

Evaluation of the Commercial Potential of Novel Organic
Photovoltaic Technologies

by

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B.S. Materials Science and Engineering, Northwestern University, 2004

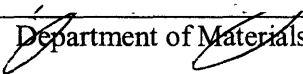
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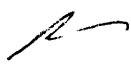
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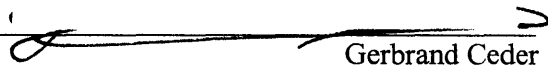
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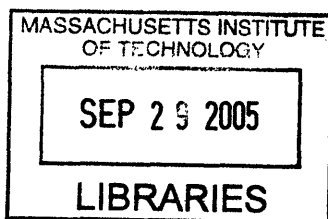

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ABSTRACT

Photovoltaic cells based on organic semiconducting materials have the potential to compete with the more mature crystalline and thin film based photovoltaic technologies in the future primarily due to the expectation of significantly reduced manufacturing costs. Stabilized power conversion efficiencies of organic photovoltaics are still well below those of crystalline Si photovoltaics, however a continuous, high throughput, roll-to-roll manufacturing process involving low temperature deposition or printing techniques is expected to partially account for their reduced efficiency and boost their commercial attractiveness. In addition, organic photovoltaics are flexible, light weight, and not fragile which makes them particularly suitable for transportation and portable electronics applications.

Four organic photovoltaic technologies as well as the advantages and setbacks of each are described including Graetzel (wet) cells, blended photovoltaics, asymmetric tandem cells with hybrid planar-mixed molecular heterojunctions, and external antenna photovoltaics. A variety of start-up companies in various stages of commercialization of these technologies as well as the intellectual property related to these technologies is also discussed. A simplified cost model is presented to quantitatively estimate the possible cost reductions that continuous roll-to-roll production could entail for three different scenarios. Finally, a discussion of potential business strategies for licensing and commercializing organic photovoltaics is presented.

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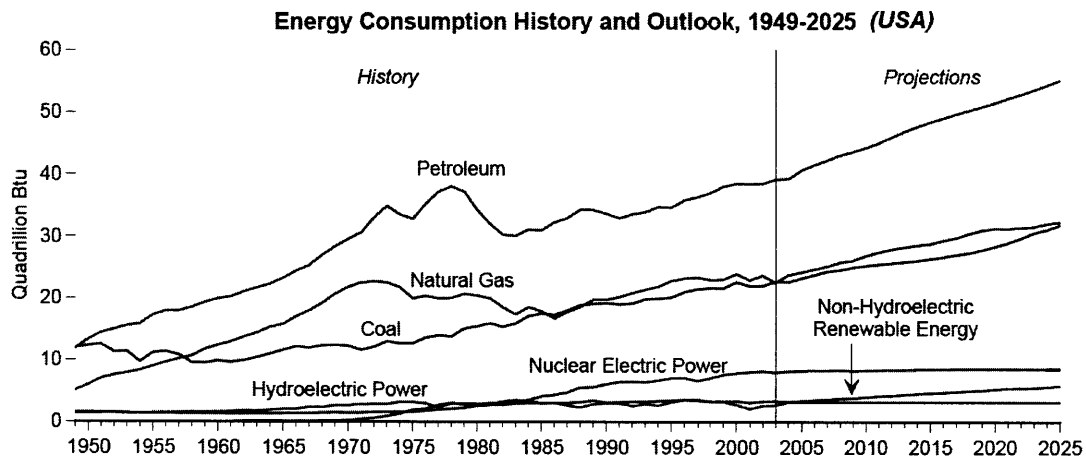
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1 Introduction—Energy Situation

Fossil fuels including petroleum, natural gas, and coal provide the world with approximately 86% of its energy needs. These fuels, especially petroleum, are excellent in terms of energy density (energy harvested per mass or volume of input fuel) and are relatively inexpensive. For example, unleaded gasoline costs \$2.44/gal on average in Boston¹ while bottled water costs \$1.19/liter at Laverde's (~\$4.50/gal). These fuels, despite their finite abundances on Earth, will continue to supply the world with the majority of its energy for centuries to come. However, when these fuels are burned, they release carbon dioxide, NO_x, SO_x, as well as other harmful particulates into the atmosphere, irreversibly changing the world's climates and elevating global mean surface temperature. Concerns regarding these emissions have elevated dramatically in recent history and have helped fuel the push for clean, renewable energy sources.



Energy Information Administration / Annual Energy Review 2003
Figure 1: Energy Consumption History and Outlook, USA, 1949-2025²

Including geothermal, tidal, biomass, wind, solar thermal, and solar photovoltaic, renewable energy sources are becoming an important member of the world's energy portfolio but as of 2002 only contributed 3.3 quads (quadrillion BTUs) out of a total of 411 quads, approximately 0.8% of global energy consumption.³ Wind and solar photovoltaics have been identified as two of these renewable energy sources with the

most potential for significant contributions to the world's energy portfolio due to their enormous room for expansion, particularly solar photovoltaics.

2 Introduction to Photovoltaics

The sun constantly radiates energy into space, and of this, an average of 844 W/m^2 reach the Earth's surface during daylight. While this solar flux is highly dependent on global location, time of day, and time of year, it is a significant amount of power—approximately 1600 TW strike the continental US, which is about 500 times more than our countries' current overall consumption.⁵ Thus all our electricity needs would be met if 2% of this land were covered with 10% efficient devices, which is not entirely unreasonable. As a frame of reference, about 1.5% of the USA's land is covered by interstate highways.⁵

Photovoltaics are devices which absorb solar photons and convert them into electrical energy which can be connected to power grids for general electricity needs, integrated with buildings, and even used to power portable electronics devices. Some parameters that describe the effectiveness of a photovoltaic device as well as its marketability are its efficiency, stability and lifetime, flexibility, aesthetic appeal to a lesser extent, and of course the costs associated with the production of these devices.

2.1 Basic Operation

Solar cells are composed of semiconducting materials with electrical contacts plus protective layers. A variety of materials may be used as the semiconducting material and based on the properties of the chosen semiconductor, the overall devices can vary widely in production cost, thickness, and photoconversion efficiency. Polycrystalline Si is the most commonly used semiconductor, however others include single-crystal Si, the thin film materials—amorphous Si, CdTe, and CuIn(Ga)Se₂, and organic materials, for example copper phthalocyanine (CuPc) and C₆₀.

Conventional solar cells are those incorporating inorganic semiconductor materials (Group IV or III-V) and are comprised of p-n junctions which maintain an electric field at equilibrium. When light shines on the device, charge carriers are created and dissociated by the internal field causing a photocurrent, I_{SC} . This current along with the established

voltage, V_{OC} produce electrical power, P , according to the following formula. The fill factor, FF , accounts for all deviations from ideality due to losses.

$$P = FF \times I_{sc} \times V_{oc} \quad (\text{Equation 1})$$

Organic photovoltaics do not rely on an internal electric field, rather they commonly involve a heterojunction design shown in Figure 2. Originally proposed by Tang at Kodak, the hole transport layer (HTL) and the electron transport layer (ETL) are two different thin film organic semiconducting materials with different highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels. Copper phthalocyanine (CuPc) and fullerenes (C_{60}) are common candidate materials for these layers. Tightly bound electron-hole pairs (excitons) form when incident photons strike the device which possess greater energy than the energy gap of the semiconducting materials. These excitons may then diffuse to the HTL/ETL interface where the offset in HOMO and LUMO levels provides the driving force for dissociation of the exciton provided that the offset is greater than the exciton binding energy, generally on the order of 1eV. Now separated, these electrons and holes diffuse out of the device and contribute to the photocurrent.⁴

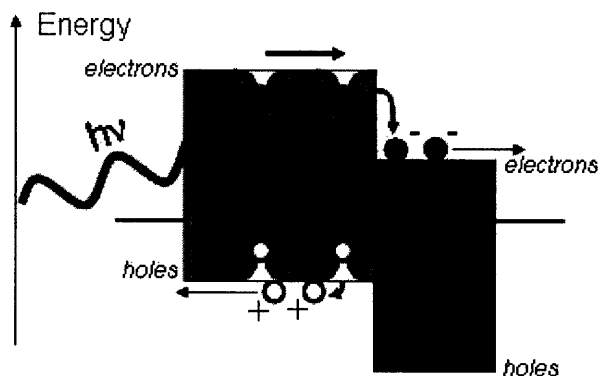


Figure 2: Schematic of a Conventional Heterojunction Photovoltaic⁶

2.2 Important Characteristics of Photovoltaics: Efficiency, Cost, and Lifetime

2.2.1 Efficiency

The power conversion efficiency, η_p , of a photovoltaic is its primary performance statistic, describing the fraction of incident solar energy that is converted into electricity. Efficiency is important because if a device has a low efficiency, a larger area is required to generate a given amount of power. Power conversion efficiencies can vary widely among photovoltaics comprised of different semiconducting materials in various architectures. Seen in Figure 3, the best power conversion efficiencies are up to 36% for multijunction devices with light concentrators while much lower power conversion efficiencies have been reached for photovoltaics with organic semiconductors. Equation 1 can be rearranged in terms of power conversion efficiency, shown in Equation 2 where FF is the fill factor, J_{SC} is the short-circuit current density, and P_{inc} is the incident power density.

$$\eta_p = \frac{FF \times J_{SC} \times V_{OC}}{P_{inc}} \quad (\text{Equation 2})^7$$

Best Research-Cell Efficiencies

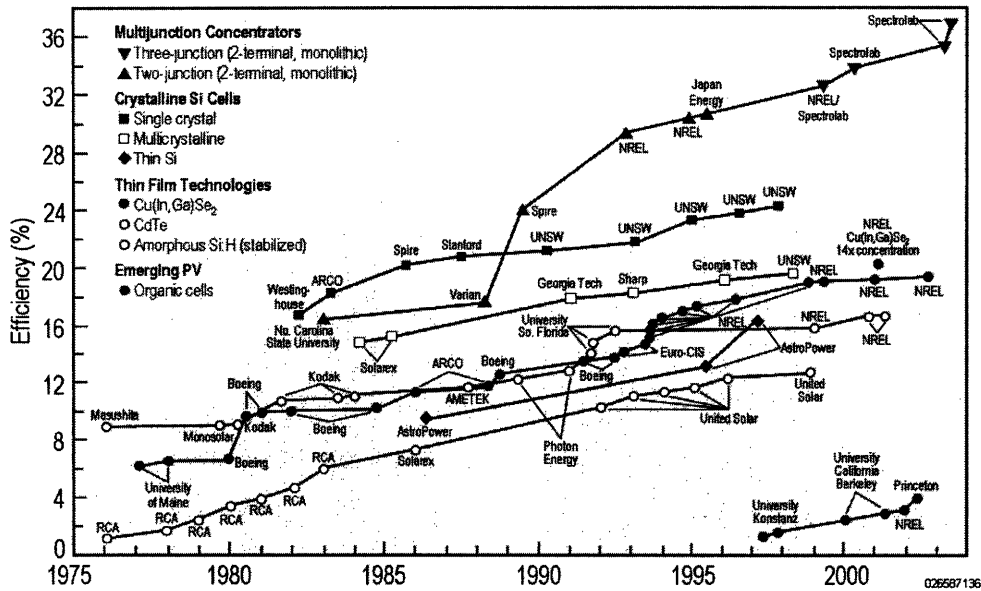


Figure 3: Best Laboratory Photovoltaic Efficiencies⁸

The internal quantum efficiency, η_{IQE} , of a photovoltaic is a measure of the ratio of the number of electrons flowing in the external circuit to the number of photons absorbed within the device and is the product of four efficiencies, each corresponding to a step in the charge generation process.⁷ In the following formula, η_A is the absorption efficiency of light within the active region of the solar cell, η_{ED} is the excitation diffusion efficiency to a dissociation site, η_{CT} is the charge transfer efficiency, and η_{CC} is the charge collection efficiency:

$$\eta_{IQE} = \eta_A \times \eta_{ED} \times \eta_{CT} \times \eta_{CC} \quad \text{(Equation 3)}^7$$

A third measure of device efficiency is the external quantum efficiency, η_{EQE} , which takes into consideration the optical losses that occur on coupling light in the device active region. In the following formula, R is the reflectivity of the substrate-air interface.

$$\eta_{EQE} = (1 - R) \times \eta_{IQE} \quad \text{(Equation 4)}^7$$

2.2.2 Cost

The second key characteristic of a photovoltaic device is the cost of producing it. Production costs include materials costs, manufacturing and equipment costs as well as various others. These costs associated with the module are added to the 'balance-of-system' costs to yield overall photovoltaic system cost. Costs are generally measured in dollars per Watt-peak ($\$/W_p$) and vary depending upon the technology employed and the application in mind. Grid-connected photovoltaic system costs range from 2-8 $\$/W_p$ based on the semiconductor material used.

Many consider the photovoltaics industry to be in a catch-22 situation. Present costs are too high for the technology to diffuse on a very large scale, but in order to reduce costs enough to make this possible, production capacity would have to grow to the level that could supply widespread diffusion of the technology. Thus lowering module costs is of great importance. Two different avenues exist for realizing reductions in cost—gradual improvements in manufacturing technology of the market dominated inorganic Si technology including economy of scale benefits, and researching newer technologies like organic photovoltaics which could hypothetically see vastly decreased manufacturing costs for a variety of reasons including high through-put, low temperature fabrication.

2.2.3 Lifetime

The lifetime of a photovoltaic device is also of great importance if the devices are going to see growing commercial success. A lifetime of 3-5 years (3000-5000 operational hours) is regarded as the market-entry point for low-cost devices.⁹ This requirement is derived from the typical usability lifetime of electronic goods that could potentially be powered by photovoltaics. Much greater lifetimes of 20-25 years are vastly more desirable but tend to be more expensive.

2.3 Global Market

Photovoltaic devices currently contribute over 1 MWe of power globally with industry revenues worth \$7 billion. This industry has witnessed consistent growth in capacity of 25-35% annually and CLSA Asia Pacific Markets predicts this to continue, with the industry contributing 3.2 GWe by 2010 with revenues increasing to \$30 billion globally, shown in Figure 4.¹⁰ Inorganic technologies continue to dominate, shown in Figure 5, however organics have real potential to enter the market in the near future.

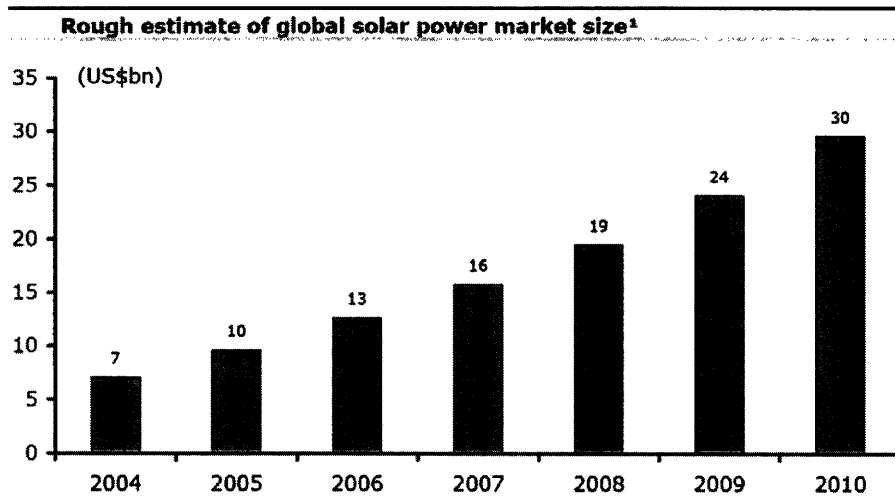


Figure 4: Estimate of Global Photovoltaic Market Growth¹⁰

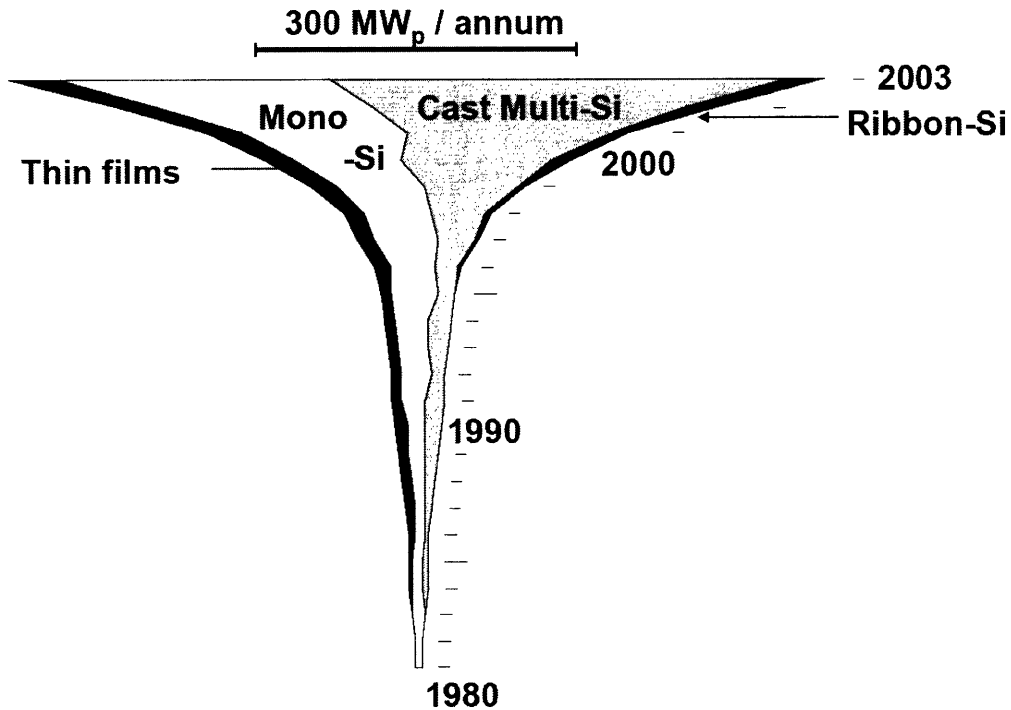


Figure 5: Power Capacity Growth of Photovoltaics by Type⁵

While photovoltaics have found sizable niche markets, considerable time still exists before a breakeven point is reached, i.e. when photovoltaics can compete with currently available energy/power alternatives including coal, combined cycle natural gas, and nuclear fission. An interesting figure is the cost gap, which is the difference between the cost of the cumulative production before the breakeven point and the cost of this production if instead an already competitive technology were used. Based on photovoltaics learning and progress models, the cost gap is substantial, on the order of \$50-100 billion.¹¹ In order for photovoltaics to diffuse on a very large scale and be cost-competitive with other energy/power technologies within the next 20 years, most likely various policy measures will be needed in support of photovoltaic technologies. Government subsidies may help to overcome the cost gap, however they can have adverse effects including market distortion. For example, lobbying groups may hinder the removal of subsidies when they are no longer necessary.¹² An alternate approach would be to require utility companies to have a specified minimum percentage of

photovoltaics in their generating portfolio and the extra cost would be passed on to customers. Yet another strategy would be for governments to place emissions taxes on competitive energy/power suppliers which would make renewable energy forms like solar and wind more attractive since they are essentially emissions free. Germany and Japan are the world's two largest producing countries of photovoltaics, partly due to their favorable governmental conditions.

2.4 Applications

Applications of photovoltaics include grid-connected electricity, stand-alone electricity, building-integrated electricity, power for portable electronics, as well as power for spacecraft and satellites. Grid-connected photovoltaics are most common in industrialized nations, particularly Japan, Germany, and the USA. Stand-alone photovoltaics are common in rural areas where electricity transmission is costly or non-existent, making photovoltaics competitive. Photovoltaics are becoming increasingly common on building rooftops including commercial buildings, residential buildings, and office buildings where rooftop space would be otherwise unused. Some photovoltaics companies have even proposed integrating photovoltaics into portable tents for military operations, especially those in rural, arid conditions like the Middle East. Organic-based photovoltaics have an advantage in their flexibility and low weight and may see a growing market in portable electronics powering for laptop computers, cellular phones, and other devices. Flexible photovoltaics could also see applications for vehicles including cars, and trucks. Photovoltaics for space applications tend to be different than those for terrestrial applications because in space, area is limited and weight must be minimized, thus very expensive, high efficiency photovoltaics compete in this niche market.

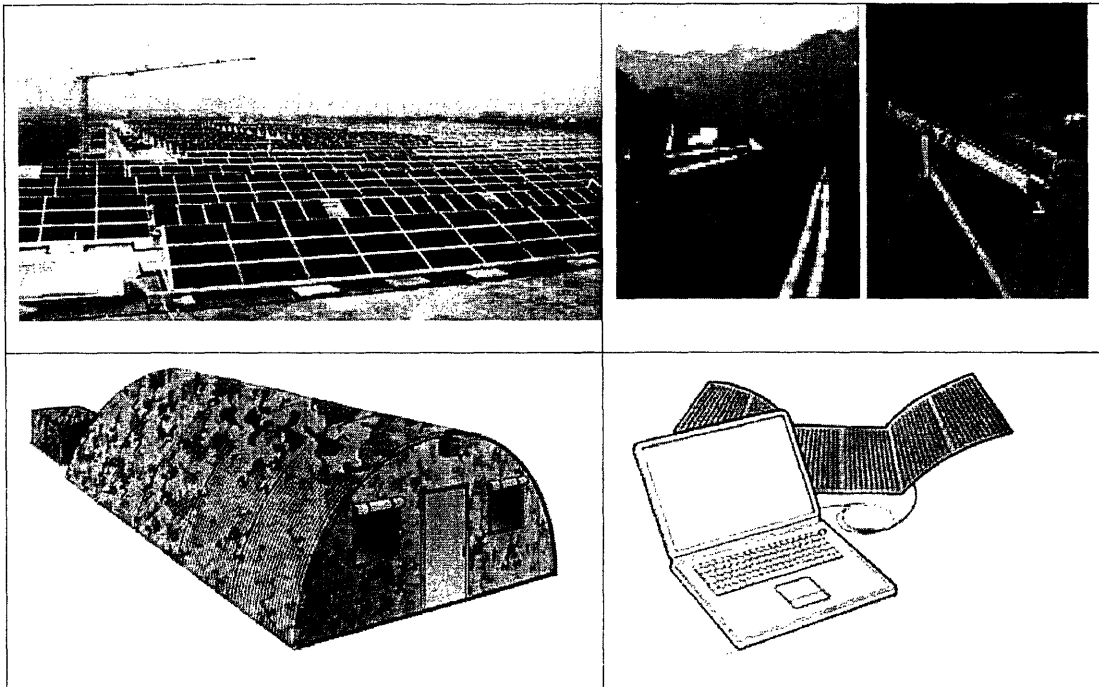


Figure 6: Applications of Photovoltaics: Building Integrated (left) on top of a warehouse and on a military tent, stand-alone (top right), and for portable electronics (bottom right)^{5,13,14}

3 Photovoltaic Technologies

The three key elements of a photovoltaic cell are the semiconductor which absorbs photons and converts them into excitons, the semiconductor junction which splits excitons into electrons and holes, and the contacts on the front and back of the device which allow current to flow to the external circuit. The semiconductor material has traditionally defined the type of photovoltaic, thus the various technologies include photovoltaics made from crystalline silicon, photovoltaics made from thin film semiconductors, and photovoltaics made using completely or partially organic semiconductors. In addition to discussions of these three technologies, this section discusses manufacturing technology related to each class.

3.1 Crystalline Si

3.1.1 Overview

Crystalline Si photovoltaics encompass all photovoltaic devices using silicon as the semiconductor, except for those using thin films of amorphous silicon. They include poly/multi-crystalline Si, mono/single-crystal Si, and ribbon-grown Si. Crystalline silicon was the first semiconductor material to be used in a photovoltaic cell and has always dominated the global photovoltaic market. Crystalline Si photovoltaics account for ~93% of the overall global photovoltaics market as of 2004: 56% multicrystalline, 33% monocrystalline, and 4% ribbon/sheet crystalline as seen in Figure 7.¹⁰

Solar power market share by technology

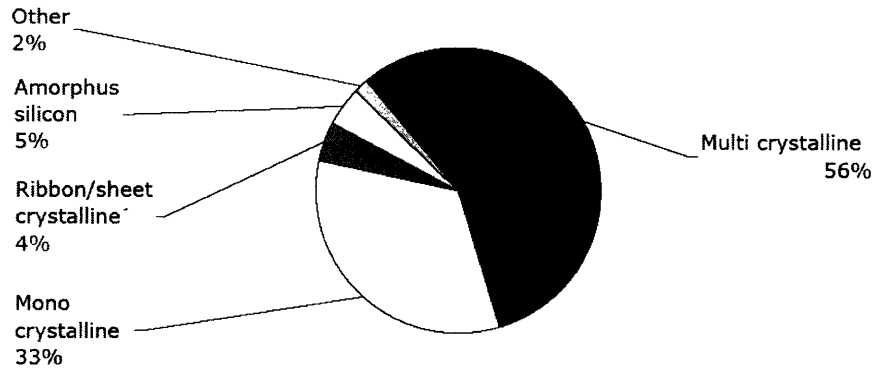


Figure 7: Photovoltaic Market Share by Technology, 2004¹⁰

For crystalline photovoltaics, the semiconductor homojunction is generally formed by doping n-type phosphorus into the top surface of p-type, boron-doped silicon. Printed contacts are then applied to the top and bottom of the cell; the top (front) contact specially designed to facilitate light absorption.

As a class of photovoltaics technology, crystalline Si has various advantages and disadvantages relative to other classes of photovoltaics. First created in the early 1950's, production and processing of crystalline-Si photovoltaics has borrowed much knowledge from the silicon microelectronics industry. This advantage of relevant, existing processing knowledge has probably been most responsible for the market dominance of this technology. Another key advantage is that crystalline Si photovoltaics have exhibited excellent stability, especially relative to amorphous Si thin film photovoltaics. Crystalline Si photovoltaics generally operate with good power conversion efficiencies, in the range of 11-16%. Some disadvantages regarding crystalline Si technology exist, including the relatively poor photon absorption efficiency of crystalline-Si, and therefore a thicker layer of semiconductor (several hundred microns) is required than in other technologies. Also, while crystalline Si photovoltaic fabrication has had decades to learn and improve, it still involves the use of many high temperature and high cost procedures which are not likely to see any dramatic improvements in the future. Finally, crystalline

Si photovoltaics are fragile and rigid and thus inappropriate for many applications including portable electronics where light-weight is important.

3.1.2 Manufacturing

The manufacturing process for crystalline Si photovoltaic modules can be broken into four major processes: crystal growth, wafer slicing, cell processing, and module manufacturing. In order to reduce module costs, significant efforts have been made to improve the cost efficiency of all four processes. A schematic of the manufacturing process used by Siemens Solar Industries is shown below.

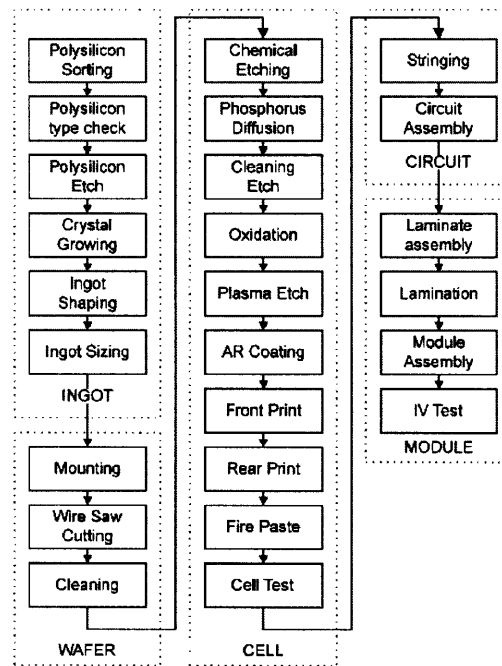


Figure 8: Siemens Solar Industries Si manufacturing process¹⁵

The first process, crystal growth, involves sorting, cleaning, and feeding the raw polysilicon particles into the growing machines. Ingot growth from a seed (Czochralski Growth) then takes place at high temperatures followed by a shaping operation which makes the ingot cross section square or semi-square. Ingot growth is a very energy intensive process, requiring up to 100kWh per kilogram of silicon ingot produced,

however this number has been reduced to 40kWh through design improvements and gas-flow dynamics improvements.¹⁵

Wafer slicing is next which involves mounting the ingot, sawing, and finally etching and cleaning the damaged surfaces. Historically the inner diameter blade saws were used in this process, however the industry has shifted to the wire saw due to the fact that it enhances yield through minimizing damaged surfaces which contribute to wasted silicon.

The etched and cleaned Si wafers are then processed into solar cells by diffusing a dopant into the wafer's surface, applying an anti-reflective coating, and printing on contact strips from which the power produced by the cells is gathered. The cells produced are transferred from step to step at high speeds. Originally this was done by hand, however increases in the level of automation have almost doubled the procedure's yield.

The final step involves assembling the photovoltaic modules. First the cells are connected into a circuit which is then laminated behind tempered glass. External electrical connectors are then applied and the module is completed. Cost improvements from this step have been realized through the production of larger modules, because larger modules produce more watts per unit and thus have lower labor intensive processing such as module handling and junction box installation. Further improvements continue to be sought through increasing the use of automation equipment in the future.

An interesting figure of merit regarding any energy production device is the energy payback time, which for photovoltaic modules is defined as the time necessary for the module to generate the energy equivalent to that used to produce it. The energy required to produce the module includes the energy consumed directly by the manufacturer during processing as well as the energy consumed to produce the raw materials used in the process. Improvements to manufacturing processes have reduced the energy payback time from over 5 years in 1990 to approximately 3 years in 2000 for modules produced by Siemens Solar Industries.¹⁵

3.1.3 Manufacturing by Crystalline Si Photovoltaic Type

Among the classes of crystalline Si, monocrystalline Si typically has a higher efficiency than polycrystalline Si and therefore monocrystalline modules tend to be slightly smaller than polycrystalline modules. Monocrystalline Si wafers are cut from a silicon boule that has only grown in one plane or direction while polycrystalline Si wafers are cut from a silicon boule that has grown in many directions. While monocrystalline Si is typically more efficient than polycrystalline Si, it is also more expensive.

Ribbon/sheet silicon refers to silicon produced either as a plain 2-dimensional strip or as an octagonal column, by pulling it from a melt. Production of silicon in this manner is advantageous in that it bypasses some of the inefficient processes like wafer sawing and 3-dimensional crystal growing. This technology is quite new compared other crystalline Si processing methods and thus only accounts for 4% of the global photovoltaics market.

Of the costs associated with the production of non-ribbon grown crystalline Si photovoltaic modules, approximately 40-50% comes from Si wafer production (crystal growth and wafer sawing), about 20-30% from cell fabrication, and about 30% from interconnection/lamination of the modules.^{5,15} Therefore one of the best approaches for reducing module costs is to improve the most expensive step—Si wafer production. The ribbon/sheet processes are a unique solution to traditional methods for producing and sawing Si wafers that may significantly reduce photovoltaic module costs. Despite this, crystalline Si manufacturing is full of high temperature processing steps which are fundamentally necessary to produce working photovoltaic modules and thus manufacturing improvements are slow to make significant cost reductions.

3.1.4 Evaluation of Start-ups

3.1.4.1 Evergreen Solar

Evergreen Solar is a public, USA based company which develops and manufactures photovoltaic modules which incorporate a proprietary crystalline silicon technology known as “String Ribbon”. Founded in 1994, Evergreen Solar still remains a small

company today and is not yet profitable, with \$9m in 2003 revenue, operating margin of -163%, and \$-9m in operating cashflow. According to CLSA Asia-Pacific Markets' *Sun Screen*, Evergreen's production technology has the potential to reduce costs > 30% below other crystalline production technologies. With capacity growing from 15MW in 2004 to over 60MW by 2006, Evergreen Solar will potentially see increasing economies of scale in the near future helping it compete with other technologies.¹⁰ *Sun screen* believes that Evergreen's string ribbon production technology is the "most likely nominee" to replace conventional crystalline Si technologies and that Evergreen is taking realistic steps to capture a leadership position by 2007-2008.

3.1.4.2 Q Cells

Q Cells is an East German based company that manufactures and supplies high efficiency, low cost crystalline solar cells to module manufacturers globally. Q cells began production of mono- and multicrystalline cells in 2001 and has quickly grown to see revenue greater than \$372m with a capacity of ~350MW_p in 2005. It is believed that Q cells has the fastest ramp-up time for new cell manufacturing capacity and has potential to be first-to-market with a series of incremental cell improvements for the next few years.¹⁰

3.2 Thin Film – a-Si, CdTe, CuIn(Ga)Se₂

3.2.1 Overview

The relatively high cost of silicon wafers and processing techniques associated with crystalline photovoltaics, along with the poor light absorption of silicon led researchers to design cells using various thin film semiconductor materials—materials which absorb light so well that only a thin film, ~1 micron, is needed. These materials include amorphous silicon, CdTe, and CuIn(Ga)Se₂. The semiconductor junctions in thin film photovoltaics are either p-i-n junctions for amorphous Si or bulk heterojunctions for CdTe and CuIn(Ga)Se₂. A transparent conducting oxide is used as the front contact and metal is used as the back contact.

Many advantages are associated with thin film photovoltaics.. The primary advantage of thin film photovoltaics relative to crystalline Si photovoltaics is that thin film photovoltaics have lower manufacturing costs. Thin film photovoltaics are amenable to large area deposition and therefore high volume manufacturing. Instead of the costly batch-and-repeat processes needed in crystalline Si photovoltaics manufacturing, thin film devices can be continuously printed roll-to-roll on sheets of either coated polymer, glass or stainless steel. In addition to high throughput manufacturing, thin film photovoltaics can exhibit good power conversion efficiencies relative to organic-inorganic hybrid photovoltaics, above 13% in laboratory testing, however on average module efficiencies are more in the range of 5-8%.

Of all the disadvantages associated with thin film photovoltaics, the most significant reason why thin film photovoltaics occupy a dramatically smaller global market share than crystalline Si is perhaps the complexity of the technology and lack of maturity of the industry. Many thin film technologies have taken longer than 20 years to transition from laboratory testing to commercial manufacturing. The other disadvantage of many thin film technologies is that their power conversion performance degrades over time. Amorphous Si photovoltaics are one of the thin film technologies that suffer from performance degradation, due to the Staebler-Wronski effect. This effect can cause drops in performance by 15-35% when exposed to sunlight.¹⁶ In addition, some thin film materials are known to be hazardous including Cd, and therefore CdTe thin film photovoltaic manufacturers face additional marketing challenges.

Shown in Figure 7, amorphous Si holds a 5% market share of all global photovoltaics while CdTe and CuIn(Ga)Se₂ combine to account for the majority of the 2% listed in the figure as “other”. Amorphous Si is the most well developed thin film photovoltaic technology and may see improvements through the use of microcrystalline Si, which would hypothetically combine the high throughput, low cost manufacturing of thin film photovoltaics with the stability of crystalline photovoltaics.

3.2.2 Manufacturing

As previously mentioned, the ability to manufacture thin film photovoltaics considerably more cheaply than crystalline Si photovoltaics is their primary advantage. Roll-to-roll production, specifically, allows for much higher throughput continuous manufacturing with more automation and higher yield than batch-and-repeat crystalline Si photovoltaic manufacturing. A schematic of the production diagram for an amorphous Si triple junction thin film photovoltaic is shown below in Figure 9.

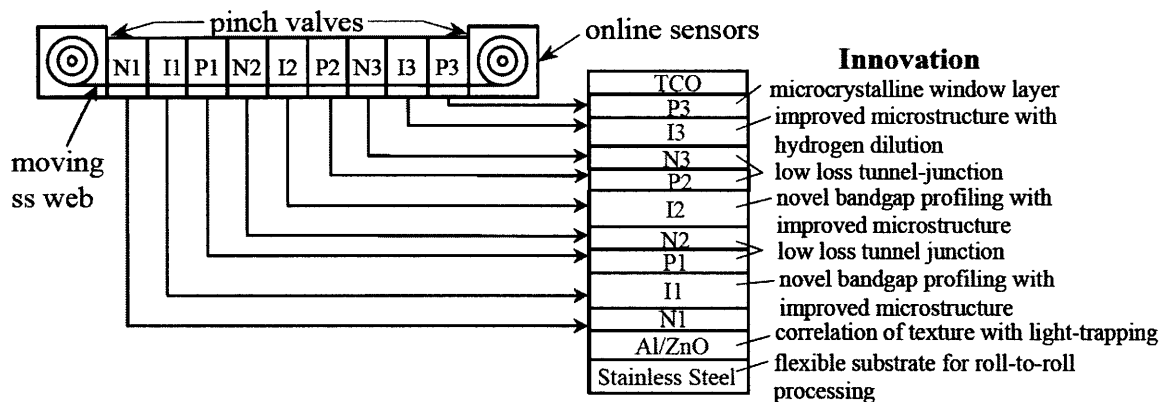


Figure 9: Schematic of the roll-to-roll deposition process and triple junction structure¹⁷

The manufacturing process begins with ~2500m long, ~125 μ m thick rolls of substrate of either stainless steel foil, polyimide or similar polymer, or a glass. First the rolls are washed, then Al and ZnO are sputtered onto the rolls creating the back reflector. Then nine layers of amorphous Si and amorphous SiGe are deposited creating the triple junction. First are six layers of amorphous SiGe, with the middle layers of different Ge concentration than the bottom layers. Then three layers of amorphous Si are deposited on top. The reason for three separate junctions is that they have different bandgap energies and therefore absorb different portions of the solar spectrum, enhancing photoconversion efficiency—single layer cells have a stabilized efficiency around 5% while triple layer cells have a stabilized efficiency up to 13%^b. Finally indium tin oxide (ITO) is deposited on top which serves as the anti-reflection coating.¹⁸

Once all deposition processes are completed, the rolls are then cut into slabs using a semi-automated press. Coupons are also cut at preset intervals along the rolls which are then tested for quality assurance/quality control. Slabs are processed to define cell size, passivated to remove shunts and shorts, and tested to ascertain quality. Grid wires and contact pads are next applied and the slabs are cut into predetermined cell sizes for various product requirements. Next the cells are interconnected and the cell-block is laminated to provide protection from the environment. Depending on the application, frames and junction boxes are added and the finished modules undergo a final performance measurement under global AM1.5 illumination before they are shipped out.¹⁸

3.2.3 Evaluation of Start-ups

3.2.3.1 Iowa Thin Film Technologies

Iowa Thin Film Technologies (ITFT) is a privately held, American company developing manufacturing technologies for the roll-to-roll production of amorphous Si thin film photovoltaics on flexible sheets of polyimide, as well as the products themselves. ITFT is one of only two companies currently marketing roll-to-roll produced solar cells in significant volume.¹⁹ According to ITFT's website, ITFT's PowerFilm™ photovoltaic modules are ultra flexible, durable, lightweight, and are sold to three primary markets: consumer electronics, outdoor and recreation, and remote and military. ITFT also is developing integrated PowerFilm™ products for building integrated photovoltaics, and is forming strategic partnerships with major building materials companies.²⁰

3.2.3.2 Energy Conversion Devices

The other company of the only two that are currently marketing roll-to-roll produced solar cells in significant volume, Energy Conversion Devices (ECD), through its subsidiary Unisolar, manufactures and develops technology associated with amorphous Si thin film photovoltaics, roll-to-roll produced, and deposited on stainless steel foil.

ECD recently completed a new manufacturing plant and can now produce 30MW annually²¹, with sales ranging between ~65-90 million annually since 2001.²²

3.3 Organic-Inorganic Hybrids

3.3.1 Overview

Organic-inorganic hybrid photovoltaics involve the use of organic semiconductors, either by themselves or in conjunction with inorganic semiconductors. This class of photovoltaics is the newest of the three, primarily due to the recent growth in knowledge regarding various nanomaterials which make organic-inorganic hybrid photovoltaics possible. Organic-inorganic hybrids include the Graetzel cell, semiconductor heterojunction cells, and various other designs using organic semiconductors in specific architectures. The Graetzel cell, which involves light-sensitive organic dye molecules adsorbed on colloidal TiO₂ in an electrolyte solution, is one of the most advanced of the organic-inorganic hybrid photovoltaics class, with laboratory power conversion efficiencies up to 8%. This technology is discussed in greater detail in section 4.1.

The primary advantage of this class of photovoltaics is the potential for extremely low manufacturing costs since production would almost certainly involve high throughput roll-to-roll printing using small amounts of material per cell. No high-temperature processing steps would be needed and large amounts of photovoltaics could be continuously produced. Another advantage of organic-inorganic hybrid photovoltaics is that they are light, flexible, and not too fragile. This makes them particularly appropriate initially for transportation and personal electronics applications.

The primary disadvantage associated with photovoltaics using organic semiconductors is that power conversion efficiencies are still very low, making it extremely difficult for these photovoltaics to economically compete with crystalline Si and thin film photovoltaics. While research efforts aimed at improving the efficiencies of organic photovoltaics are constantly expanding, results have been somewhat slow. Ching Tang of Kodak first proposed semiconductor heterojunction photovoltaics using organic

materials in the mid-1980's but it wasn't until about 15 years later than any improvements in device efficiency were made.

3.3.2 Manufacturing

The pursuit of manufacturing—even cheaper than that needed for the roll-to-roll production of thin film photovoltaics is the primary reason why organic photovoltaics have considerable commercial potential in the future. There are many types of organic-inorganic hybrid cells and manufacturing techniques would vary somewhat among these types, but they would most likely have many similarities to each other and to thin film photovoltaic cells. Like the previously described amorphous Si photovoltaic manufacturing process, organic-inorganic hybrid cells would also involve long, thin rolls of substrate upon which the functional and protective layers would be deposited. However organic-inorganic hybrid cells could potentially bypass the chemical vapor deposition processes used in a-Si photovoltaic manufacturing for printing processes including microcontact/soft lithography, inkjet or offset printing¹⁹. Since deposition via printing is less costly than that involving chemical vapor and does not require as high temperatures, organic-inorganic hybrids could realize all the advantages of a-Si roll-to-roll manufacturing with additional advantages, ultimately making them the cheapest photovoltaic to produce.

3.3.3 Evaluation of Start-ups

3.3.3.1 Konarka Technologies

Konarka Technologies is a private USA based company which designs and manufactures photovoltaic platforms comprising Graetzel cell technology. Founded in 2001, Konarka posted \$0.5m in sales in 2003²² however research contracts are most likely responsible for this number rather than product revenue. Konarka was the first company to commercialize photovoltaics using organic semiconductor materials. They acquired Siemens' organic photovoltaics research activities in 2004 and continues to partner with other leading photovoltaics and nanoscience companies.

3.3.3.2 Nanosys

Founded in 2001, Nanosys is a private USA based company which researches, develops, and designs nanomaterials for photovoltaics, flexible electronics, non-volatile memory, and fuel cells. With \$3.0m in 2003 sales, Nanosys continues to grow, building partnerships with various companies and US government agencies.²²

3.3.3.3 Nanosolar

Also founded in 2001, Nanosolar is a private USA based company which develops and designs process technology for the rapid printing of organic-inorganic photovoltaics. Like Nanosys' photovoltaics, Nanosolar's photovoltaics use a nanostructured inorganic element combined with an organic polymeric component to facilitate efficient charge separation.¹⁹ Nanosolar continues to strengthen their intellectual property portfolio as well as partner with various companies and US government laboratories and hopes to begin commercialization in the near future.

3.3.3.4 SolarAmp

SolarAmp LLC was started in 2001 and aims to develop photovoltaic technology involving the use of light-harvesting nanorods to enhance efficiency. SolarAmp's goal is to partner with other companies who will commercialize their technology rather than commercialize the technology themselves.²³ In 2002 SolarAmp LLC and BP Solar established a joint development program directed at developing the first commercial solid-state molecular photovoltaic module. SolarAmp continues research and development today and will most likely be the last of the four discussed organic-inorganic hybrid photovoltaics companies to see significant sales.

4. Current Research Strategies

A key difference between semiconducting organic materials and semiconducting inorganics which limits the efficiency of organic photovoltaics is the binding energy of the charge carriers. In conventional covalent inorganics, carriers are delocalized and therefore have low binding energies on the order of 0.01eV. Organic semiconductors, however, exhibit weak intermolecular van der Waals interactions which strongly localize charge carriers and as a result these excitons have much greater binding energies, on the order of 1eV. These relatively large binding energies increase the probability of recombination, thus excitons have a finite lifetime and therefore a finite diffusion length. This leads to an important tradeoff between photon absorption and exciton dissociation efficiency. In order to increase the number of absorbed photons, one might increase thickness of these semiconducting layers. However, as thickness increases, more and more excitons will be wasted as they will be absorbed at a distance from the HTL/ETL interface greater than their diffusion length and will recombine before being able to contribute to the photocurrent.

Two possible solutions proposed to overcome this tradeoff are to increase the exciton diffusion length and/or to increase the area of the HTL/ETL interface. The former may be achieved by reducing the number of defects which can trap excitons or by directing excitons to the interface rather than relying on their random diffusion. A third method of increasing the exciton diffusion length is to convert singlet excitons into triplet excitons where decay is mostly disallowed.

4.1 Graetzel (Wet) Cell

In order to get around this tradeoff by increasing HTL/ETL interface area, Michael Graetzel invented a photovoltaic design comprising a monolayer of organic light-sensitive dye molecules adsorbed on the surface of colloidal TiO_2 , seen in Figure 10. This design includes an electrolyte solution to extract charge so that it may contribute to photocurrent. Since colloidal TiO_2 is used, the resulting interface between acceptor and donor is approximately 10^4 times greater than in a planar interface.⁴ Laboratory power

conversion efficiencies around 8% have been realized for photovoltaics of this design however some disadvantages exist that may hinder growth of this technology commercially. In the Graetzel cell, the fill factor, FF , is generally quite low and open circuit voltage, V_{OC} , is difficult to control. In addition, very few candidate materials exist for the donor, acceptor, and light-sensitive dye molecules in this photovoltaic design. Finally, the presence of a liquid electrolyte in this design may present packaging difficulties.

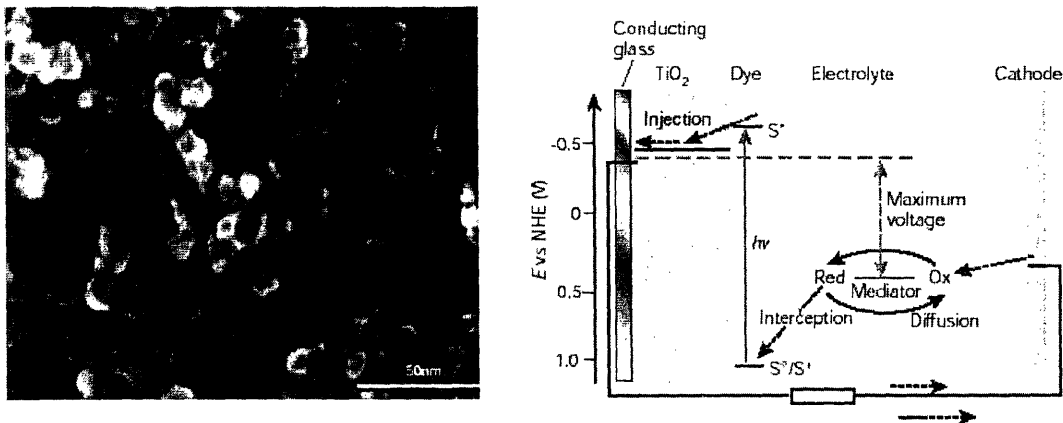


Figure 10: Colloidal TiO₂ (left), Schematic energy diagram (right)⁴

4.2 Blended Photovoltaics

Another current research strategy which aims to overcome the problem of relatively short exciton diffusion lengths involves the use of blended donor-acceptor network composites. These composites, generally 1000-2000 Å thick, have been made using the semiconducting polymer MEH-PPV and the functionalized derivatives of C₆₀. The advantage of a blended donor-acceptor layer is the increased exciton dissociation efficiency which is primarily due to the dramatically increased interfacial area between donor and acceptor materials. Therefore exciton recombination is inhibited.²⁴ The blended donor-acceptor layers are attached to a metal electrode on one side and ITO along with a glass or plastic substrate on the other side, seen in Figure 11. A disadvantage of this design is that charge extraction through the blended films is generally poor, restricting power conversion efficiencies of blended photovoltaics to less than 4%.

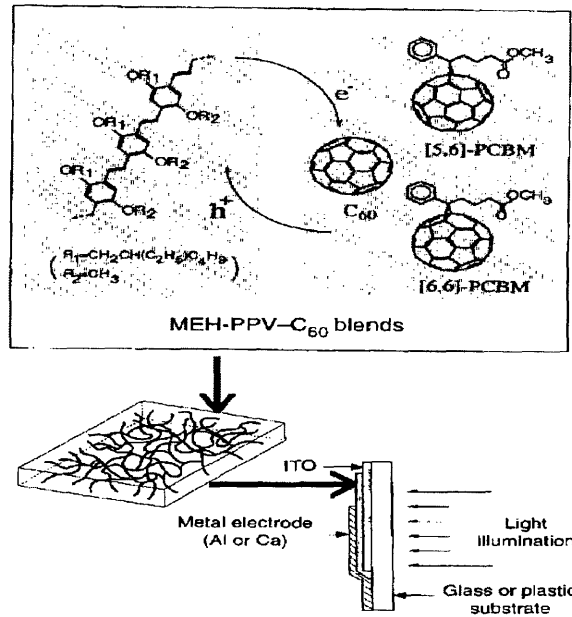


Figure 11: Schematic diagram of the photoinduced charge transfer process in MEH-PPV:C₆₀ donor-acceptor blends²⁴

4.3 Asymmetric Tandem Cells with Hybrid Planar-Mixed Molecular Heterojunctions

Expanding on the aforementioned strategy of blending donor and acceptor materials to enhance device properties, researchers have recently achieved some of the best organic power conversion efficiencies of $\eta_p = (5.7 \pm 0.3) \%$ by sandwiching blended layers between homogenous layers in both a front and back cell, an idea known as asymmetric tandem PM-HJ cells.²⁵ This concept combines the good transport of photogenerated charge carriers to the electrodes characteristic of homogeneous materials with the high exciton diffusion efficiency in blended regions. This design includes layers of PTCBI and BCP as exciton-blocking layers and Ag nanoclusters as recombination centers in p-doped m-MTDATA between the front and back cells. The asymmetry of the device refers to the difference in spectral response in the front and back cells at different wavelengths. The back cell exhibits significantly greater external quantum efficiency at lower wavelengths ($\lambda \approx 450\text{nm}$) and the front cell does the same at higher wavelengths ($\lambda \approx 650\text{nm}$). According to Xue *et al.*, the ultimate advantage of this structure lies in the ability to incorporate different donor-acceptor material combinations in the individual

subcells to cover a broader solar spectral region than the current CuPc/C₆₀ system. Hypothetically the solar spectral coverage could be increased by employing a third subcell, primarily absorbing in the near infrared.²⁵

While this design has achieved some of the best organic power conversion efficiencies, its drawbacks include low fill factors which become an increasing concern with large device thicknesses and the fact that it is composed of a large number of layers which suggests that the commercial processing of these structures would be costly and yields might not be as high as desired.

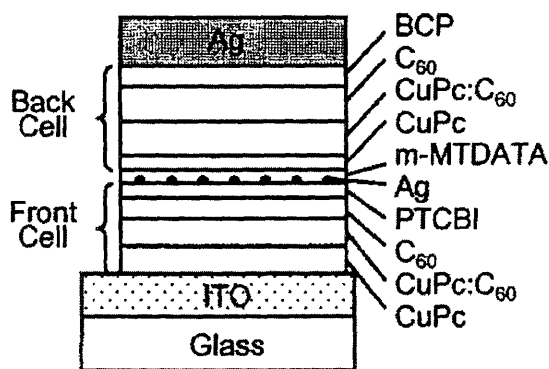


Figure 12: Structure of an organic tandem PV cell formed by stacking two hybrid PM-HJ cells in series²⁵

4.4 External Antenna Photovoltaic

While the Graetzel cell achieves vastly increased HTL/ETL interface area, the design has not yet been achieved completely in solid state. Thus researchers explore new ideas to overcome the tradeoff between optical absorption and exciton dissociation efficiency. One such idea involves the separation of the optical and electrical functions of a photovoltaic as is found in natural photosynthetic life forms. The advantage of this separation of functions is that optical absorption could be maximized independently of electrical conversion of dissociated excitons. The material responsible for optical absorption, known as the external antenna, could be vastly larger than in traditional organic photovoltaics, approaching 100-200nm as seen in Figure 13 and would absorb a

large number of photons. This material could be either photosynthetic or a synthetic CuPc type structure.

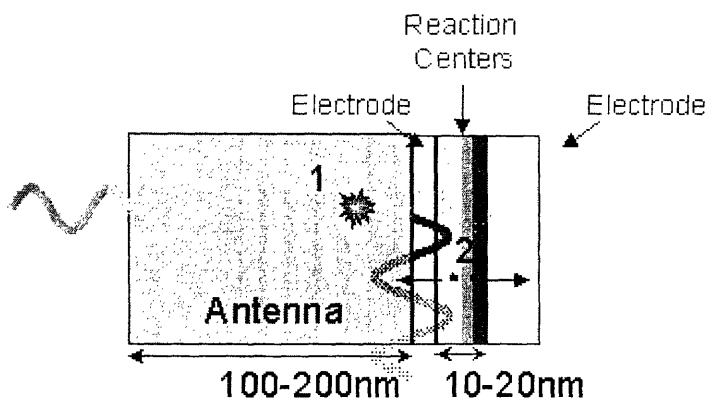


Figure 13: Photons are absorbed in the external antenna (1), surface plasmons are created perpendicular to the incident light and the energy is absorbed by the thin layer of reaction centers (2)²⁶

The material responsible for converting excitons into charge could be quite thin to maximize the percentage of excitons that reach the HTL/ETL interface before any recombine, possibly achieving an internal quantum efficiency, η_{IQE} , approaching 100%.

In order for this design to be effective, there must be some mechanism responsible for transporting excitons through the large external antenna. This mechanism consists of two processes which must both be efficient. The first process involves photon absorption in the external antenna. Then the antenna must efficiently re-radiate the photons into guided optical modes, known as surface plasmons. These surface plasmons are created in the thin photovoltaic electrode/reaction center/electrode region, and should be an effective method for transferring energy across the intervening metal electrode. The second process involves energy in the plasmon modes propagating perpendicularly to the incident light and then efficient absorption of this energy by the thin layer of reaction centers.²⁶

Baldo et al. have demonstrated that photosynthetic complexes may be integrated with electronics in the solid state with considerable performance.²⁷ The external antenna layer

could also incorporate light harvesting structures from algae, as these life forms have had over two billion years of evolutionary adaptation to optimize their photosynthetic performance. The layer of reaction centers would most likely be made of a traditional organic photovoltaic material like CuPc or C₆₀. The electrodes would be made of silver due to its low electrical losses.

Researchers have shown that the previously described second process (absorption of plasmon modes) will function sufficiently and are running simulations to test the feasibility of the first process (photon absorption and re-emission into surface plasmons). This external antenna photovoltaic device architecture has great promise for overcoming the optical absorption vs. exciton dissociation efficiency tradeoff and could someday see commercialization at the level of the Graetzel cell and potentially much greater.

5 Intellectual Property

Intellectual property is extremely valuable and necessary for any company or individual seeking to profit from the development of any of the photovoltaic ideas discussed in this paper. In today's "information age", a great deal of technology is shared across and within various industries, thus the ownership of key patents is vital. When new ideas are presented, the existing intellectual property must be thoroughly analyzed to determine whether the idea may be considered new art or whether previously filed patents block the given idea. Many different patents are of importance regarding previously discussed technologies including patents on device architectures, production processes, and the use of certain materials. Some of the most important patents are discussed in this section while many additional patents are detailed in the appendix.

5.1 Crystalline Si

Crystalline Si photovoltaics have been manufactured longest of all classes of photovoltaics and thus many of the important, general patents have expired by now. The use of ribbon/sheet silicon and related processes however are much newer and still have many patents active. The key patent regarding ribbon-grown Si for photovoltaics is held by Emanuel Sachs (#4,661,200), titled "String stabilized ribbon growth", and was filed April 28, 1987. This patent's primary claim is: "A method of continuously growing crystalline or semicrystalline ribbonlike bodies from a melt of the same material wherein the ribbonlike body has a thin flat unobstructed elongate center section grown directly from the melt surface comprising; the steps of: drawing the ribbonlike body from the surface of the melt; and stabilizing the edge positions of the ribbonlike body with strings positioned along the edges thereof, which strings are frozen into the growing ribbon." This patent also describes a technique for minimizing the introduction of impurities from the melt into a ribbon by constantly flowing the melt under the growth interface in a direction perpendicular to the plane of the growing ribbon. Sachs is a member of Evergreen Solar, the company commercializing string-ribbon grown Si photovoltaics. This patent as well as related patents keeps this technology exclusive to Evergreen Solar, however this patent only remains active until 2007.

5.2 Thin Film

Many key patents related to thin film photovoltaics discuss techniques to allow for economical, high throughput, roll-to-roll manufacturing, which is perhaps the most important advantage thin film photovoltaics have over crystalline Si photovoltaics. On September 20, 1993, Derrick Grimmer of Iowa Thin Film Technologies filed a patent (#5,385,848), titled “Method for fabricating an interconnected array of semiconductor devices.” This key patent provides a novel method for economically producing a series interconnection in an array of photovoltaic devices. This patent also provides a novel method for interconnecting in series an array of semiconductor devices by slitting a flexible substrate web, which may be electrically conducting, along its length, and then interconnecting the resultant portions of strips parallel to the length of the web as well as a novel method for interconnecting an array of photovoltaic devices in series by using a slitter and laminating rollers.

Energy Conversion Devices, Inc., also a significant manufacturer of thin film photovoltaics, is the assignee of patent #4,663,828, titled “Process and apparatus for continuous production of lightweight arrays of photovoltaic cells.” This patent, filed on October 11, 1985 by Joseph Hanak, claims a process for producing relatively large-area, lightweight arrays of thin film semiconductor alloy photovoltaic cells comprising: continuously depositing a thin semiconductor alloy film on a traveling surrogate substrate; continuously applying a transparent support material to said deposited thin film semiconductor alloy film opposite said traveling surrogate substrate; and continuously separating said alloy film and support material from said surrogate substrate. This patent along with various others held by Energy Conversion Devices protects their roll-to-roll printing of photovoltaics onto stainless steel foil substrates and gives them a competitive edge, similar to that provided to Iowa Thin Film Technologies by their intellectual property portfolio.

5.3 Organic-Inorganic Hybrids

5.3.1 Graetzel Cell

A key patent for Konarka Technologies describes the general idea of the Graetzel cell. Named for its inventor, Michael Graetzel, along with Mohammad Nazeeruddin and Brian O'Regan, the patent (#5,350,644) titled "Photovoltaic cells" was filed on October 15, 1992. This patent claims a solar-light-responsive photovoltaic cell comprising a light transmitting electrically conductive layer deposited on a glass plate or a transparent polymer sheet to which one or more preferably porous high surface area TiO₂ layers have been applied, in which at least the TiO₂ layer may be doped with a divalent or trivalent metal ion. The photovoltaic cell also comprises two electrodes, one of which is transparent, and a receptacle between the two electrode plates in which an electrolyte is located. Konarka's possession of this patent has helped them to become the leading commercializer of Graetzel cell photovoltaics.

5.3.2 Surface Plasmon Enhanced Photovoltaics

Many recent research strategies for improving the efficiency of organic photovoltaics have involved the use surface plasmons as a method for transferring energy across distances that would ordinarily be too large. Surface plasmons are guided electromagnetic waves which involve oscillations in the valence electron density at a conducting surface. Lynn Anderson was first to patent the idea on April 19, 1983, titled "Solar energy converter using surface plasma waves" (#4,482,778). Anderson's patent claims an apparatus for converting sunlight to electricity by extracting energy from photons therein comprising an electrically conducting member, means for dispersing sunlight over a surface of said member to polarize the surface charge thereon thereby inducing oscillations in the valence electron density at said surface to produce surface plasmons and for phase-matching photons and surface plasmons of the same energy so that energy is transferred from said photons to said plasmons, and means for extracting energy from said surface plasmons and converting the same to electricity. This patent, while noteworthy, is now expired.

A more detailed description of a photovoltaic device benefiting from surface plasmon enhancements was described in Thio Tineke's August 15, 2000 patent titled "Surface-plasmon enhanced photovoltaic device" (#6,441,298). Thio's patent claims: "A surface-plasmon enhanced photovoltaic device comprising a first metallic electrode having an array of apertures, the first metallic electrode having an illuminated surface upon which light is incident and an unilluminated surface, at least one of the illuminated and unilluminated surfaces having an enhancement characteristic resulting in a resonant interaction of the incident light with surface plasmons on the surface; a second electrode spaced from the first electrode; and a plurality of spheres corresponding to the array of apertures and disposed between the first metallic and second electrodes, each sphere having a first portion of either p or n-doped material and a second portion having the other of the p or n-doped material such that a p-n junction is formed at a junction between the first and second portions, an individual sphere being disposed in the apertures such that one of the first or second portions is in electrical contact with the first metallic electrode and the other of the first or second portions is in electrical contact with the second electrode." This idea is relatively novel and any attempts to commercialize photovoltaics as described in this patent will most likely be realized in the distant future, if at all.

5.3.3 Others

Ching Tang of Eastman Kodak, one of the great pioneers of organic photovoltaics research, along with Alfred Marchetti and Ralph Young were first to patent a photovoltaic element featuring the use of organic photoconductive materials which could achieve power conversion efficiencies significantly greater than those that were common at that time for organic photovoltaics, which was 0.05%. Filed on March 13, 1978 and titled "Organic photovoltaic elements" (#4,125,414), this patent discussed a photovoltaic element having enhanced electrical response to incident light because of the use of certain organic photoconductive compositions. More specifically, there is provided a photovoltaic element comprising a layer of a photoconductive composition having opposed surfaces, such composition comprising an electrically insulating binder, a

pyrylium-type dye salt and an organic photoconductor, and an electrical conductor adjacent each of said layer surfaces. This patent has expired many years ago but is noteworthy due to the great impact it had on advancing organic photovoltaics research.

Another noteworthy patent pertaining to a wide variety of organic photovoltaics is #5,454,880 titled “Conjugated polymer-acceptor heterojunctions; diodes, photodiodes, and photovoltaic cells.” Invented by N.S. Sariciftci and Alan Heeger and filed on January 12, 1994, this patent claims a method for the production of electricity from light through a photovoltaic heterojunction device comprising a layer of an undoped conjugated polymer serving as a donor adjacent to a layer of an acceptor material selected from the group of fullerenes and related derivatives and organic or polymeric acceptors. Claims also include that in said photovoltaic heterojunction device, one or more of the layers has been produced by applying onto a substrate in fluid form, either a solution or a melt at temperatures below 300°C and that the heterojunction has been formed in situ by controlled segregation during solidification from a solution containing both the donor and the acceptor moieties.

Also of particular importance is the patent behind one of the most efficient organic photovoltaic architectures—the stacked, multilayer structure discussed in section 4.3. Invented by Stephen Forrest and Peter Peumans and filed on June 11, 2004, “Solar cells using fullerenes” (#6,580,027) discusses the use of exciton blocking layers and the use of fullerenes in the electron conducting layer to enhance photovoltaic device efficiency. Single heterostructure, stacked, and wave-guide type embodiments are disclosed as well as devices having multilayer structures with an exciton blocking layer. The patent’s primary claim is an organic photosensitive optoelectronic device comprising an anode, a hole transport layer formed of a photoconductive organic semiconductor material, an electron transport layer comprising a fullerene over the hole transport layer, an exciton blocking layer, and a cathode, wherein the device is capable of an external power conversion efficiency of at least ~3.6%.

6 Economic Analysis of Photovoltaic Technologies

The relatively inexpensive manufacturing associated with organic photovoltaic technologies is what gives these photovoltaics so much commercial potential and research attention. This point has been discussed throughout this paper qualitatively thus far. However, this section describes quantitative estimates of how potential manufacturing savings affect overall module prices.

Equation 5 relates module efficiency (η), solar flux ($\Phi = 844\text{W/m}^2$ at AM1.5), and production cost ($\$/\text{m}^2$) to the overall module cost ($\$/\text{W}_{\text{peak}}$). Module costs are an important parameter for photovoltaics, and researchers and manufacturers constantly attempt to reduce this figure as much as possible. Equation 5 shows that module cost may be reduced by either decreasing costs associated with producing the module or by increasing the power conversion efficiency of the photovoltaic cells in the module. The cheapest module prices currently available in August 2005 are $\$3.84/\text{W}_p$ for a crystalline Si module and $\$3.66/\text{W}_p$ for a thin film module.¹⁶ This thin film module is assumed to be approximately 6% efficient, and at AM 1.5 conditions, corresponds to a production cost of about $\$185/\text{m}^2$. This production cost is the sum of materials costs and manufacturing costs, seen in Equation 6. The materials cost accounts for semiconductor materials as well as substrate, laminate, connector, and other materials while manufacturing cost accounts for necessary machinery, the energy needed to power these machines, labor, and various other costs. Generally, materials costs are approximately equal to manufacturing costs²⁸ (Equation 7).

$$C_{\text{module}} \approx \frac{C_{\text{production}}}{\eta \times \Phi} \quad (\text{Equation 5})$$

$$C_{\text{production}} = C_{\text{materials}} + C_{\text{manufacturing}} \quad (\text{Equation 6})$$

$$C_{\text{materials}} \approx C_{\text{manufacturing}} \quad (\text{Equation 7})$$

Manufacturing organic photovoltaics in a continuous, high throughput, roll-to-roll manner where materials are printed instead of deposited via chemical vapor is believed to reduce both materials and manufacturing costs relative to thin film photovoltaic

production. Three scenarios are shown in Table 1, an optimistic one (corresponding to largest cost reductions), a mid-range one, and a pessimistic one, corresponding to smallest cost reductions. For example, the optimistic scenario predicts that the manufacturing cost associated with organic photovoltaics will be 50% of the manufacturing cost associated with thin film photovoltaics and the materials cost will be 70% of that associated with thin film photovoltaics. Since these costs contribute to production cost about equally, the average of these (60% cost reduction) would translate to a production cost of $0.60 \times \$185/\text{m}^2 = \$111/\text{m}^2$.

Scenario	% $C_{\text{materials}}$	% $C_{\text{manufacturing}}$	% $C_{\text{production}}$	$C_{\text{production}}$ (\$/m ²)
Thin film (baseline)	100	100	100	185
Optimistic	70	50	60	111
Mid-range	80	65	72.5	134
Pessimistic	90	80	85	157

Table 1: Three scenarios for production cost reductions of organic photovoltaics relative to thin film photovoltaics

The production costs for the three scenarios in Table 1 may then be inserted into equation 1 at various organic photovoltaic power conversion efficiencies to calculate module costs, shown in Table 2. From this table it can be seen that in the mid-range scenario, stabilized efficiencies of only slightly more than 5% would be required to yield a very competitive $\$3/W_p$ module price. It is more likely, however, that the pessimistic scenario will be the most realistic of the three, especially in the short term, and thus a stabilized efficiency of greater than 6% will be required to yield a $\$3/W_p$ module price. The US Department of Energy has established goals of reducing module prices well below $\$1/W_p$ for thin film photovoltaics which are said to require stabilized efficiencies around 15% with production costs around $\$50/\text{m}^2$.²⁸ Table 2 shows that the $\$1/W_p$ price is achievable at only 13% efficiency for organic photovoltaics under the most optimistic conditions, and if a production cost of $\$50/\text{m}^2$ were reached, a stabilized efficiency of only about 6% would be required.

OPV Efficiency, η	Optimistic Scenario (\$/W _p)	Mid-range Scenario (\$/W _p)	Pessimistic Scenario (\$/W _p)
5%	2.63	3.18	3.72
6%	2.19	2.65	3.10
7%	1.88	2.27	2.66
8%	1.64	1.98	2.33
9%	1.46	1.76	2.07
10%	1.32	1.59	1.86
11%	1.20	1.44	1.69
12%	1.10	1.32	1.55
13%	1.01	1.22	1.43
14%	0.94	1.13	1.33
15%	0.88	1.06	1.24

Table 2: Organic photovoltaic module prices for three scenarios at various power conversion efficiencies

Essentially zero detail regarding current manufacturing and materials contributions to photovoltaic module prices is available and thus the presented model and data are rough estimations of the potential of organic photovoltaics. Many experts believe that a stabilized efficiency of about 10% is required for organic photovoltaics to significantly break into the growing photovoltaic market.¹⁹ The data presented here does not correspond to this exactly, most likely due to the fact that this is a simplified cost model which does not account for lifetime/reliability issues, balance of system costs (including installation, inverters, batteries, and charge controllers), and other costs related to research, development, and marketing. Despite this, the model shows that significantly reduced module prices are clearly possible for organic photovoltaics in the future.

7 Potential Business Strategies

If an idea for a new type of photovoltaic is patented, demonstrated, and shown to be truly unique and valuable, three possible business strategies become viable options to profit from this invention. The first option is to allow a university technology licensing office (MIT TLO) to control licensing of the patent. This is advantageous because it requires the least commitment of time and money. The TLO would pay the patent fee but would also take a percentage of licensing fees. This option has the least risk involved and subsequently affords the least amount of profitability.

The second option is to form an IP licensing company. This effort would require moderate investments in order to continue work to strengthen the company's IP portfolio and extensive legal assistance would be required. Most likely this would only succeed through the uniting of various technical pioneers to ensure a truly strong and powerful IP portfolio. A moderate level of risk is associated with this option as well as a moderate amount of profitability. There exists some doubt, however, that this can be a truly profitable option in the long term because many believe that the value of a patent is in demonstrating that it works, not just in possessing it. Therefore the commercialization option must be explored.

The third option is to form a commercialization company. This would require vast investments and commitments. A strong management, technical, and legal team would be essential to the success of a photovoltaic commercialization start-up company. The company's IP portfolio would also need to be dramatically strengthened and the best way to do this would be to merge with a company that already has some commercialization experience and expertise. This option is the most risky but allows the possibility of the greatest profitability.

Many photovoltaic companies are just now starting to become profitable. However, larger commercialization companies still remain hesitant to invest in radically new technologies as substantial investments in the 1990s in thin film photovoltaics were not as successful as investors had hoped. Instead, larger companies seek cost reductions

primarily through incremental manufacturing improvements. Due to the relatively small pool of expertise regarding photovoltaic manufacturing, there remains to be a significant barrier to entering the photovoltaic market as a commercialization start-up company.¹⁰ Therefore this option seems least appropriate given the uncertainty of the technology as well as the large commitment and investments required.

8 Conclusion

Global energy concerns regarding declining fossil fuel supplies and increasingly harmful effects on Earth's environment make the need for a clean, renewable energy source like photovoltaics imperative. Crystalline Si modules dominate the continuously growing global photovoltaics market however significant attention and resources are being devoted towards newer technologies which incorporate organic molecules and nanostructured materials particularly due to the enormous potential for significantly reduced manufacturing costs.

Some current research strategies for organic based photovoltaics which have the potential to become cost-competitive with crystalline Si photovoltaics in the future are the use of Graetzel cells, blended photovoltaics, asymmetric tandem cells with hybrid planar-mixed molecular heterojunctions, and the external antenna photovoltaic. All of these photovoltaics present interesting options for bypassing fundamental tradeoffs that are intrinsic to photovoltaics, most importantly the tradeoff between photon absorption and exciton dissociation efficiency. The Graetzel cell, already being commercialized by Konarka Technologies, incorporates a liquid electrolyte along with photosensitive dye molecules on colloidal TiO_2 to vastly increase ETL/HTL interface area. Blended photovoltaics along with planar-mixed heterojunctions also involve increased interface area in unique device architectures. A slightly different approach to overcoming said tradeoff involves the use of surface plasmon waves to carry the energy of photons absorbed in an enlarged external antenna to the ETL/HTL interface.

All of the discussed technologies have considerable commercial potential because their manufacturing costs are expected to be much lower than those for crystalline Si photovoltaics. This is because organic photovoltaics will be produced in a high throughput, continuous, roll-to-roll manner on flexible substrates requiring no high temperature processing steps, while crystalline Si photovoltaic production involves a slower batch-and-repeat process with various steps including ingot growth at significantly elevated temperatures.

Section 6 presents a simplified cost model for production of photovoltaics which estimates the module price reductions that are possible for organic photovoltaics. Three scenarios corresponding to small, medium, and large production cost reductions are presented and various module costs are given which correspond to different stabilized power conversion efficiencies. The simplified model shows that organic photovoltaics have serious potential to become economically competitive with the much more mature crystalline Si technologies.

Intellectual property is imperative for any individual or company seeking to profit from the creation of a novel photovoltaic design or manufacturing process. Many companies possess similar knowledge bases, therefore the possession of key patents affords the given companies important competitive advantages.

Commercialization is not the only option for those seeking profit in the growing photovoltaics industry. A less risky alternative is to license one's patents to commercialization companies and this option is probably most appropriate for many individuals holding key patents because of the significant barrier to entering the photovoltaics commercialization industry. An even less risky alternative requiring the least amount of resources is to allow an external entity like a university technology licensing office to handle patent licensing and this option may also be appropriate for many.

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APPENDIX

Noteworthy Patents:

Crystalline Si:

US Patent # 4,661,200: “String stabilized ribbon growth” Sachs, 28 Apr 1987.

Thin Film:

US Patent # 4,663,828: “Process and apparatus for continuous production of lightweight arrays of photovoltaic cells” Hanak (Energy Conversion Devices, Inc.) 12 May 1987.

US Patent #5,385,848: “Method for fabricating an interconnected array of semiconductor devices” Grimmer (Iowa Thin Film Technologies, Inc.) 31 Jan 1995.

Graetzel Cell:

US Patent # 4,684,537: “Process for the sensitization of an oxidation/reduction photocatalyst, and photocatalyst thus obtained” Graetzel et al., 4 Aug 1987.

US Patent # 5,350,644: “Photovoltaic cells” Graetzel, et al., 27 Sep 1994.

Surface Plasmon Enhanced:

US Patent # 4,482,778: “Solar energy converter using surface plasma waves” Anderson, 13 Nov 1984.

US Patent # 6,441,298: “Surface-plasmon enhanced photovoltaic device” Thio, (NEC Research Institute, Inc.), 27 Aug 2002.

Other Organics:

US Patent # 4,125,414: “Organic photovoltaic elements” Tang, et al. (Eastman Kodak Company), 14 Nov 1978.

US Patent # 5,454,880: “Conjugated polymer-acceptor heterojunctions; diodes, photodiodes, and photovoltaic cells” Sariciftci, et al. (UC–Oakland), 3 Oct 1995.

US Patent # 5,698,048: “Photoresponsive materials” Friend, et al. (Cambridge Display Technology Limited), 16 Dec 1997.

US Patent # 6,420,648: “Light harvesting arrays” Lindsey, 16 Jul 2002.

US Patent # 6,580,027: “Solar cells using fullerenes” Forrest, et al., 17 Jun 2003.

US Patent # 6,596,935: “Solar cells incorporating light harvesting arrays” Lindsey, et al., 22 Jul 2003.

US Patent # 6,657,378: “Organic photovoltaic devices” Forrest, et al., 2 Dec 2003.

US Patent # 6,812,399: “Photovoltaic cell” Shaheen, et al. (QSEL), 2 Nov 2004.