	100
Weight g/m2)	800	120	220
Safe bending radius (cm)	4	4	40
RTR processable?	yes	likely	unlikely
Visually transparent?	no	some	yes
Max process temp (°C)	1000	180, 300	600
TCE (ppm/°C)	10	16	5
Elastic Modulus (GPa)	200	5	70
Permeable O_2, H_2O?	no	yes	no
Coeff Hydrolytic Exp (ppm/%RH)	none	11, 11	none
Pre-bake required?	no	yes	maybe
Planarization necessary?	yes	maybe	no
Buffer layer necessary?	yes	yes	maybe
Electrical conductivity	high	none	none
Thermal conductivity (W/m·°C)	16	0.1-0.2	1
Plastic encapsulation substrate thickness for TFTs in neutral plane	8x	1x	5x
Deform after device fabrication	no	yes	no

Figure 2-2 Substrate Comparison [3]

After examining the technical characteristics of stainless steel and plastic, no clear winner emerges for all roll-to-roll manufacturing applications. In the following sections, properties are discussed in which each substrate type has an advantage and then conclusions about which substrate type will most likely be used for R2R are discussed.

2.1.1.1. Properties that Favor Stainless Steel Substrates

The stainless steel substrate offers a much higher thermal conduction, which allows it to dissipate heat generated by the display at a faster rate than a plastic substrate. Additionally, stainless steel is a good moisture and oxygen barrier; the same cannot be said about plastic substrates. This is important because the emissive layer of the display must be protected from oxygen and moisture or it will suffer from lifetime problems and degradation [8].

Barrier coatings are used to protect the emissive layer in OLEDs, which is unstable in air. The efficacy of the barrier layer has a direct effect on the lifetime of the display. Since currently there is no standard for the testing of barrier layers (every company has their own internal procedures), there can be wide variances in reported display lifetimes from the manufacturer and the actual user. Several barrier layer technologies are being developed by companies such as Vitex Systems, Symmorphix, and GE [4, 5, 6]. Additionally, Dow Corning has developed a R2R tool for barrier coating films that is currently installed and operational as of December 2005 [7].

Due to the plastic material's low resistance to moisture and oxygen, a device that utilizes a plastic substrate requires barrier coatings on both the device side and the substrate side, whereas with a stainless steel substrate a barrier coating is only required on the device side [8]. This allows the stainless steel device to have a simpler structure and a simpler fabrication process.

Additionally, the processing temperature of the substrate material is a very important parameter. A higher processing temperature is advantageous because the deposition of high mobility poly-crystalline silicon TFT requires a post-deposition annealing heat treatment, which takes place at a temperature of about 400°C. If the substrate cannot endure the high temperature required to anneal the poly-crystalline silicon then an amorphous silicon TFT can be used instead, which offers lower mobility and poor video performance. A stainless steel substrate is capable of withstanding a maximum processing temperature of 1000°C, whereas a plastic substrate can only endure temperatures of around 300°C. For this reason, the use of a plastic substrate will prevent the display from being compatible with poly-crystalline silicon processing, thus limiting the material sets available for the backplane with a possible repercussion of limiting the performance of the display to low frame-rate applications (electronic-paper, digital signage, point of purchase displays, etc.).

The coefficient of thermal expansion (CTE) is important to consider because a CTE mismatch between the substrate and the TFT backplane or emissive layers will cause cracks in these functioning layers. Glass substrates are a close CTE match with the functioning layers, and plastic is worse than stainless steel (see Figure 2-2 on page 12). Attention must be given to the temperature reached when depositing silicon because if the substrate is heated significantly when a CTE mismatch is present, the yield of the manufacturing process could decrease significantly. A longer term quality issue arises with the use of plastic because the substrate will deform after device fabrication. Over time the polymer substrate can exhibit problems such as loss of transparency, degradation, and long term instability that could limit the applications to which plastic substrates could be used.

2.1.1.2. Properties that Favor Plastic Substrates

The surface roughness of plastic is lower than that of stainless steel; this smoother surface is important and beneficial so that sharp features do not penetrate into the functional TFT or emissive layers. Transparency is also an advantage of plastic because if the substrate is transparent then the device structure can be either top or bottom emission. The stainless steel device can only be top emission, which offers less flexibility in device design and integration. Another problem associated with stainless steel is that since the material is electrically conductive, it is necessary to apply an insulating layer between the substrate and the TFT. The use of a plastic substrate obviates the need for this additional layer. Moreover, stainless steel foil denting and plastic deformation are problems in moving to roll-to-roll processing. The cost, arguably the most important parameter when considering candidacy for R2R processing, of stainless steel is about a tenth of the cost of glass and the cost of plastic is about $1/20^{th}$ the cost of glass [8].

2.1.1.3. Conclusions: Stainless Steel vs. Plastic Substrates

The technological advantages of stainless steel make it the most probable candidate for early adoption into a roll-to-roll display manufacturing facility, especially after considering its proven use in other industries such as solar panel manufacturing. For example, Uni-Solar uses R2R manufacturing to process amorphous silicon on a 125 micron thick stainless steel substrate for its photovoltaic panels [9]. The existing industrial knowledge of the use of stainless steel in a roll-to-roll electronics manufacturing environment makes it the most plausible short term solution. However, in the long run, the cost advantage offered by plastic could allow it to eventually displace stainless steel in R2R operations assuming that the technological quirks associated with using plastic for R2R are worked out. Moreover, plastic substrates may be adopted early on in some cost-sensitive niche applications where lifetime requirements are more lax.

2.1.2 Functional Materials

The two most salient functional materials in a display that are critical to the development of roll-to-roll processing of display materials are the front plane materials and the thin film transistor (TFT) backplane.

2.1.2.1. The Front Plane

OLEDs

The front plane creates the image on the screen of the display. In Organic Light Emitting Diodes (OLEDs), the front plane consists of an emissive layer in which the electron and hole recombine to generate a photon; the color of the photon depends on the chemistry of the organic material. The two primary types of OLED emissive layers are small molecule and polymer layers, each of which exhibit a different material structure. In the small-molecule case, the basic structure is usually a metal core surrounded by organic ligands, whereas the polymers used as OLED emissive materials tend to be long carbon chains with alternating single and double bonds [10]. The emissive layer organic materials for red and green OLEDs are ready for commercial applications, however, the blue organic materials are only recently becoming acceptable [11]. The lifetime of organic emissive layer materials is a concern for researchers, although for most applications the lifetime of the existing materials is adequate. Many companies are developing organic emissive layer materials, including DuPont, Cambridge Display Technologies, Kodak, and Universal Display Corporation to name a few. These companies are also working to develop their organic materials such that they will be inkjet printable or compatible with other R2R friendly processes. Several active matrix OLED displays have been incorporated in commercial applications such as mobile phones, cameras, and television sets that have met the technical requirements for these applications. One of the limitations of OLED emissive layers is the trade-off between device operating brightness and the device lifetime. OLEDs operate efficiently at a brightness of around 300-400 nits, whereas at a brightness of 5000 to 6000 nits (the minimum brightness necessary for outdoor applications such as electronic billboards) OLED quantum efficiency is decreased and operating lifetime is reduced [12, 13].

QD-LEDs

A different type of front plane material has been developed by QD Vision, consisting of a layer of inorganic quantum dots in an OLED device structure. Due to the inorganic crystal structure of the emissive quantum dot layer, these materials are inherently more stable in the presence of water vapor and oxygen than the organic luminescent molecules. Additionally, the quantum dots are compatible with solution based processing techniques such as inkjet printing and direct contact printing and are therefore attractive for large area and R2R manufacturing approaches [14].

E-Ink

A third type of functional material that has been developed by E-Ink Corporation is a microencapsulated electrophoretic display that is capable of producing images with paper-like readability. The E-Ink display technology is based on microencapsulated oppositely charged colored particles that move in an electric field (see Figure 2-3).

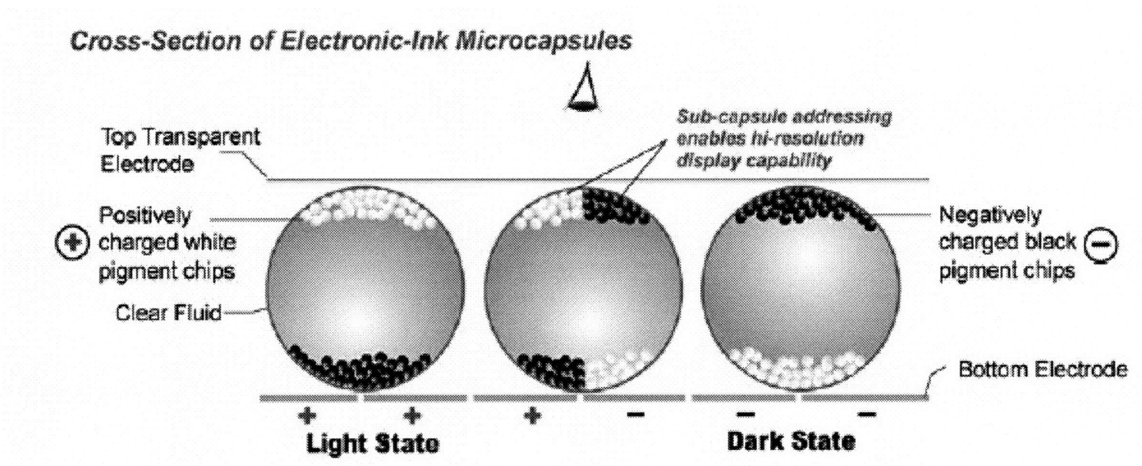


Figure 2-3 E-Ink Display Technology [15]

When an electric field is applied across the microcapsules by the backplane, the charged particles align themselves within the microcapsule to produce the desired image on the transparent top electrode. The device structure of an E-Ink Display is shown on the following page in Figure 2-4.

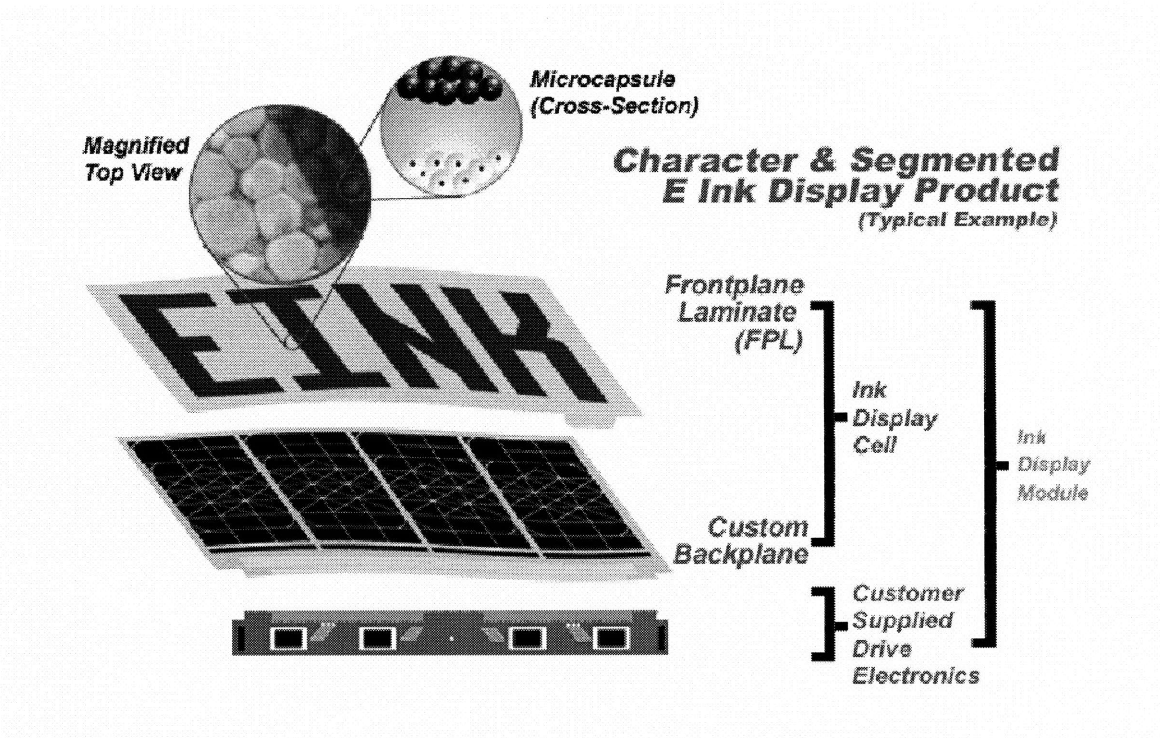


Figure 2-4 E-Ink Device Structure [15]

This technology has many advantages including that it is compatible with flexible substrates, flexible backplane technology, and roll-to-roll processing. The E-Ink displays also have paper-like viewing characteristics; they are easily readable in bright sunlight as well as room light (the same can not be said of OLED and LCD technologies). Additionally, the technology is bi-stable and therefore no power is required to maintain an image [15]. Since power is only used to change the image on the display, very low power consumption can be achieved for many applications: E-Ink's technology used in the Sony Reader can turn 7500 pages per battery set [16]. One of the disadvantages of the E-Ink technology is that it is having difficulty approaching an acceptable video quality frame-rate due to the inherent time lag that the particles require to move within the fluid inside the microcapsule. Additionally, the technology currently requires the use of color filters in order to achieve a full color image.

There are some very promising aspects of the E-Ink technology from the perspective of implementing the technology in a roll-to-roll manufacturing facility. Firstly, there is no fundamental limit to the size of the single sheets of electronic ink that can be produced. Secondly, E-Ink has demonstrated roll-to-roll technology, with coatings hundreds of feet long currently in production, although at narrower (10" to 22") widths. The factor that currently limits the size of displays that E-Ink can cost effectively produce is the availability of low cost backplanes, which are preventing the technology from being applied to full wall size displays [17].

2.1.2.2. TFT Backplanes

The thin film transistor (TFT) backplane is situated between the functional layers and the substrate and acts as an array of switches that control the amount of current or voltage applied to each pixel in the front plane, signaling each pixel's brightness. OLED devices are current-driven, whereas LCD devices are voltage-driven. As mentioned earlier, two primary TFT backplane technologies, poly-Silicon (poly-Si) and amorphous-Silicon (a-Si) are used today in displays. However, next-generation technologies such as organic and metal oxide TFTs are also under consideration, which are both conducive to printing and roll-to-roll compatible manufacturing methods [18].

The deposition of a-Si and poly-Si TFT backplanes on flexible substrates by conventional approaches has been demonstrated by several companies, including Philips, the Palo Alto Research Center (PARC), and Samsung [19, 20, 21]. The traditional techniques used to pattern the a-Si and poly-Si TFTs are chemical vapor deposition (CVD), sputtering, or evaporative methods, which are very expensive to use with large substrates, and therefore are not well suited to R2R processing techniques. An alternative organic TFT material or polymer-based TFT material that is conducive to printing and compatible with R2R processing could enable the cost effective fabrication of large area displays. Such materials are under development by organizations such as the Industrial Technology Research Institute (ITRI) and the Palo Alto Research Center [22, 23]. Additionally, Cabot is developing electronic inks for traditional printing presses for low-cost production of electronics that could potentially be used for R2R compatible deposition of TFTs and electrodes [24].

Many of the materials discussed have already approached or even exceeded the requirements of a particular application. Yet the ultimate test of this technology lies less in the reliability and performance of the organic components, but rather in the ability to manufacture products at a very low cost [25]. In order for these emissive layers, TFT backplanes, and organic electronic materials to be compatible with R2R processes these materials must be able to be produced in a form that is compatible with a R2R patterning technique, such as those suggested in the next session.

2.2 Patterning Techniques

There are several patterning techniques that are being considered as having the potential to be implemented into a roll-to-roll processing line. Three of these techniques are shown in the viewgraph on the next page, and will be discussed in detail in the following sections.

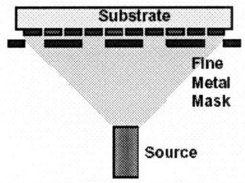
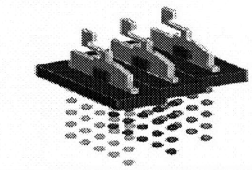
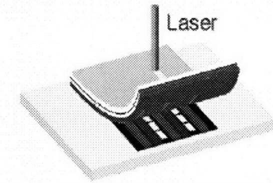
Items	Evaporation (Shadow Mask)	Ink-Jet Printing	LITI
			
Materials	Small Molecule (SM)	Polymer (LEP)	LEP, SM, Hybrid
Position Accuracy	± 15㎛	± 10㎛	± 3.5㎛
Resolution	~200ppi	~200ppi	~300ppi
Aperture Ratio (Top Emission)	30~50%	40~50%	40~60%
Scale-up ability for large size	• Proven Technology • High OLED Performance • Limited shadow mask alignment	• Scalable to large size mother glass • Simple/Economic process • Relatively low performance of LEP	• Scalable to large size mother glass • Dry Patterning /multi-stacking • Donor film required

Figure 2-5 Patterning Techniques [26]

2.2.1 Evaporation

Evaporative methods are by far the most common means for depositing OLED or small-molecular weight films onto a substrate in the display industry. This process involves the heating of the source material in a vacuum chamber with the substrate located several centimeters away, usually above the source. The evaporated source material travels to the substrate, which is covered by a shadow mask, and is deposited on the exposed regions of the substrate (see Figure 2-5). Vacuum thermal evaporation is widely used in the processing of inorganic semiconductor devices because of the precision with which layer thicknesses can be controlled (typically to within ± 0.5 nm), and the relative simplicity of the process [25]. This evaporation technique has been used to manufacture commercial quality OLED displays.

The most salient disadvantage of evaporative deposition, especially from a cost perspective, is the large amount of expensive organic materials that are wasted due to the large portion of masked substrate area. This makes evaporative techniques less attractive for R2R integration when compared to additive techniques such as inkjet printing. However, evaporation and shadow masking are likely to be integrated into the first R2R pilot lines due to their proven performance and reliability.

2.2.2 Direct Contact Printing

Direct contact printing (which includes both stamping and gravure methods) is the "holy grail" of R2R due to its simplicity and potential to be an extremely low cost technique. The ultimate method for printing low cost materials over a large area is exhibited by the newspaper industry; thousands of square feet of printed material can be produced for a few cents. Direct contact printing efforts hope to model a display manufacturing process after the low cost and scalable newspaper and magazine printing process in order to achieve significant cost reductions.

Direct contact printing is being developed in a joint effort between HP and Iowa Thin Film Technologies for roll-to-roll manufacturing of electronics on flexible substrates. HP is operating under the belief that ultimately R2R will be the best way to produce backplanes for displays and other electronic devices. The process that they are developing involves three steps in series: the deposition of the metals, semiconductor materials, and polymer coating onto the substrate, then stamping the material to achieve a 3D structure, and finally etching away the remaining polymer to achieve the completed pattern (see Figure 2-6) [27].

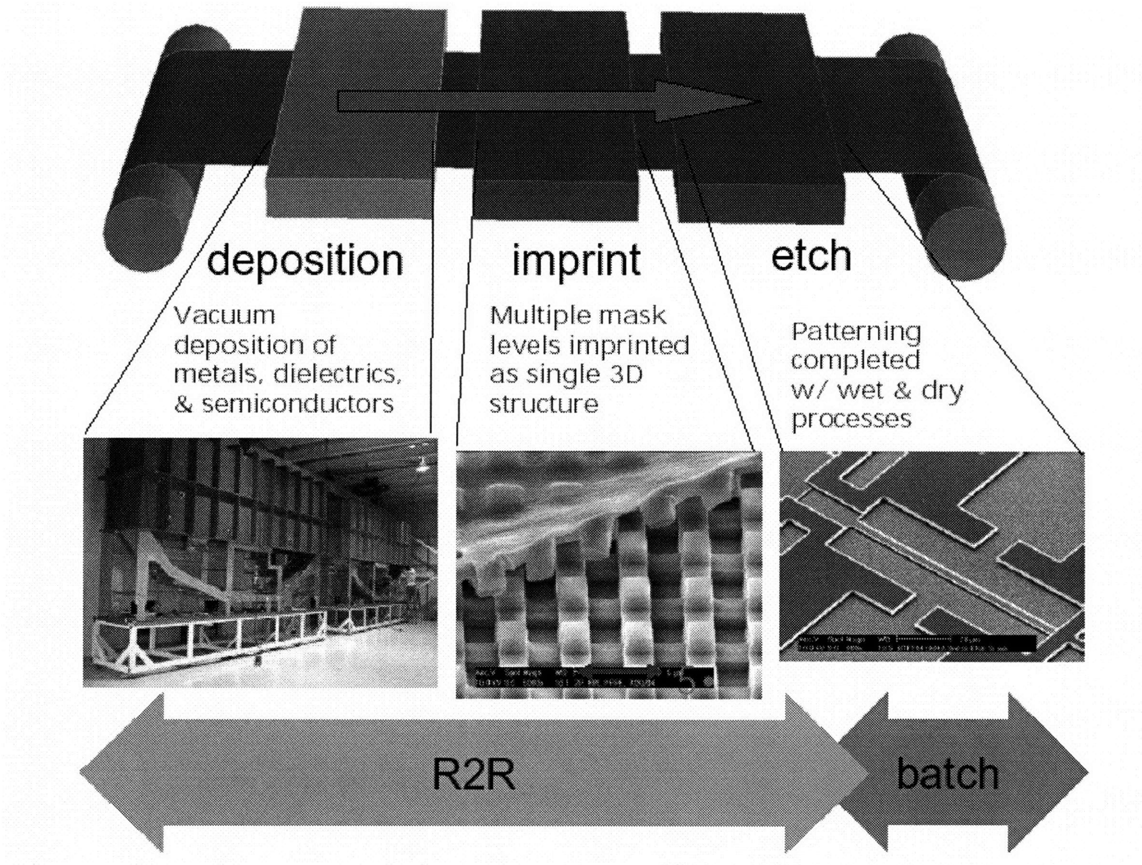


Figure 2-6 HP Imprint Lithography [27].

The stamping operation has been very successful in achieving high resolution (40nm wide lines), verified throughput (5 meters/min) and the capability for multi-level masks [27]. One of the disadvantages of the process is that it still requires a batch etching operation after the materials deposition and stamping, which precludes the overall process from maintaining continuity. This is significant because the batch operation acts as a constraint since it is unable to continuously process material like the R2R operations. Therefore material that is web processed will have to wait in queue for the batch etching operation to process it in "chunks." This has especially adverse effects on the overall throughput of the manufacturing line considering the location of the etch operation as one of the end steps in this process. Carl Taussig, a representative from HP, announced that one of the next steps in developing their stamping technology is to incorporate the etch steps to achieve a fully integrated R2R manufacturing process.

Kodak is also engaging in research to use laser imaging to produce "masters" that can be used with traditional printing methods such as offset, flexo, and gravure. The gravure technique involves engraving the pattern into a cylinder that translates the pattern to the substrate with a rotary printing press. Cabot is developing metal inks for gravure printing and has achieved a layer thickness of 2-6 microns and 100nm layer smoothness [32]. Gravure printing and other direct contact methods such as stamping are considered to have the potential to be capable of achieving higher throughputs than inkjet printing approaches. However, Kodak researchers have asserted that "photolithography will certainly maintain its position as an excellent patterning tool for years to come" [28]. Work done by DuPont and the University of Illinois also demonstrates that microcontact printing could be used to manufacture electronic devices [29].

2.2.3 Inkjet Printing

Inkjet printing is a method of patterning an ink or other material onto a surface where droplets of the material are ejected from a print head and then travel to the surface of the substrate. Inkjet printing is an additive process that only consumes that amount of material that is actually used in the product, whereas conventional masking processes tend to waste much more material than the amount that is actually deposited on the substrate. For this reason, inkjet technology offers economic advantages in cases where the material to be deposited is expensive, management of the waste fluid is an issue, and variable patterns are desired [30].

Most commercial and industrial ink jet printers use a thermal or piezoelectric system, and thermal inkjet dominates the consumer marketplace. Inkjet technology has been established as having consistent drop volume, accurate drop placement, high reliability, and high productivity. Pilot and production lines for using inkjet to manufacture polymer LED displays exist in Europe and Asia, and large commercial systems are currently available at prices from $100K to more than $500K from companies such as Cabot, Litrex, and Dimatix (see Figure 2-7) [31].

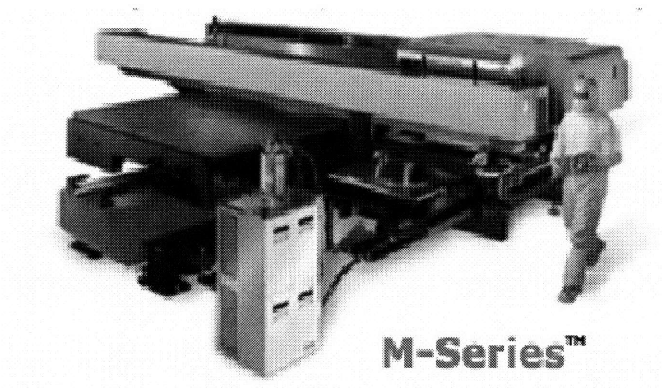


Figure 2-7 Litrex Inkjet System [32]

As displays continue to move to larger substrates inkjet printing becomes more attractive due to the material consumption efficiency, high reliability, and high throughput. The cost benefits associated with inkjet technology are derived from several capabilities: the reduced consumption of expensive materials, the reduction of equipment and floor space by approximately 70% compared with sputtering/photolithography, and the low processing temperature that permits the use of lower cost plastic substrates [32]. Piezoelectric inkjet printing offers a combination of high productivity, high reliability, and jetting uniformity (drop volume consistency, velocity characteristics, and jet straightness) that is suitable for manufacturing electronics. In many cases, the limit to penetrating these markets is not the printhead, but the availability of the commercial jettable fluids [30].

2.2.4 Thermal Transfer

Researchers from 3M and Samsung recently developed the laser-induced thermal imaging (LITI) process, which utilizes a laser and galvanometer scanning system for a high-resolution solid-to-solid transfer of thin polymer or molecular films and layer stacks [33]. In this approach, a laser or other localized heat source is used to achieve a dry transfer of a polymer or small-molecular-weight material from a 'donor' or material source sheet to the 'receiver' or target substrate (see Figure 2-8).

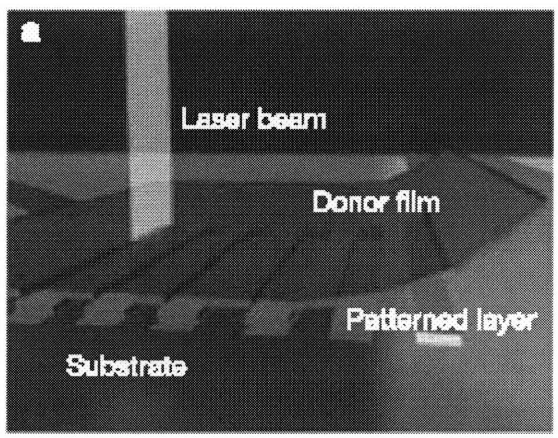


Figure 2-8 LITI Process [25]

The transfer occurs by ablation of materials that are pre-deposited onto the donor sheet held in contact with the substrate. This process can be used to fabricate organic transistor backplanes and emissive layers for OLEDs. The transferred material must be optimized such that its resistance to thermal degradation and mechanical properties are suitable for this laser-induced process. Although this optimization can lead to compromises in device performance, laser-induced thermal transfer of organics is showing early promise as a route for realizing practical macroelectronic integrated circuits [25].

2.3 Equipment and Facilities

At the equipment level, several commercial systems are readily available in a range of scales for roll-to-roll layer deposition and patterning. For example, Applied Films has developed the SMARTWEB™ technology that is capable of depositing multilayer stacks of most materials R2R without breaking vacuum or damaging the surface [34].

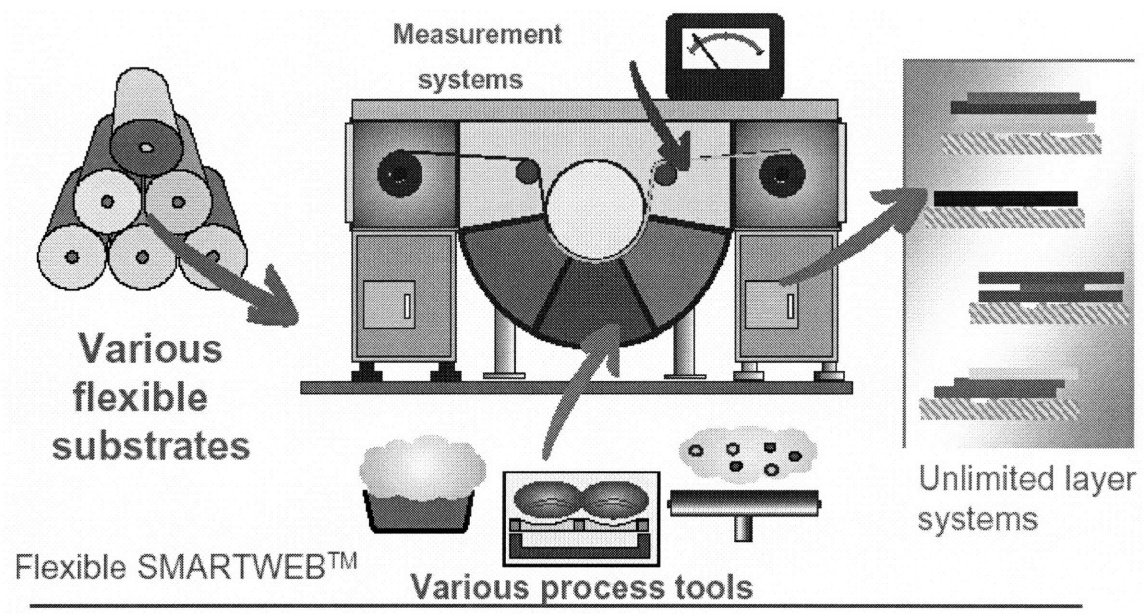


Figure 2-9 Applied Films SMARTWEB Equipment [34]

In addition to the Applied Films equipment, several other film deposition and coating devices are available at Kodak, which has some excess capacity due to the advent of digital photography. Kodak recently acquired Creo in an attempt to leverage this capacity in the printable electronics space. As mentioned earlier, several inkjet equipment systems are commercially available from companies such as Litrex and Cabot.

However, despite the availability of this equipment little success has been made in achieving an integrated roll-to-roll facility to manufacture displays. Attempts are being made to bring together some of technology pieces at the equipment level to achieve a functional manufacturing line for displays. One such effort is called the Center for Advanced Microelectronics Manufacturing (CAMM), and represents a partnership between industry, government, and academia to demonstrate the process feasibility of roll-to-roll electronics manufacturing. The focus of the CAMM is on the ability of R2R to lower manufacturing costs of electronics as opposed to exploring some new functionality associated with flexible displays. The CAMM is planning to bring together roll-to-roll coating, lithographic, inkjet printing, direct contact printing, etching, and evaporation processes in a web based manufacturing facility to build a roadmap for the development of R2R electronics manufacturing in a collaborative environment [35].

Aside from the CAMM, a few companies are attempting to demonstrate the viability of a R2R manufacturing prototype line. For example, Plastic Logic is developing equipment that allows additive direct writing to achieve large area coatings with a throughput of 100 substrates/week. This company is using E-Ink's front plane technology and is striving to demonstrate the validity of their prototype line to key customers [36]. As mentioned earlier, HP and ITFT have also attempted to develop a R2R stamping line that can integrate the etch steps into the web process [27]. Additionally, outside of the display space R2R facilities have been successful in manufacturing solar panels at a relatively low cost.

2.4 Cost Modeling

The primary reason for interest in the roll-to-roll manufacturing of displays is because of the potential of this manufacturing approach to lower the cost of producing an electronic display. In order for a roll-to-roll manufacturing process to displace processes currently used to manufacture LCDs or OLEDs, it must be able to produce a similar product at a lower cost. Although there is some industry speculation that unique performance characteristics of flexible substrates will command a higher price, the key driver for R2R is cost [37].

In order to assess the potential cost reductions associated with roll-to-roll manufacturing processes, a cost model developed by Abbie Greg, Inc. for an active matrix manufacturing process will be referenced. The cost model assumes that the operations in the process flows are proven conventional operations (lithography, etching, sputter deposition) that are adapted to R2R equipment [For details regarding the process flow operations and tools used in the model, see Appendix A.1]. The model also assumes that 1000 feet by 2 feet rolls of PET are used to make 3.25 inch by 3.25 inch displays on an 18 inch by 24 inch format. This model was built for mobile displays, and it is a good benchmark for how R2R manufacturing could be lower cost than LCD manufacturing approaches. Figure 2-10 shows how the cost per square foot of active matrix OLED and passive matrix PLED displays are expected to decline with increases in volume.

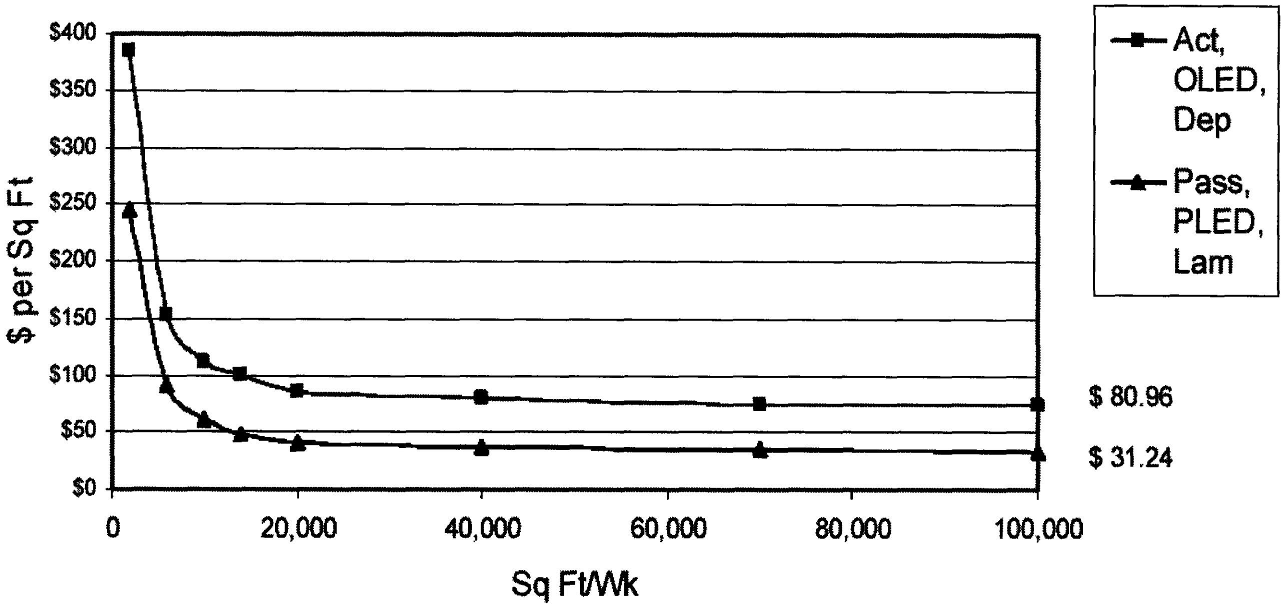


Figure 2-10 Cost per square foot vs. Volume [38]

From the figure above it is evident that the minimum efficient scale (MES) for the operation of a roll-to-roll display manufacturing facility is around 20,000 square feet per week. MES is defined as the minimum capacity at which a plant needs to operate to achieve a flattening of the unit cost curve. Many markets and application areas could support a plant operating at a capacity of 20,000 square feet per week if you assume that the displays could be sold into these markets at a sufficiently high volume to sustain the manufacturing operation.

If the plant operated at a capacity of 100,000 square feet per week, the active matrix line could achieve a cost per square foot of $81. The model predicts that in two years a R2R display could be manufactured at about half the cost of a LCD display when the cost of the two types of displays are compared at the same point in time. The cost savings associated with R2R when compared to conventional batch manufacturing approaches are derived from savings in the huge substrate handling costs when moving the work-in-progress inventory from operation to operation inside the plant. With batch processes, small amounts of the product are carefully moved to different operations one glass sheet at a time, which is expensive due to the cost of handling the fragile substrates. However, with a roll-to-roll scenario, extremely large amounts of product can be moved to the next operation in a reel, thus significantly reducing the cost of transferring materials to different operations within the facility [39].

Another potential source of cost savings outside of Abbie Gregg's model is that if an additive deposition process could be integrated into a R2R manufacturing line, then there could be a significant materials cost saving over a vapor deposition process (which is currently used in the model). When examining the predicted cost structure of a R2R manufactured active matrix display, it is expected that materials costs will account for over half of the total manufacturing cost of the display (see Figure 2-11).

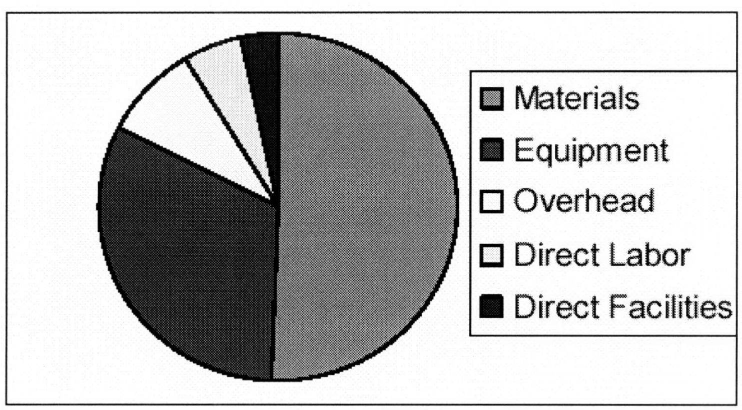


Figure 2-11 Cost Structure of Active Matrix R2R Line [38].

This suggests that the savings in materials cost from using inkjet or another additive process could be significant, especially considering that vapor deposition or lithography wastes well over half of the material consumed in the process.

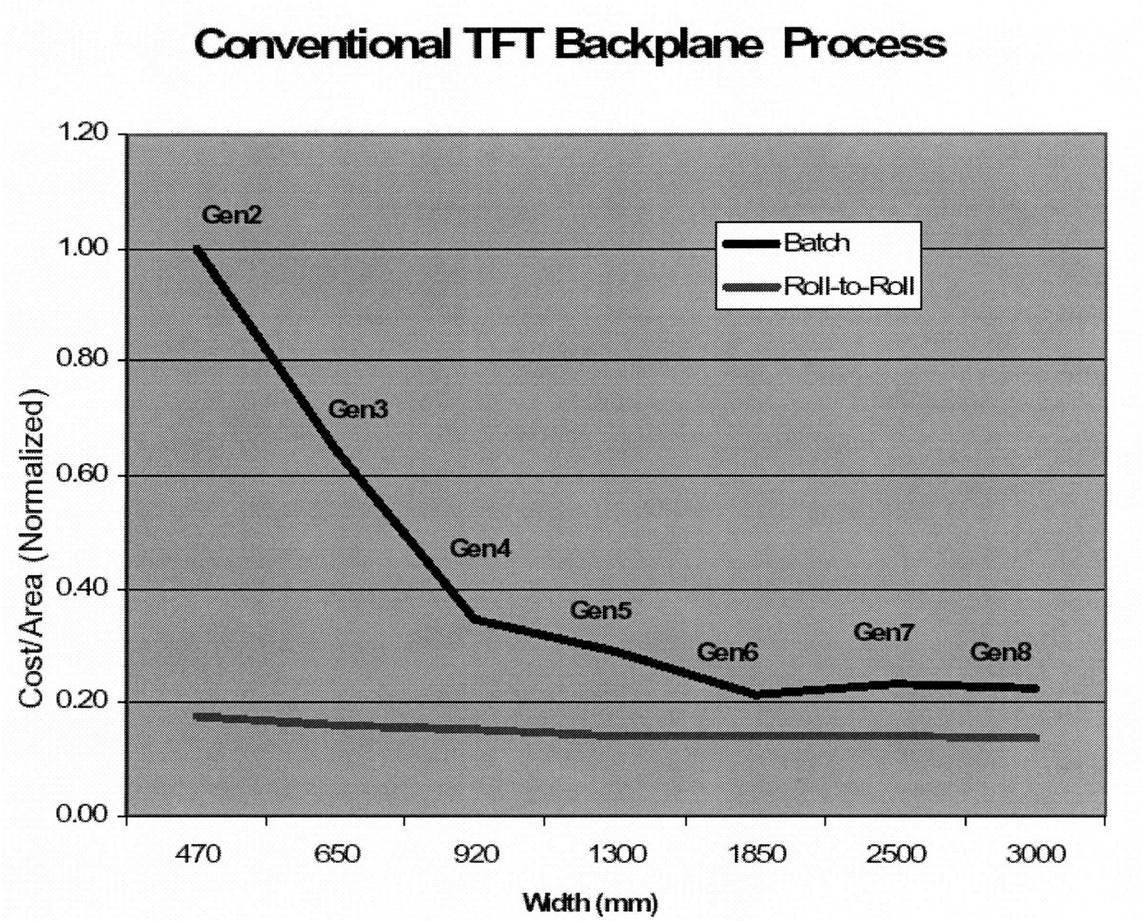


Figure 2-12 Comparison of Batch and Roll-to-Roll Backplane Costs [35]

The above figure shows how the TFT Backplane cost-per-unit area is expected to decline with increasing substrate size for batch and R2R processes. This graph was developed from a model by JEM, which assumed an amorphous silicon backplane technology would be used [35]. This model by JEM suggests that R2R may have an advantage in the smaller display sizes, although the scope of this model is limited to the TFT Backplane deposition, and not the overall display cost.

Nearly every model in this industry predicts that a roll-to-roll manufacturing facility could offer significant cost savings if it could be integrated successfully. However, the projected minimum investment for a one-up tool set for a R2R active matrix line is 181 million dollars [38]. This is significantly more than the $10MM that many U.S. organizations are willing to invest in pilot lines. From the perspective of a company considering investing in R2R infrastructure, one thing is clear: the amount of money that the company will spend on a R2R facility ($100 MM+) is much more certain and known than the amount of money that it will save each year after making the investment. In addition to the financial risk associated with a $181 MM investment, there are significant technological and engineering risks that are coupled to attempting to integrate the technology pieces (materials, patterning techniques, and equipment) that are necessary to achieve a fully integrated R2R manufacturing line.

2.5 Conclusions from Technology Assessment

It is evident that in the display industry there is much interest in developing materials, processes, and equipment that could allow the roll-to-roll manufacturing of electronics to come to fruition. However, the practical implementation of R2R technology will ultimately be decided by the ability to produce devices and circuits at a cost that is significantly below that needed to manufacture conventional electronic circuits based on, for example, silicon [25]. The cost models visited in this work suggest that R2R could achieve significant cost advantages over conventional display manufacturing processes. The question is whether or not the technology is sufficiently developed to justify the investment in a roll-to-roll manufacturing facility that could be capable of realizing these potential cost reductions. To answer this question, each technology piece (materials, patterning techniques, and equipment) will be addressed in the context of whether or not it is ready for a full scale R2R manufacturing facility. To frame the question in another way, each technology piece will be considered in response to the recurring question in the industry: "Are we there yet?"

2.5.1 Materials

For the materials technology piece, the answer to the question above is "Yes." Stainless steel has been proven as a viable roll-to-roll substrate in other industries, including solar power. Additionally, several front plane materials have been proven to meet lifetime and product reliability specifications that are required to compete with the entrenched LCD technology. OLED displays have been used in products such as cameras and mobile phones, and E-Ink's technology was recently released in the Sony Reader electronic book. Although there is still room for improving aspects of the materials such as the substrate processing temperature or the printability of some electronic inks, the state of the materials technology is not what is preventing R2R from being realized in industry.

2.5.2 Patterning Techniques

The answer is "No" for the technological state of the patterning techniques that could be used for roll-to-roll manufacturing. Although several R2R patterning techniques have been demonstrated by companies such as HP, Vitex, and Samsung, no dominant process flow has emerged that would allow these techniques to be integrated into a manufacturing environment [38]. Additionally, many of the patterning techniques surveyed in Section 2.2 still have significant engineering barriers to overcome in terms of achieving acceptable quality, yield, and throughput that is required for manufacturing real products. The proof of concept of R2R patterning techniques has been accomplished, but these patterning techniques still require significant development in terms of how they will fit into an overall roll-to-roll process flow before they are ready for integration into a R2R facility. More investment is needed at the equipment level in order to combine some the patterning techniques to achieve a viable process flow for R2R manufacturing.

2.5.3 Equipment and Facilities

Again, the answer to the question "Are we there yet?" for the equipment technology is "No." Layer deposition equipment and large scale inkjet equipment is available that is compatible with roll-to-roll manufacturing processes, and custom tooling for R2R can be built at premium prices. However, very limited equipment orders have been made to date and vendors of specialized equipment are hard pressed to spend significant amounts of money on non-recurring engineering in order to make the equipment compatible with the manufacturing process [38]. This high cost of developing specialized equipment creates a chicken and egg problem in the tooling industry: the tooling companies do not want to invest the money to build standardized equipment until they get sufficient orders to justify the investment; on the other hand, the manufacturers are not placing orders because the custom equipment is too expensive. Above all, the overarching question at the facility level is, does anyone want to spend the $181 M minimum investment for a one-up tool set to find out if roll-to-roll is real? Thus far, the industry's answer to that question has been "No."

CHAPTER

3 Markets and Application Areas

3.1 Application Areas and Market Segmentation

At a high level the display market can be segmented into two types of displays: individual communication displays and mass communication displays. Individual communication displays are designed to communicate a message to one person or a small group. Most individual communication displays can be found in consumer based markets, and include products such as televisions, books, and cell phone displays. On the other hand, mass communication displays are designed to communicate a message to many people or a large group. Most of these displays are in commercial markets and include devices such as billboards, point of purchase (POP) displays, and trade show graphics. Figure 3-1 on the following page conveys how the mass communication and individual communication display markets are further broken down into application areas and the current market size of each application area [40].

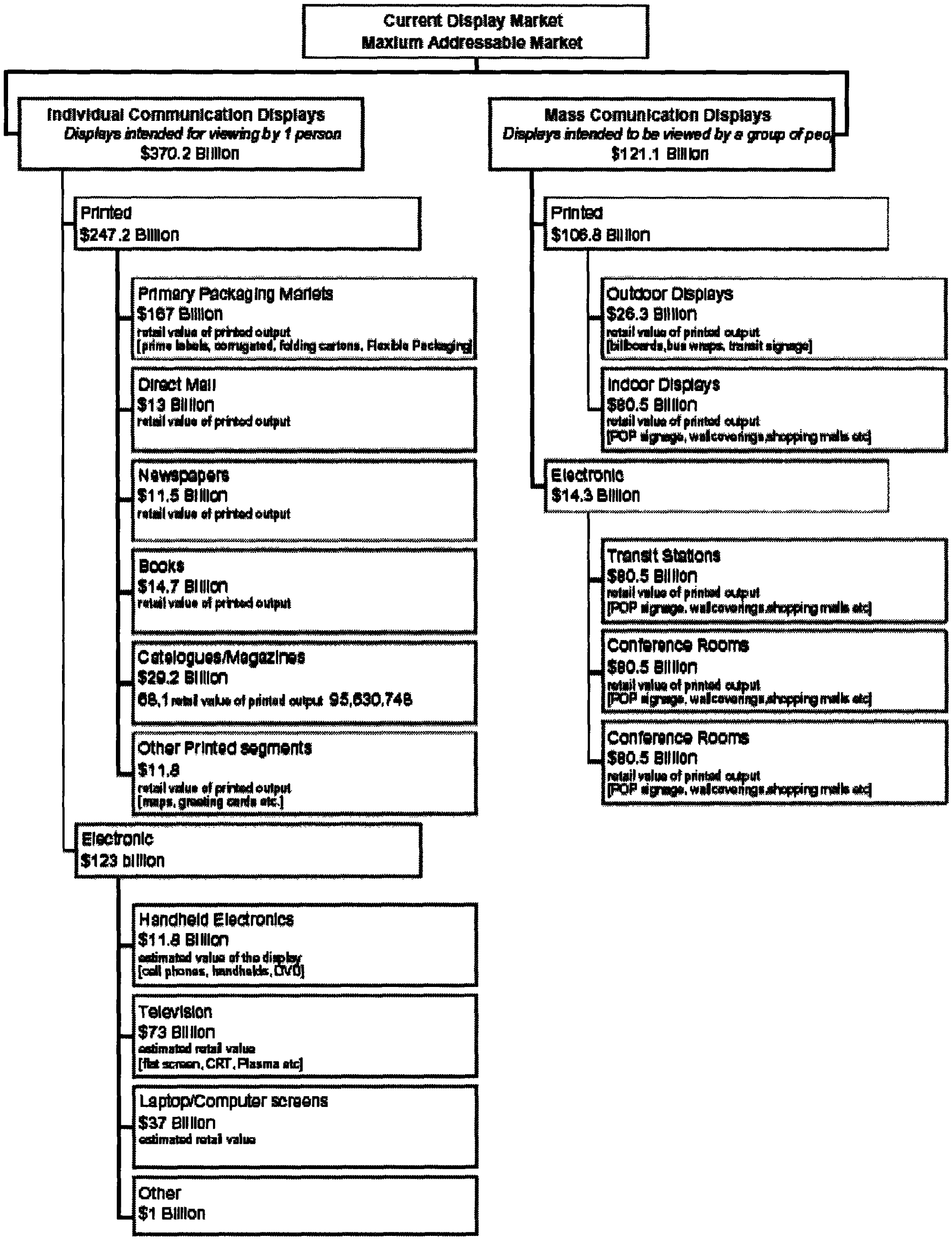


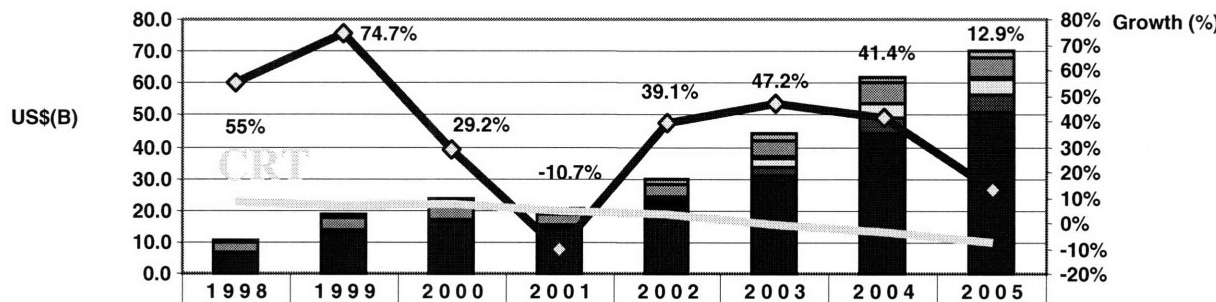
Figure 3-1 Display Market Segmentation and Size [40]

There is a consensus within the industry that if R2R manufactured displays are going to be adopted in the market, it will be on the basis of lower cost. However, there are a few applications within the individual communication display segment where flexibility could be desired. The most commonly discussed application is the flexible mobile phone display, which is being explored by Polymer Vision, Inc. as a way that mobile displays can achieve both a large screen size and an ease of transport [41].

Figure 3-2 Applications for Flexible Displays [40]

Another application where flexibility could be valuable is in the development of an electronic newspaper. E-Ink is an advocate of pursuing this market, and newspaper companies are investing in E-Ink in an attempt to capture some of the value that has been lost from the drop in newspaper subscriptions over the past few years [42]. The problem with attempting to displace traditional newspapers is that the current price of delivering the news to a customer's doorstep is extremely cheap and traditional newspapers are easy to use. Electronic newspapers would require the user to download new content every day (which would take time) and the user would have to keep track of the electronic newspaper, whereas the traditional newspaper can be trashed after its use. For these reasons, electronic newspapers do not appear to be a high potential application for flexible displays.

The markets for R2R manufactured displays that are proven to be attractive to consumers and cost driven are the markets in which LCD technology currently dominates. These application areas include televisions, mobile displays, conference room displays, and computer screens among others and are large enough (approximately $ 100B) to justify an investment in a full scale manufacturing facility. The flat panel display (FPD) market alone has experienced double digit growth from 1998 to 2005 (with the exception of 2001) and has grown to a 70 billion dollar market [43].



	1998	1999	2000	2001	2002	2003	2004	2005
Others	0.9	1.1	1.4	1.7	1.8	1.9	2.1	2.0
PMLCD	3.0	3.7	5.3	4.2	4.0	5.2	6.3	6.1
OLED	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.5
PDP	0.2	0.3	0.4	0.8	1.4	2.8	4.3	5.1
LTPS TFT LCD	0.1	0.3	0.4	0.5	0.8	2.9	4.8	5.5
a-Si TFT LCD	6.4	13.1	16.4	14.2	21.8	30.8	44.2	50.8

Figure 3-3 Annual Flat Panel Display Revenues and Growth [43]

LCD technology currently has about a 70% market share in the FPD space. If R2R can realize a cost advantage over conventional manufacturing approaches, then R2R products will surely be in demand by the FPD market. Although the ability of R2R products to gain share in markets occupied by LCD technology would ensure the commercial viability of R2R, there are some smaller markets that could be easier for R2R technology to permeate initially.

3.2 Initial Markets for R2R Manufactured Displays

There are several markets in which a low cost R2R manufactured display could potentially gain share. Figure 3-4 below depicts Kim Allen's (iSupply, Inc.) view on how flexible display applications will fit into the market structure, where the shading on each bar from pale to dark indicates the increasing units in that application [44].

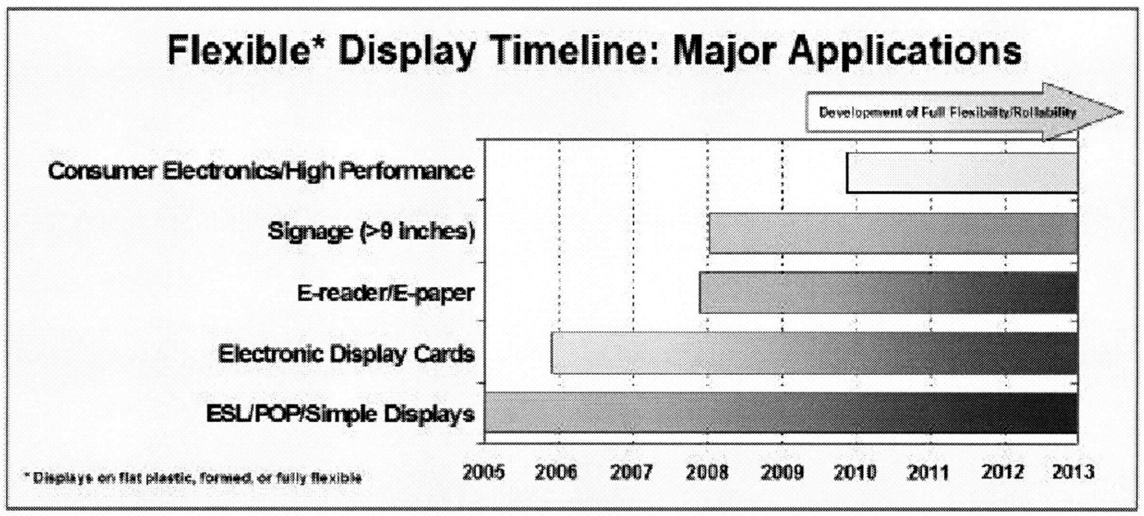


Figure 3-4 Expected Market Adoption Timeline [44]

Kim predicts that the early penetration of simple applications like POP signage, shelf labels, and electronic display cards can provide a revenue stream to assist with the development of larger and more advanced flexible displays for signage, e-readers, e-newspapers, and, ultimately, active matrix applications [44]. However, the markets involving these simple applications (POP signage, shelf labels, and display cards) are extremely price sensitive, which makes it difficult for a company to deliver a value proposition in these applications that can command a premium price for an electronic display over a paper display.

A return on investment (ROI) model developed by I.T. Strategies takes a closer quantitative look at the value proposition associated with entering the POP signage market. The POP market is about a 40 Billion dollar market that is driven by advertising dollars. The economic drivers for introducing a R2R electronic display are to reduce the cost of printing the paper signage, installing and changing the paper signs, shipping the signage, and reducing the cost of lost signage (estimated to be 50% by POPAI). Additionally the electronic displays would reduce the complexity of managing pricing and sales and allow the retailer to quickly respond to local pricing competition. The ROI model predicts that if a large size retailer (1200 sites) replaces all of the signs at its store sites with electronic displays then it would see a breakeven in year 4, and a medium size retailer (700 sites) would realize a breakeven in year 8 [40]. This basic model (see Appendix B) does not take into account the replacement and maintenance costs that will be encountered with the electronic display and neglects to use a discount rate when evaluating the impact of the cost savings over time. Aside from those issues, however, a 4 or 8 year ROI will not be attractive to a retailer considering making the investment in using electronic displays for POP signage, especially when the large risk of implementing and operating the electronic displays is taken into account.

An initial market that may be more likely for R2R electronic devices to enter could be the market for large electronic billboards. According to the Outdoor Advertising Association of America (2004), the global outdoor advertising market is approximately $19 Billion; the United States is expected to surpass $5.5 billion this year. Billboards accounted for 60% of this revenue [45]. The number of billboards currently installed in the U.S. is 143,230; legally this number is difficult to expand [40]. Therefore, in order to gain more advertising revenue from existing billboards there is a need to increase the content that the board is capable of delivering. The use of large area electronic displays for billboard applications could deliver more content and also exploit the scalability associated with the R2R manufacturing. Another attractive aspect of this market is that the top 10 companies in this space (Clear Channel Outdoor, Viacom Outdoor, Lamar Advertising Company, etc) control over 85% of the revenues in the market [40]. This makes the customer identification and sales process much easier than in a highly fragmented market, assuming that the vendor can show a strong value proposition to these customers. One of the negative aspects of this market is that it will probably only make sense to use electronic displays in high traffic and metropolitan areas (i.e. Times Square), and it is unclear whether or not these metropolitan markets are large enough to support a large scale implementation.

In summary, potential entry markets exist that could generate sufficient interest and revenues to propagate the development of roll-to-roll technology. The question is whether or not the development of these entry markets will create sufficient value to sustain an entire new industry. This question leads back to a point that has been made several times: R2R is all about cost. In order for a widespread adoption of R2R manufactured displays to occur in the marketplace these displays must be cheaper to produce than the incumbent technologies in these markets.

CHAPTER

4 Competitive and Complementary Technologies

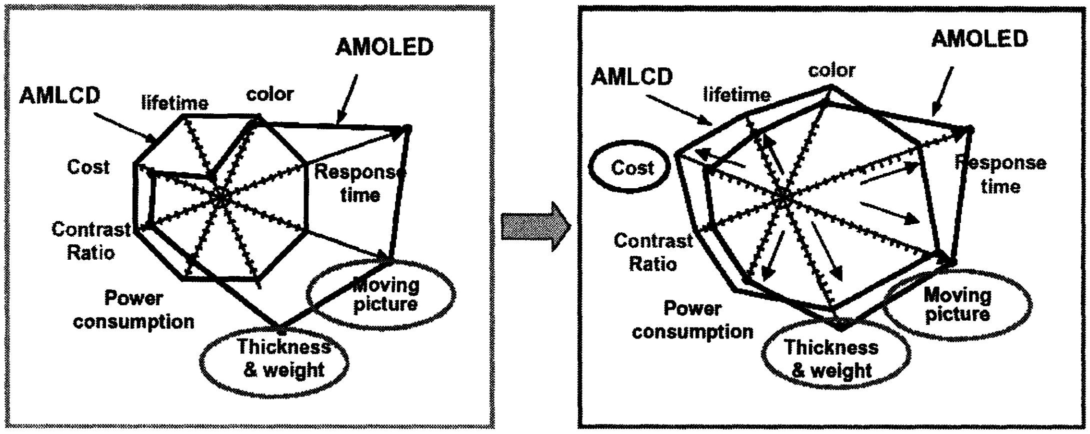
4.1 Competitive Technologies

The display technologies that could compete with R2R manufactured displays are usually a function of the application or market space in which the display is being used. For example, in outdoor display applications R2R technology will be competing against either modular LED displays or paper/paint, whereas in a television application the technological competition would be LCD, plasma, or CRT displays. This application dependent competition exists because the price/performance characteristics of some technologies are more suited to certain applications than are other technologies. For instance, LCD technology is not well suited to outdoor applications due to the physical limitations on the maximum brightness that can be achieved with LCD displays. Four technologies that are competitive with R2R manufactured displays will be discussed in the following sections. Three of the technologies are incumbent in their respective marketplaces (LCD, Modular LED, and Paper/Paint); the other technology (Electrotextiles) has not yet been commercialized in any display market.

4.1.1 Liquid Crystal Displays (LCDs)

LCD technology currently dominates the flat panel display markets, as has been illustrated in Figure 3-3. The two other large markets in which LCD is an incumbent technology are handheld electronics and laptop/computer screens, which have total market sizes of $11.8 Billion and $37 Billion, respectively [40]. LCD displays have realized large market shares in these application areas because the technology has been adequately refined to enable the delivery of high performance, reliable displays at a cost that is below that offered by alternative technologies. However, LCD displays have not been adopted in extremely large area markets because it becomes very difficult to manufacture LCD displays that have sizes on the order of meters instead of inches (Gen 8 is the largest size currently available at 2160mm x 2400mm). Moreover, LCD displays are not suitable for outdoor signage applications due to their brightness limitations and have only attained a small share of printed markets due to the significant cost differential over printed materials (paper, cardboard signs, etc).

The structure of an LCD display can be viewed in Figure 2-1, where the LCD device structure is compared to an OLED type device. Five years ago it was the case that organic emissive technology could notably outperform LCD technology in metrics such as response time, thickness, and weight; the consensus in the industry at that time was that if OLEDs could resolve the lifetime and color issues then OLED manufacturers could charge a premium for the superior performance. The ability to capture a higher price for OLED devices was critical to the commercial success of OLEDs because they were, and still are, more expensive to manufacture than LCDs. However, over the past five years LCD technology has significantly narrowed the performance gap between the two technologies to the extent that any performance advantage that OLED has over LCD is not valued by the end viewer (it is difficult for the human eye to perceive performance above that of High Definition LCD displays).



AMLCD vs. AMOLED
(2001)

AMLCD vs. AMOLED
(2005)

Figure 4-1 Evolution of LCD Performance [26]

Given the continuous advances in performance of LCD technology, it is clear that if roll-to-roll manufactured displays (regardless of the emissive technology used) are going to compete with LCD, the axis on which they will compete is cost. From glancing at Figure 2-1, one may assume that the more complex LCD device structure is more expensive to manufacture than the printable organic emissive type devices – yet this is not the case. LCD technology is much more mature than any technology that is being considered for R2R manufactured displays and over the years the LCD manufacturing process has been driven by economies of scale to achieve reductions in unit costs. As more and more displays are processed on one large sheet of glass, the materials cost of LCD is becoming the largest component in the cost structure on a per unit basis. Nikkei Microdevices recently published their 2006 Flat Panel Display Yearbook, in which they suggest that "by 2010, parts and material costs will account for 80% of the total cost of large-size LCD panels" [46]. As the cost structure of LCDs becomes more and more dominated by materials, it becomes clear that if R2R manufacturing is going to displace

LCD in a long term battle then it must offer a reduction in materials cost over LCD processing.

The price point that R2R will have to beat in order to see adoption in the marketplace is a moving target: the average prices of 42-in high definition LCD panels fell by about 35% in 2005 as compared to 2004 [47]. This price drop was partially influenced by an oversupply in the market, and probably does not correlate directly with a 35% reduction in the actual manufacturing cost of an LCD display. However, the incremental reduction in the cost of manufacturing LCDs poses a formidable challenge to the introduction of a new manufacturing technology such as R2R: the new technology must match LCD in performance and reliability yet also drastically beat LCD on cost in order to warrant the investment in new manufacturing infrastructure.

4.1.2 Modular Light Emitting Diodes (LEDs)

Modular LED technology is the leading technology in the electronic billboard, sports stadium, and arena markets. Applications in these markets all require large area displays, which is what modular technology is well suited to. The limit on the size of a LED display is almost endless: the display in Turner stadium below is nearly 80 feet wide.

Figure 4-2 LED Display at Turner Staduim

A display is assembled with modular LED technology by combining panels of LEDs to form the image of a seamless screen: the display shown above consists of 266 panels that each contains 20 lighting units, resulting in a screen that can faithfully reproduce one billion colors, and be clearly seen from almost any viewing angle [48]. The modular installation approach allows the cost of the LED display to scale linearly with size, although the cost per square foot decreases a little as the size increases due to the economies of scale associated with certain fixed costs such as the cooling system, controlling circuits, etc. The screen installation usually accounts for 25-30% of the overall cost of the screen, however, the installation price can vary significantly based on the location (Times Square install prices are roughly double other locations). For example, the total cost of a screen approximately 20 feet by 40 feet is around 1.5 million dollars, and with about 100 screens sold last year the market is growing [13].

LED screens have a near monopoly in the electronic outdoor display market segment (LEDs compete only with paper and paint in the overall outdoor segment) because most alternate electronic technologies cannot achieve the brightness of 5000 to 6000 nits for outdoor applications. OLED and LCD emissive technologies are usually only capable of operating at around 300-400 nits, with a brightness of 1000 nits being the upper limit of these technologies [12]. The E-Ink technology is viewable in sunlight; however, it is not quite ready for video speed response time at this point.

The high price of modular LED screens restricts their application to high traffic locations. If large area R2R manufactured displays could be produced at a much lower cost, there is opportunity to not only grow the size of the outdoor signage market that uses electronic displays, but also displace LED as a competitive technology in this space. There are unique challenges associated with operating an outdoor display, such as water proofing, cooling the system, and achieving contrast in daylight [13]. If R2R manufactured displays can meet these challenges and deliver a low cost reliable product, then the markets in which LED dominates have the potential to be very lucrative. Additionally, these markets offer opportunities for growth into advertising markets that currently utilize paper and paint to display information.

4.1.3 Paper/Paint

Initially, it may seem counterintuitive to consider paper and paint as technologies that are competitive with a roll-to-roll manufactured electronic display. After all, from a technological standpoint, paper and paint cannot offer near the functionality that an electronic display can offer. However, when assessing which technologies are competitive with electronic displays from the perspective of the marketplace, it quickly becomes evident that paper and paint are fierce competitors in very large markets that roll-to-roll manufactured displays could potentially enter.

As suggested in Figure 3-1, the largest revenue segments for displays are the printed markets, which use paper, paint, or inkjet on vinyl to deliver the desired content. These markets include newspapers, books, direct mail, packaging, billboards, and many other types of signage. These markets are traditionally very price sensitive because the high volume, short product lifecycles, and limited number of viewers do not warrant the investment in more expensive display technologies. The cost of printing inkjet on vinyl is between 4 and 7 dollars per square foot as compared to the 31 or 81 dollars per square foot projected cost of a R2R manufactured passive matrix or active matrix display (see Figure 2-10) [45]. For this reason, the extent to which R2R electronic displays can permeate markets in which paper and paint are the incumbent technologies will depend on the value of the added functionality offered by the electronic display in that application.

An interesting case study of a technology that is attempting to penetrate a market that has been traditionally printed paper is the launch of Sony's Reader, which uses E-Ink's front plane technology.

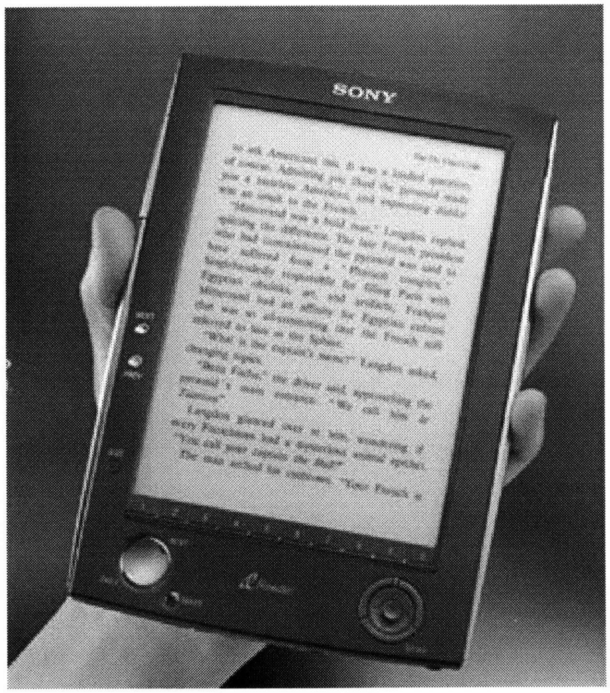


Figure 4-3 Sony Reader

If this entry is successful in gaining share in the book market, then it could set the stage for entry into larger area markets such as newspapers, magazines, or indoor/outdoor signs.

4.1.4 Electrotextiles

Of the competitive technologies surveyed thus far, electrotextiles is the only technology that is not an incumbent in any display markets. The field of electrotextiles can best be described as the space where the two ostensibly disparate fields of electronics and textiles could potentially intersect. These two mammoth industries are very similar in size: 480 Billon dollars per year for textiles and 450 Billion dollars per year for traditional electronics [49]. Traditionally there has been very little collaboration between the two mature industries due to the seemingly fundamental differences in their products; however, recent research efforts indicate that there may be new and unique applications that justify some level of collaboration. The driving force for the development of electrotextile technology is the expectation that lower manufacturing costs will be achieved through the use of textile manufacturing processes that are appropriately modified to incorporate electronic components [50]. "Using today's technologies, intricate woven fabric structures can be manufactured continuously at high speed with low production costs" [51]. Using both conducting and non-conducting fibers as the weave in the inherently low cost textile manufacturing process could result in the ability to cost effectively produce large area devices by selectively interconnecting the conducting fibers during the weaving process. Several broad functions may be incorporated into electrotextile devices as exhibited in Figure 4-4 below.

Sensing	Ability to integrate a large number of sensors to quickly cover a large area. Platform modular sensors (Acoustic, chemical, biological, thermal, optical, etc.)
Actuation	Multiple nano/micro actuators can achieve macro effects: shaping, flexing, or conforming.
Logic	Move processing closer to sensing/actuation hub, greater number of nodes allows higher fault tolerance
Power Sources/Generation	Fiber batteries, fuel cells, or solar cells distribute power throughout the system
Communication and Connectivity	Wireless, radio frequency, acoustic, fiber optics, etc.
Control/Adaptation	Ability to reconfigure on the fly

Figure 4-4 Functionality for Electrotextiles [50]

There are a number of different techniques that have the potential to form the interconnects at crossover points on woven circuits: resistance welding, air splicing, ultrasonic welding/bonding, laser beam welding, conductive adhesive bonding, microwave bonding, and solvent bonding. Work done at NC State University has identified and demonstrated that resistance welding is an effective method of producing crossover point interconnects in an electrotextile circuit [51]. The setup requirements necessary to achieve an electo-woven circuit include: variable speed weaving machine with rapier filling system capable of handling any yarn type and size, jacquard head with individual control of warp yarns, woven fabric CAD system, creel with individual tension control of each yarn, filling feeder for ribbon yarns, splicer for interconnect formation combined with cutting tools for disconnect, and resistive welding tool for the interconnect/disconnect that is capable of working in harmony with the fabric formation mechanisms [52].

Electrotextiles have to potential to be a low cost method to manufacture low resolution displays. Research to achieve a woven display has been conducted by graduate students in the materials science and engineering department at the University of Texas at Dallas [53]. These students have developed materials and processes that allow the fabrication of a woven display based on OLED and PLED materials by interweaving LED strips with conducting and insulating fibers as shown in Figure 4-5.

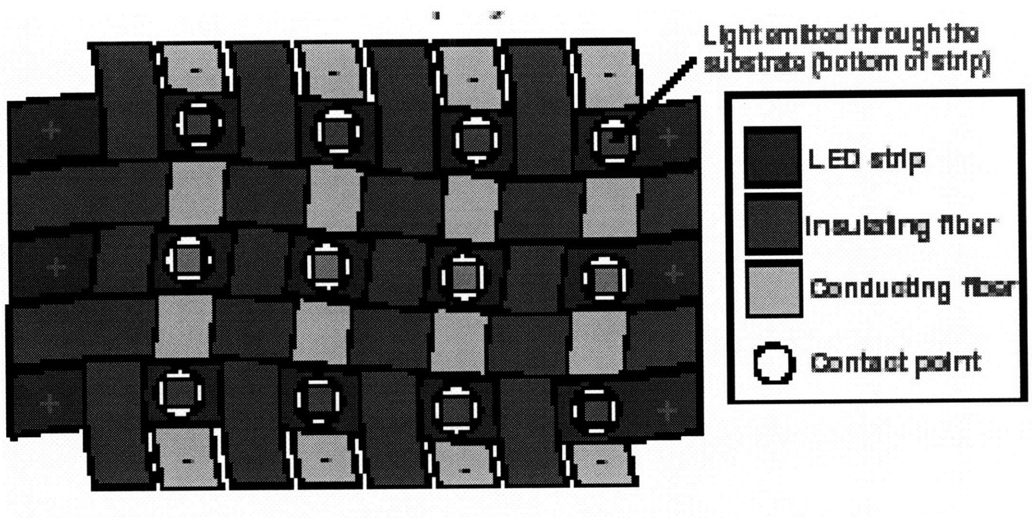


Figure 4-5 Woven Display [54]

The intersections between the LED strip and the conducting fiber form a contact point that causes the pixel to emit light. With this approach, the researchers have achieved a flexible, fabric-like display in which costs (estimated to be \$20 - \$30 per square foot) will scale linearly with area. Additionally, no large and expensive fabrication equipment would be necessary to fabricate displays of this nature.

The challenges that need to be addressed in order to achieve commercial success with electrotextiles include attaining reliable and robust interconnects, improving signal integrity, maintaining textile characterstics (lightweight, flexibility, strength, conformability, etc.), providing efficient means of power generation, and addressing washability and weatherability for wearable electrotextiles.

Elextrotextile technology is most applicable where the large area can be exploited for performance gains (such as an acoustic array) or where flexibility is needed and yet high performance computing is not a strong requirement [50]. Applications that meet these criteria include large area or wearable electronics and displays, flexible or conformable solar cells, and devices for military use such as battlefield acoustic arrays and precision airdrop parafoils. If elextrotextile technology is developed to compete with R2R displays, it will most likely position itself for the lower end of the display price/performance applications such as billboards and signage. The electronics and textile industries are historically driven by economies of scale, and the limited range of applications of electrotextile technology may not be sufficient to justify the investment in large scale facilities.

4.2 Complementary Technologies

4.2.1 Flexible Electronics

There are a few technologies that are not explicitly labeled as roll-to-roll display technologies, yet have considerable overlap and contribution to the development of R2R. The first of which, flexible electronics, entails an effort to develop electronic circuits and displays on flexible substrates for unique applications. Roll-to-roll display manufacturing is a goal of the flexible electronics research community, however, the scope of the interests of the flexible electronics field is much broader to include RFID and mobile applications that do not necessarily involve R2R. A very large component of the research done by the flexible electronics community at the materials level is directly applicable to R2R and will continue to complement its development.

4.2.2 OLED

The second complementary technology, the organic light emitting diode (OLED), was introduced as a front plane material in Section 2.1.2.1. OLEDs are considered to be a key enabler of R2R due to their proven performance and printability. OLED emissive materials are highly compatible with many of the R2R patterning techniques such as inkjet, direct contact printing, evaporation, and thermal transfer. Additionally, OLED devices have already been introduced into the market as viable products in a narrow range of applications such as mobile phone displays and digital camera displays. As OLED materials become optimized to function with flexible substrates and barrier layers, the lessons learned will be ultimately applicable to the success of roll-to-roll manufacturing.

CHAPTER

5 Industry Structure and Business Models

5.1 Understanding the Supply Chain

In order to understand how a roll-to-roll enabling technology could be commercialized, it is important to understand how it will fit into the supply chain into which it is being injected. Figure 5-1 gives a rudimentary depiction of what the supply chain looks like for the display industry.

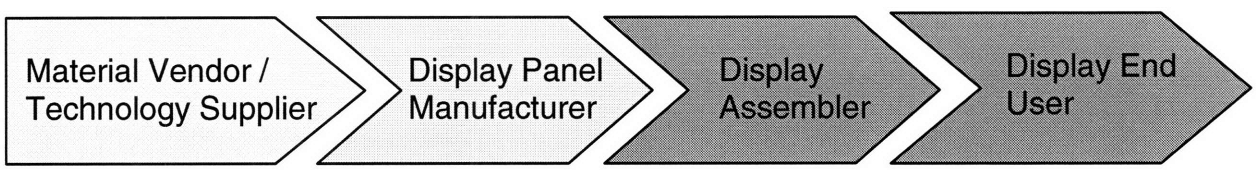


Figure 5-1 Supply Chain Structure

The material vendor or technology supplier sells substrates and emissive materials to the panel manufacturer, who integrates the drive electronics and other components of the display. The panel manufacturer then sells the display module to an assembler, where the display is incorporated into the actual product (cell phone, 42" TV, laptop screen). Finally, the display assembler sells the product to the end user – the consumer.

After interviewing companies at each level of the supply chain, it has become evident that there is much price pressure on the display panel manufacturers by the display assemblers. The tight profit margins at the display manufacturer level leave little cash to invest in innovations and new technologies coming from lower levels in the chain. The display assemblers have much buyer power in the supply chain, which allows them to force the manufacturers to compete on price and short term contracts. This supply chain structure is causing new technology and materials companies to focus on their core competencies and partner with companies at the higher levels in order to extract value. For example, DuPont's strategy for its OLED materials is to combine their strengths in solution materials with partners to meet the challenges of the industry [1]. A smaller company, Zikon Corp. is taking a similar approach to addressing the challenge: "We are competing with E Ink in what is currently a small market, so there are some hurdles. We first need to create some partnerships" [55].

The supply chain for E Ink's technology as introduced in the Sony Librie (called the Sony Reader in the U.S.) involves relationships with several levels of the chain. E Ink makes the liquid ink in Boston, and ships it to Toppan. On a toll basis, Toppan coats the ink in rolls and converts the rolls into sheets. E Ink then sells the sheets to PrimeView (the panel manufacturer), who laminates the TFT glass, seals the edges, and adds drivers. PrimeView then sells the display module to Sony (the display assembler) where the display is integrated into the Reader product [56]. E ink has been able to inject their technology into the supply chain by outsourcing the manufacturing and focusing on how the company can offer materials solutions and engineering to the industry at all levels of the value chain.

In order to realize the development of R2R manufacturing, many different technologies at the materials level will need to be brought together. This will involve a number of partnerships, as indicated by Universal Display Corporation's supply chain for their prototype flexible display on steel foil.

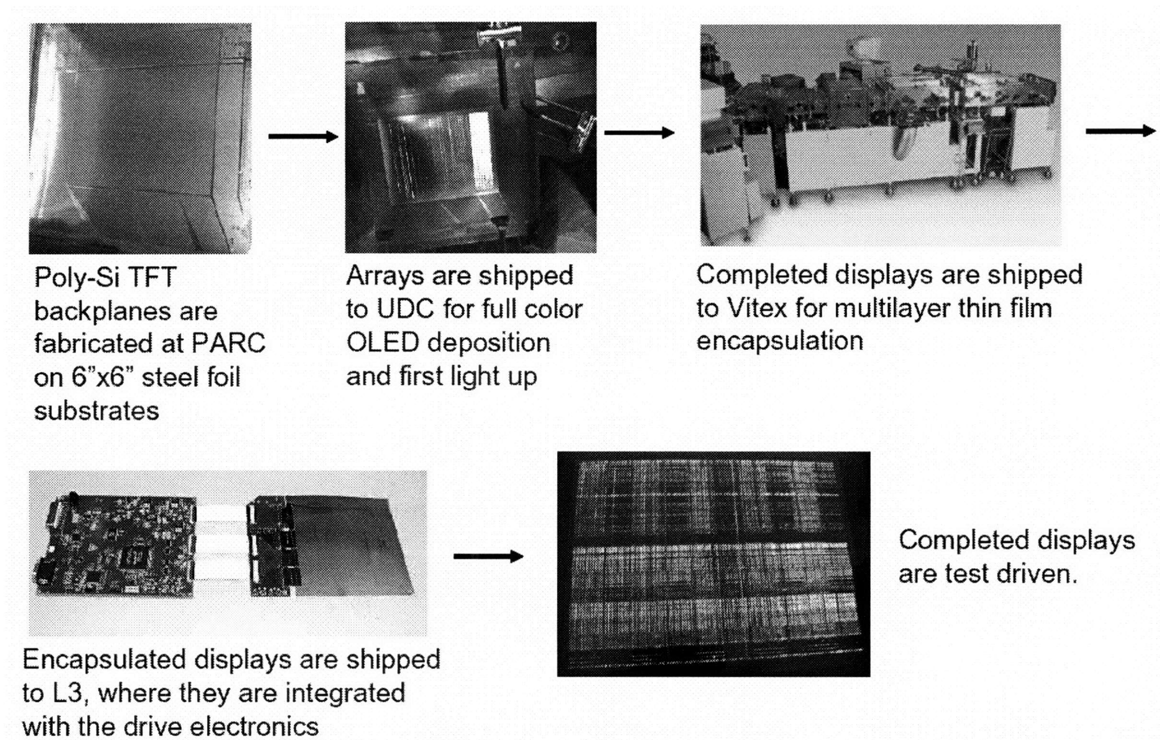


Figure 5-2 UDC Process Flow for Prototype Display [57]

The state of the supply chain in the display industry brings to the table several challenges for R2R. Firstly, many of the companies that are developing critical R2R enabling technologies are small, and need partnerships to create revenue or funding. However, it will be difficult to convince the panel manufacturers to invest in roll-to-roll technologies because their margins are suppressed by the display assemblers. Moreover, these smaller companies do not have the capital to be vertically integrated and manufacture the displays themselves. This puts them in a position of having very little supplier power in the chain because the small technology companies cannot threaten to forward integrate into manufacturing, and are therefore dependent on companies in the other levels. Given the state of the supply chain, it may be deduced that a large, vertically integrated company will need to invest in developing their own materials and patterning technologies or bringing outside technology pieces into their manufacturing facility if roll-to-roll manufacturing is going to happen.

5.2 Intellectual Property Landscape

The intellectual property (IP) that has been created in efforts to develop roll-to-roll manufacturing of displays is treated differently depending on how much protection patents can actually offer in the case of the technology. Where some innovations are easy to protect because knowledge about them is tacit and they are well protected legally by patents, other innovations are difficult to protect because they can be easily imitated and legal protection of the IP is ineffective [58]. For this reason, intellectual property for R2R will be discussed in the context of each technology level (materials, processes, and equipment) and how well it can be protected at each level.

5.2.1 Material Level

At the material level, patents are relatively strong and defensible. This characteristic of the IP allows the companies that are developing materials technologies to be very open about sharing how their technology works in quantitative detail. At conferences, the representatives from the materials companies are content to discuss how the materials work, how they are made, and how the material performs; these presentations are usually replete with charts and graphs containing performance metrics and experimental data.

Many companies, both small and large, hold IP positions at the materials level that could be critical to the development of roll-to-roll manufacturing. Vitex, for example, has patents that cover their multilayer Barix coating and encapsulation technology that is essential for the lifetime of OLEDs on plastic substrates. With 51 U.S. and 59 foreign patents – along with an additional 61 pending – Vitex's IP portfolio covers a broad range of areas, including: chemistry, structure, application, performance, process, tool, substrate preparation and flexible substrate [59]. Universal Display Corporation (UDC) has one of the largest patent portfolios in the OLED field, with, as of November 2004, almost 300 pending and issued patents in the United States and well over 300 corresponding international patents and applications. UDC's IP portfolio provides a broad coverage of OLED materials, manufacturing, and packaging technologies including phosphorescent and transparent or top-emitting OLEDs [60]. Many companies are patenting their technologies at several levels of the supply chain in order to position themselves to extract as much of the value that their technology adds out of the supply chain as possible. E Ink holds patents on their electrophoretic ink technology and uses of the technology. Other examples of IP protected materials include Plextronics' Plexcore ink formulation technology, DuPont's Teijin Films material, and QD Vision's quantum dot materials.

5.2.2 Process Level

At the process level IP is more difficult to police, resulting in less transparency about how proprietary processes work at conferences and trade shows. Although patents are still utilized at this level, a larger degree of trade secrets and know-how are also developed in conjunction with the patents. As mentioned in section 2.2.2, several proprietary processes have been developed for roll-to-roll manufacturing including HP and IFTF's self-aligned imprint lithography (SAIL), 3M and Samsung's Laser Induced Thermal Imaging (LITI) process, and Cabot's Inkjet printing process, to name a few. If these technologies are to be transferred into an outside manufacturing facility, much of the IP will be transferred through the sale of know-how in the form of engineering services, optimization, or non-recurring engineering (NRE) to the customer. These engineering services costs can be prohibitively expensive in a situation where very few units of low margin panels are being manufactured and shipped to the display assemblers.

5.2.3 Equipment Level

The effects of the weak IP coverage at the process level can be felt at the equipment level: it is difficult to integrate processes into equipment when nobody is talking about their processes. The Center for Advanced Microelectronics Manufacturing (CAMM) is addressing this problem with a novel IP model that takes advantage of its university partnership with Binghamton University. Companies can use the CAMM facilities to develop processes and keep control of the IP developed at the CAMM facilities. This encourages companies to work towards integrating their processes at the equipment level. The current IP coverage at the equipment level is in the form of patents that protect discrete pieces of equipment. Examples of patent protected equipment include Litrex inkjet systems and Applied Films SMARTWEB™ system.

5.3 Financing Approaches

Several of the smaller materials companies that are developing R2R enabling technologies have been supported by venture capital dollars. This financing mechanism can be appropriate where the company has significant growth potential and a viable exit strategy that is capable of resulting in a liquidity event in less than ten years. Examples of companies that have been venture backed include E Ink and QD Vision. The Series A or first round of financing in this industry is usually less than 10 million dollars, and can be expected to sustain the company for about two years. E Ink has raised over $120 Million from venture firms and strategic investors, and remains a privately held organization [61].

A second source of funding for companies that are developing R2R technologies are government organizations such as the United States Display Consortium (USDC), the Army Research Labs (ARL), or the Defense Advanced Research Projects Agency (DARPA). The USDC has awarded around one hundred contracts in ranges of size from as small as $100K to as large as $6 Million [62]. Funds from government agencies can be valuable to small companies that are eager to obtain early revenue streams, or for larger diversified companies that are interested in applying their materials expertise to the display field.

The other financing approach that is prevalent in this industry is the use of partnerships to finance or co-develop technologies. Many large organizations (DuPont, Samsung, Kodak) are looking to partner with companies in order to address the technological challenges associated with R2R display products. In some cases these companies are willing to finance the smaller companies through co-investment deals. As an example, TOPPAN Printing Co., Ltd. became E Ink's largest investor in connection with a significant expansion to their strategic partnership to commercialize electronic paper [61]. Additionally, partnerships and co-development deals have the potential of positioning smaller companies for an exit strategy through acquisition by the larger partner.

5.4 Business Models

In this section, two business models will be visited that exemplify how companies that have developed R2R enabling technologies are attempting to commercialize these technologies. The two organizations being considered, E Ink and Vitex Systems, have developed materials technologies that could enable flexible or roll-to-roll manufactured displays, yet their technologies also apply to fields outside of R2R. For example, although E Ink's emissive technology is R2R compatible, it can also be used for rigid products that are batch processed such as the Sony Reader.

The business models of E Ink and Vitex Systems were chosen to be explored because E Ink's business model illustrates how partnerships can be exploited to successfully commercialize a fundamental technology, whereas Vitex System's business model highlights some of the challenges associated with trying to introduce a technology as a small company in the display industry.

5.4.1 E-Ink

E-Ink manufactures their proprietary liquid ink in Boston. They then outsource the coating of the ink and the conversion into film to Toppan, one of their strategic partners and investors. The partnership with Toppan has allowed Toppan to implement downstream manufacturing capacity while E-Ink focuses on the ink materials. E-Ink also performs the process development on the coating and conversion, as well the assembly into sealed display modules so that they understand how to improve the module as a whole. This essentially means that E-Ink's business model is to be a materials developer plus a display engineering company that is capable of offering a complete solution to the industry that will enable the e-paper market to grow [56].

E-Ink has a strong partnership with Toppan, but they also have the ability to work with other manufacturers in licensing their technology. The president and CEO of E-Ink stated in an interview that "we will provide our imaging film and a module reference design to any display maker on attractive terms. The reason is that we believe a new display technology requires many partners and a strong ecology if it hopes to succeed in a broad way. That is why you also see E-Ink working with other display manufacturers, and this is especially evident for flexible displays" [56]. E-Ink has clearly realized the importance of partnerships and other strategic relations in trying to extract value from the supply chain as a materials supplier and engineering services company.

The company has recently launched several products, including the Sony Reader, a Seiko watch, and a Weather Wizard device. Sales are reported to be growing quickly, and the company is currently building out new capacity with the hope of supplying film for hundreds of thousands of units or more next year [56]. Although the success of E-Ink does not entirely depend on the success of R2R, the company is well positioned to supply the front plane technology for flexible displays. The assessment of E-Ink's business model conveys how a materials developer can successfully leverage partnerships to commercialize a fundamental technology, although the long term profitability of the organization has yet to be proven.

5.4.2 Vitex Systems

Vitex Systems' proprietary encapsulation solution (Barix™) as well as its Flexible Glass substrate are developments designed to enable the cost-effective production of OLED displays on flexible substrates. Since its spin off as an individual company in 1999 from Battelle Memorial Institute, the company's business model has evolved significantly in order to address the challenges associated with introducing a new technology into the display industry [63].

The company's initial business model was to be a materials supplier to panel manufacturers for flexible displays. Vitex soon learned that these manufacturing companies have little money for the same reasons as were discussed in the supply chain section, and sales were difficult. A representative from the company recalls, "We were the tail trying to wag the dog", which compelled Vitex to modify their business model [64].

The second model attempted by Vitex was to license their extensive patent portfolio and provide engineering services to their customers. As mentioned in section 5.2.1, Vitex owns an extensive IP portfolio containing 51 U.S. and 59 foreign patents covering its technologies. Vitex partnered with an equipment manufacturer, Tokki, to license their technology. However, the engineering services and NRE associated with the licensing deal were too expense, causing Vitex to once again attempt a new business model [64].

The third strategy that the company is pursuing is to partner with tooling companies and hope that a niche OLED market such as automobile displays will take off. The evolution of Vitex's business model illustrates the difficulty of attaining a sustainable revenue stream when flexible products are not shipping. Vitex's narrower field of application compared to E-Ink's technology puts the company in a precarious position if OLEDs or flexible displays do not get traction in the marketplace. E-Ink's diversification and broader range of applications has allowed the company to obtain sales while still positioning themselves to capitalize on R2R technologies in the event that roll-to-roll or flexible displays are a commercial success.

5.5 Strategies for Commercialization

By developing a knowledge of the supply chain, the IP landscape, financing approaches, and prevailing business models in the industry, some interesting and valuable conclusions can be made regarding strategies for commercializing a R2R enabling technology. These conclusions about strategies for success in the commercialization process are summarized in the bullets below:

If you have a R2R Enabling Technology…

- ◆ Develop technology pieces that can be integrated into existing equipment
  - This reduces your customer's NRE costs
  - It also encourages implementation at the equipment level
- ◆ Focus sales efforts on Large Vertically Integrated Companies
  - They actually have money (smaller downstream suppliers are squeezed by price competition)
  - They are diversified and are willing to invest in long term opportunities (Samsung, LG Phillips, Mitsubishi Electronics, etc.)
  - They see more of the supply chain, which makes it easier to educate them on the value of your technology

- Partner to offer co-branded products, and consider selling out (acquisition) when the market value reaches a peak.
- Displays are a quick mountain and long valley industry – they become commoditized too quickly to consider being a small company for the long-run (high levels of price decay exist in this industry)

CHAPTER

6 Conclusions

Many advances have been made in materials technologies that could enable roll-to-roll manufacturing of electronic displays, but the processes and equipment available are not ready for introduction into a full scale manufacturing facility. The commercial success of roll-to-roll manufacturing is dependent upon its ability to significantly reduce the cost of manufacturing a display. This brings forth from the industry the big question, "Is roll-to-roll really cheaper?" Although cost models predict that R2R manufacturing will be lower cost than alternative approaches, this will not be certain until an actual R2R fabrication facility is operational. Moreover, even if it is assumed that R2R could allow a significant manufacturing cost reduction if a plant were operational today, this may not be the case by the time the processes and equipment are ready for a fabrication facility five years down the road due to continuous cost reductions in the competing technologies.

Although there are a few initial markets that look promising for flexible displays such as mobile phones or large area electronic billboards, the key to the widespread success of R2R relies in its ability to compete on price with LCD technology in the markets in which it has incumbency. Roll-to-roll is not about enabling new flexible applications or niche markets; roll-to-roll is about cost. In attempting to beat LCD on cost, R2R is chasing a moving target: LCD manufacturing costs are constantly being reduced through exploiting economies of scale in the LCD manufacturing process. As more and more displays are processed on one large sheet of glass, the materials cost of

LCD is becoming the largest component in the cost structure on a per unit basis. This suggests that if R2R manufacturing is going displace LCD in a long term battle in the marketplace then it must offer a reduction in materials cost over LCD processing. Therefore, the R2R manufacturing lines that are currently being developed using processes that consume much material, such as vapor deposition and photolithography, are not likely to be nearly as cost-competitive in the long term with LCDs as lines that utilize additive deposition processes such as inkjet.

Based on the supply chain, the IP landscape, financing approaches, and prevailing business models in the industry, some interesting and valuable conclusions were made about how a company can position itself for commercialization success given the structure and state of the industry. Partnerships are a necessary evil to bring technology pieces together in order to develop products. However, in order to see roll-to-roll manufacturing implemented in a full scale facility there will have to be a financial incentive for an organization to risk an estimated $181 M initial capital investment. Given that very few large display manufacturers exist in the U.S and that much of the U.S. activity in this industry is funded by the government, it is unlikely that the first commercial R2R display manufacturing facilities will be built here; most of the large vertically integrated display manufacturing companies that have money and are willing to invest in long term opportunities are located in Asia.

So what is the fate of R2R? The analysis all boils down to whether or not R2R can truly offer a leap in cost reduction, especially in the materials component of the cost structure, relative to LCD. This will depend on the trajectory of the LCD cost curve over the next five to ten years and on how quickly R2R materials, processes, and equipment can be ready for integration into a facility that produces real commercial products that people want to buy.

Appendix

A Cost Model Details

Process Flow for Active Matrix Cost Model developed by Abbie Greg, Inc.

Baseline Process Flow - Active Matrix (AM 1)

Δ	Step	Operation	Tool	Tool Action
	100	Staging Area	Stage	Stage
	130	Web Punch and Clean	Clean, Aqueous Web	Unwind, Punch, Aqueous Web Cleaner, Unpatterned inspect, Wind
	140	Vacuum Dep Dielectric Barrier Layer and Cure	PECVD, Microwave	Unwind, Microwave PECVD, Rewind
	150	Sputter Dep Gate 1 Metal	Sputter, DC Magnetron	Unwind, DC Magnetron Sputter, Rewind
	160	Clean, Coat & Cure	Roll Coat	Unwind, Dip, Spray rinse, Dry, Roll Coat, Heat, Dry, Wind
AM 3	170	Align and Expose	Exposure, Step and Repeat	Unwind, step and repeat exposure, Wind
	180	Develop, Etch (Gate Metal),Strip the photoresist then dry with air knives with extra clean rinse	Develop, Etch, Strip Line	Unwind, Conveyorized DES system w/extra clean rinse, dry system for reel to reel transport, Inspect, Wind
	190	Silicon Nitride, Amorphous Polysilicon, N+ dopant	PECVD Deposit	Unwind, PECVD Deposit, Wind
AM 2	200	PolySi Anneal	Laser, Pulsed Excimer	Unwind, XeCl Pulsed Excimer Laser, Wind
	205	Clean, Coat & Cure	Roll Coat	Unwind, Dip, Spray rinse, Dry, Roll Coat, Heat, Dry, Wind
AM 3	210	Align and Expose	Exposure, Step and Repeat	Unwind, step and repeat exposure, Wind
	215	Develop, Rinse and dry with air knives	Develop	Unwind, Conveyorized develop system w/rinse, dry system for reel to reel transport, Inspect, Wind

Baseline Process Flow - Active Matrix (AM 1) Cont.

Δ	Step	Operation	Tool	Tool Action
	220	Dry Etch (RIE Si) and Resist Strip	Reactive Ion Etch	Unwind, Reactive Ion Etch, Dry Strip, Wind
	225	Ultrasonic Clean	Clean, Ultrasonic	Unwind, Conveyorized Ultrasonic clean w/rinse &dry system, Inspect, Wind
	230	Clean, Coat & Cure	Roll Coat	Unwind, Dip, Spray rinse, Dry, Roll Coat, Heat, Dry, Wind
AM 3	240	Align and Expose	Exposure, Step and Repeat	Unwind, step and repeat exposure, Wind
	245	Develop, Etch (Nitride), Strip the photoresist then dry with air knives with extra clean	Develop, Etch, Strip Line	Unwind, Conveyorized DES system w/ extra clean rinse, dry system for reel to reel transport, Inspect, Wind
	250	Sputter Dep/ ITO	Sputter, ITO	Unwind, Sputter, Rewind
	255	Clean, Coat & Cure	Roll Coat	Unwind, Dip, Spray rinse, Dry, Roll Coat, Heat, Dry, Wind
AM 3	260	Align and Expose	Exposure, Step and Repeat	Unwind, step and repeat exposure, Wind
	265	Develop, Etch (ITO), Strip the photoresist then dry with air knives with extra clean	Develop, Etch, Strip Line	Unwind, Conveyorized DES system w/extra clean rinse, dry system for reel to reel transport, Inspect, Wind
	270	Sputter Dep Interconnect	Sputter, Interconnect	Unwind, Sputter, Rewind
	275	Clean, Coat & Cure	Roll Coat	Unwind, Dip, Spray rinse, Dry, Roll Coat, Heat, Dry, Wind
AM 3	280	Align and Expose	Exposure, Step and Repeat	Unwind, step and repeat exposure, Wind

Baseline Process Flow - Active Matrix (AM 1) Cont.

Δ	Step	Operation	Tool	Tool Action
	285	Develop, Etch (Interconnect Metal), Strip the photoresist then dry with air knives with extra clean	Develop, Etch, Strip Line	Unwind, Conveyorized DES system w/extra clean rinse, dry system for reel to reel transport, Inspect, Wind
	290	PECVD Passivation Layer	PECVD Deposit	Unwind, PECVD, Wind
	295	Clean, Coat & Cure	Roll Coat	Unwind, Dip, Spray rinse, Dry, Roll Coat, Heat, Dry, Wind
AM 3	300	Align and Expose	Exposure, Step and Repeat	Unwind, step and repeat exposure, Wind
	305	Develop, Rinse and dry with air knives	Develop	Unwind, Conveyorized develop system w/rinse, dry system for reel to reel transport, Inspect, Wind
	310	Dry Etch (RIE Passivation) and Resist Strip	Reactive Ion Etch	Unwind, Reactive Ion Etch, Dry Strip, Wind
	315	Ultrasonic Clean	Clean, Ultrasonic	Unwind, Conveyorized Ultrasonic clean w/rinse & dry system, Inspect, Wind
	320	Test and Review	Test, TFT	Unwind, TFT Active Device Test, wind
	330	Laser Repair Shorts	Laser Repair	Unwind, Laser Repair, Wind

B ROI Model by I.T. Strategies

POP Signage ROI Model

Large POP Signage

ROI- Existing Cost Reduction

Print Cost	**High User**	**Industry Average**	**Low User**
Average Display Size sq ft	20	20	20
Number of displays owned per site	20	20	20
Number of turns per year	24	12	2
Analog Cost per sq. ft	$2.50	$2.50	$2.50
Total Print Cost per year.	$24,000	$12,000	$2,000
Total Cost over 5 Years	$120,000	$60,000	$10,000
Hanging Cost			
Cost to put up each display*	$1.20	$1.20	$1.20
Number of displays placed per year	480	240	40
Total Cost	$576	$288	$48
Total Cost over 5 Years	$2,880	$1,440	$240
Lost signage cost			
% of signage lost	30%	30%	20%
Number of signs lost per year	144	72	8
Cost per sign	$50.00	$50.00	$50.00
Total Cost per year	$7,200	$3,600	$400
Total Cost over 5 Years	$36,000	$18,000	$2,000
Total Cost Per Year			
Total Costs per	**$31,776**	**$15,888**	**$2,448**
Total Costs per over 5 years	$158,880	$79,440	$12,240
Per Sign Cost			
Total Costs per sign	$1,589	$794	$122
Total Costs per sign over 5 years	$7,944	$3,972	$612
TOTAL Company Cost			
Number of Sites (each site has equal number of signs)	1,200	700	30
Total Large Company Cost per year	$38,131,200	$11,121,600	$73,440
Total per 5 years	**$190,656,000**	**$55,608,000**	**$367,200**

Print Cost	**High User**	**Medium User**	**Low User**
TOTAL Company Cost- Paper Based			
f Sites (each site has equal number of signs)	1,200	700	30
Total Large Company Cost per year	$38,131,200	$11,121,600	$73,440
Total per 5 years	**$190,656,000**	**$55,608,000**	**$367,200**
Electronic Signage cost per sign	**$6,000**	**$6,000**	**$6,000**
Cost to replace all signs per sit	$120,000	$120,000	$120,000
Total Cost to replace all signs in all stores	$144,000,000	$84,000,000	$3,600,000
Savings/ Cost Year 1	-$105,868,800	-$72,878,400	-$3,526,560
Savings/ Cost Year 2	-$67,737,600	-$61,756,800	-$3,453,120
Savings/ Cost Year 3	-$29,606,400	-$50,635,200	-$3,379,680
Savings/ Cost Year 4	$8,524,800	-$39,513,600	-$3,306,240
Savings/ Cost Year 5	$46,656,000	-$28,392,000	-$3,232,800
Savings/ Cost Year 6	$84,787,200	-$17,270,400	-$3,159,360
Savings/ Cost Year 7	$122,918,400	-$6,148,800	-$3,085,920
Savings/ Cost Year 8	$161,049,600	$4,972,800	-$3,012,480
Savings/ Cost Year 9	$199,180,800	$16,094,400	-$2,939,040
Savings/ Cost Year 10	$237,312,000	$27,216,000	-$2,865,600

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