Why silicon is and will remain the dominant photovoltaic material

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Abstract. Rising demands of energy in emerging economies, coupled with the green house gas emissions related problems around the globe have provided a unique opportunity of exploiting the advantages offered by photovoltaic (PV) systems for green energy electricity generation. Similar to cell phones, power generated by PV systems can reach over two billion people worldwide who have no access to clean energy. Only silicon based PV devices meet the low-cost manufacturing criterion of clean energy conversion (abundance of raw material and no environmental health and safety issues). The use of larger size glass substrates and manufacturing techniques similar to the ones used by the liquid crystal display industry and the large scale manufacturing of amorphous silicon thin films based modules (~ GW per year manufacturing at a single location) can lead to installed PV system cost of \$3/Wp. This will open a huge market for grid connected PV systems and related markets. With further research and development, this approach can provide \$2/Wp installed PV system costs in the next few years. At this cost level, PV electricity generation is competitive with any other technology, and PV power generation can be a dominant electricity generation technology in the 21st century.

Keywords: Solar cells, photovoltaic system, silicon, manufacturing, nanostructures, clean energy, amorphous silicon, and thin film.

1 INTRODUCTION

Humans and other living creatures on Earth rely on solar energy as the key source of energy for their existence. The earth receives 174 pettawatt (1 PW = 1015W) of solar radiations at the upper atmosphere [1]. From this amount 29% is reflected back to space 23% is absorbed by the atmosphere, and 48% (~ 87 PW) is received by the earth's surface [1]. In 2006, global energy consumption was about 16 terawatt (1 TW = 1012 W) [2], which is only 0.018% of the solar energy received by the earth. Since the invention of solar cells in 1954, photovoltaic (PV) systems have gained the reputation of a reliable power source for space and certain terrestrial applications. Mankind's dependence on fossil fuels has negatively impacted the environment and is responsible for global warming. Photovoltaics offer a unique opportunity to solve the 21st century's energy and environmental problems simultaneously, because solar energy is essentially unlimited and solar cells can convert it into electrical energy without any undesirable impact on the environment. Thus, photovoltaic (PV) technology is an ideal clean and reliable renewable source of electricity generation for space and terrestrial applications. Currently, wafer based silicon (single crystal, polycrystalline and multi-crystalline) solar cells and thin film solar cells based on amorphous silicon, CdTe, $CuInGaSe_2$ (CIGS) and III-V semiconductors dominate PV manufacturing for terrestrial applications [3]. For future generations of solar cells a number of approaches are being explored [4].

PV manufacturing based on semiconductor substrates has its origin in semiconductor manufacturing and most of the thin film PV manufacturing (use of large glass substrate) has its origin in liquid crystal display (LCD) manufacturing. Based on an examination of the fundamentals of materials, devices, systems and the experience of semiconductor

 [DOI: 10.1117/1.3196882]
Received 8 Jul 2009; accepted 15 Jul 2009; published 16 Jul 2009 [CCC: 19342608/2009/\$25.00]

manufacturing, and LCD manufacturing, it is possible to predict which semiconductor materials will be used for future generations of solar cells. The objective of this paper is to critically examine the papers published in open literature and denote the suitability or non-suitability of the particular semiconductor material for manufacturing future generations of photovoltaic modules for terrestrial applications. In the following section, we provide the system level knowledge base which is essentially required to make PV systems a significant source of electricity generation. The importance of nanostructures for future generation of solar cells is discussed in Sec. 3. Concentrator and organic solar cells are examined in the following two sections. The discussion of the paper is presented in Sec. 6. We expect that PV devices will have the same impact in energy conversion in the 21st century as their counterpart complimentary metal-oxide-silicon (CMOS) has done for the information technology industry.

2 PHOTOVOLTAIC SYSTEM REQUIREMENTS

In order to create huge PV markets, the following selection criterion must be used in the selection of appropriate photovoltaic material: (i) no material supply constraint, (ii) low cost of ownership, (iii) low production cost, (iv) the prospect of further cost reduction, and (v) green manufacturing with no environmental safety and health issues.

2.1 No material supply constraints

Subsequent to the oil embargo of 1973 [5], a number of semiconductor materials were proposed as the potential materials for manufacturing solar cells. In 1980, I published an article on the economic requirements for new materials for solar cells and predicted that silicon is the best material for large scale PV manufacturing [6]. Over the last 29 years my prediction has been correct and more than 90% solar cells manufactured in 2008 were made out of silicon. Thus it is quite relevant to refer to our 1980 paper and re-write the rules for selecting photovoltaic materials. The key guidelines from a 1980 publication [6] are given in the following paragraphs.

When examining new materials, the cost of the raw material gives a good indication to the relative cheapness of the new material for a large-scale application. Whereas the cost of refining and purification can vary substantially from one material to another, the cost for industrial grade materials sets a readily available lower bound on the cost of the purely refined material. If the raw material is too expensive, then this automatically eliminates it from consideration. If the raw material looks cheap enough, then one still has to consider the cost of refining and purification when operated on the largest scale needed. When considering the availability of materials at a reasonable cost, one has to establish the rate of production required for the application and compare it to the current world rate of production as well as to the possible total availability of the material in the earth's crust. As shown in Fig. 1, a number of elements used in solar cell manufacturing have a very low level of reserve [7].

In order to assure that the use of the material in the photovoltaic application does not drive up the cost of the material, the additional uses for photovoltaic applications must be less than about 10% of the world production (studies of world production rates of minerals show that historically the production rate of any mineral has rarely grown faster than 10% per year).

For example, due to a high demand of poly-silicon, the price of poly-silicon went high in 2008 due to an increased demand and poor supply. Fortunately, due to an abundance of the raw material, the supply chain of poly-silicon has improved again. Recently, iSuppli Corporation has reported that due to increase in production of poly-silicon by 112% in 2009, prices will drop by half [8]. It might be argued that the world production of a particular material might be low because there is presently little practical use for the material. However, once a use is found production will increase. Another way of looking at the availability of materials is to examine their atomic concentration in the earth's crust. It should be noted that there is a strong correlation between the world production of a particular element and it's concentration in the earth's crust. However, the economic availability of an element is a more complicated matter than simply measuring its concentration in the earth's crust. The production rate of the element is tremendously influenced by what material the element is found with, its distribution in the earth and whether it is a byproduct of some other element can influence the production rate tremendously.

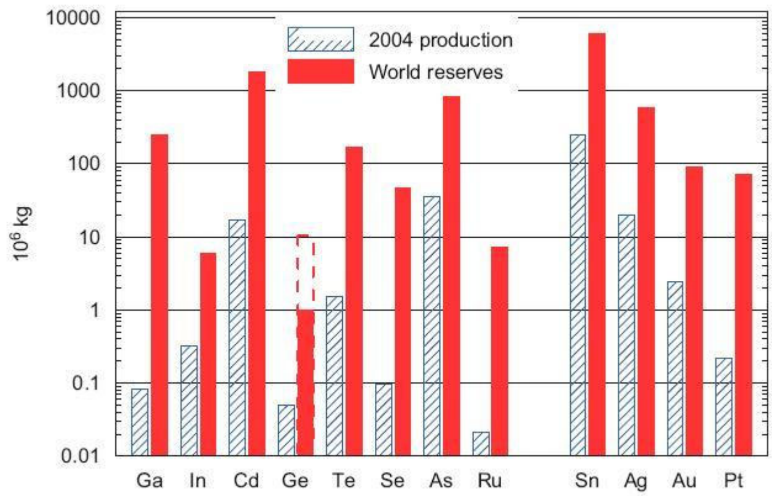

Fig. 1. Estimated 2004 annual production levels and material reserves for various materials used in the PV industry (*Courtesy of A. Freundlich, University of Houston*).

Based on the criterion listed for selecting a photovoltaic material, it is obvious that CIGS is not an ideal material. The supply of indium is very limited and the use of indium in PV will be in direct competition with the use of indium in display technologies. In the past 7 years the price of indium has gone up from about \$97/kg in 2002 to price of about \$400/kg in 2009. The concentration of indium in the earth's crust is extremely low (0.05 parts per million) [9]. The worldwide production of indium was 450 metric ton in 2005 and 490 metric ton in 2006. The production increase of about 6% is in line with our earlier statement that rarely there is an increase in the production rate per year of more than 10%. For manufacturing 1 GW PV modules, more than 20 metric ton of indium is required. Thus MW production of CIGS will not impact the increase of the price of indium; several GW productions of CIGS will have the same effect as the supply of polysilicon had on the increase of cost of PV modules in 2007 and 2008. Similar to our 1980 publication [6], concern has been recently expressed regarding the availability of gallium, indium and other elements [10]. In addition to the materials supply issues, the manufacturing technology of CIGS has a poorly established track record of cost reduction [11].

2.2 Low Cost of Ownership (COO) for manufacturing

Similar to the semiconductor and LCD manufacturing, photovoltaic manufacturing also needs huge capital investments. Ideally for a given technology the capital expenditures should be as low as possible. However, capital expenditure is only one component in the cost of ownership. Since the manufacturing of a PV module consists of a number of processing steps, the underutilization of equipment adds extra cost. Over the lifetime of the manufacturing facility, the equipment reliability, utilization, and yield of the PV modules have a greater impact on cost of ownership than initial purchase cost. The cost of ownership can be expressed by following expression [12]:

$$COO = \frac{CF + CV + CY}{TPT * Y * U},$$

where COO = cost of ownership, CF = fixed cost, CV = variable cost, CY = cost due to yield loss, TPT = throughput, Y = composite yield, and U = utilization.

The use of a roll-to-roll (RTR) process (similar to the process in which newspapers are printed) is a driving force to develop PV manufacturing processes with low capital expenditures. The success or failure of RTR and other similar processes depends on the yield of each process step and the resulting PV module yield. The above expression can be used to judge the suitability or non-suitability of a low-cost capital expenditure manufacturing process versus an alternate high-cost capital expenditure manufacturing process.

In the selection of an appropriate manufacturing process technology, process variability is one of the important issues. In other words, the power out of each device in a module and the power output of each module in a system must be as closely identical as possible. Due to series and parallel connections (to obtain a desired voltage and current), devices or modules with a minimum voltage or current will dictate the power output of the system. A sophisticated and expensive advanced process control (APC) in the manufacturing process will provide a lower cost of ownership than a low-cost statistical process control for a given process used in the PV module manufacturing. Relative to currently manufactured solar cells, the COO will be higher for nanostructure based solar cells.

2.3 Low production cost

As shown in Fig. 2, in the past the cost of PV has not decreased at a rate that is compatible to semiconductor and LCD industries. The PV industry has yet to capitalize on the concept of using large area substrates as the semiconductor and LCD industries.

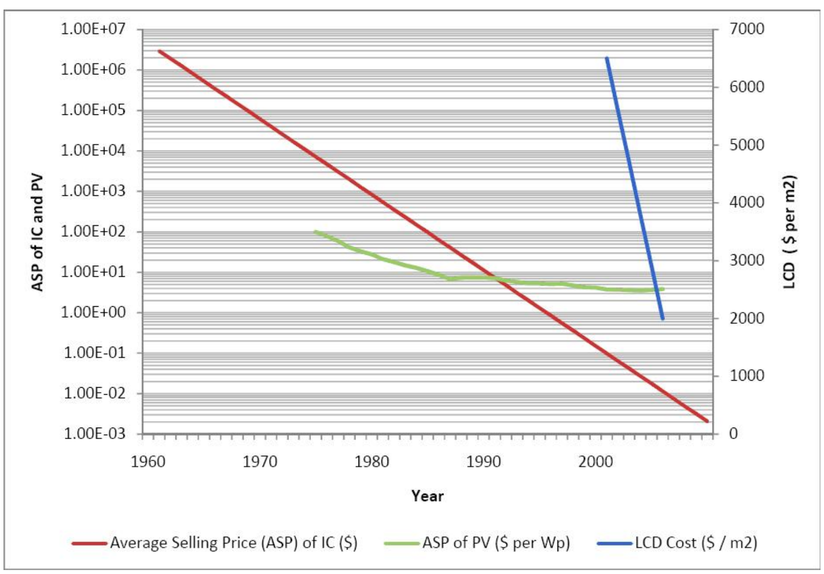

Fig. 2. Average selling price cost reduction of integrated circuit, PV and LCD products from 1960 to the present.

Currently the maximum silicon wafer diameter used by the PV industry is 200 mm, while a majority of the industry uses 150 mm square silicon substrates. Conversely, the semiconductor industry is currently using 300 mm diameter wafers with the expectation of using 450 mm diameter wafers by the end of next decade (Fig. 3).

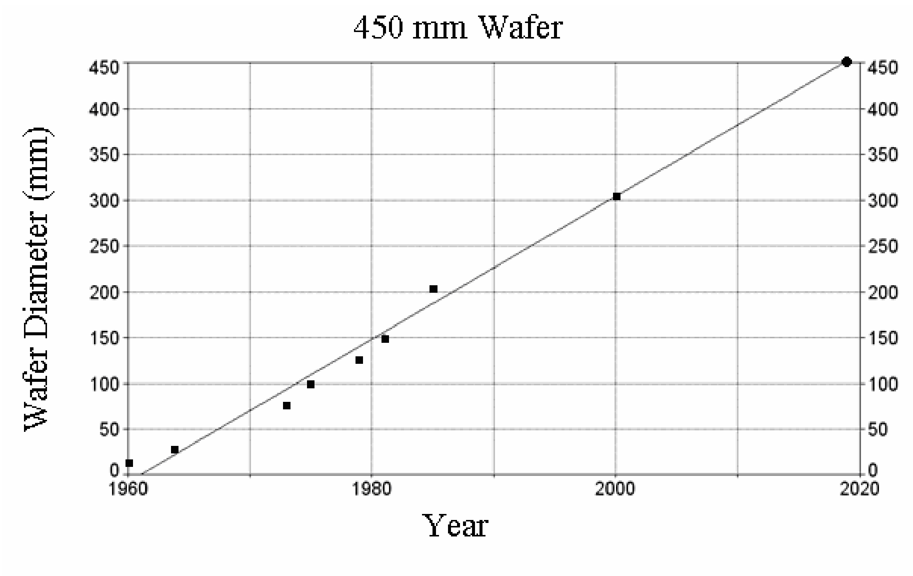

Fig. 3. For continuous cost reduction of integrated circuit manufacturing, the semiconductor industry has used larger substrates over the last 40 years.

Similar to the cost of transistors, the display cost has been reduced by using a larger and larger size of glass substrates. Fig. 4 shows that as compared to the silicon chip industry, the display industry introduces larger area substrates at a much faster rate [13].

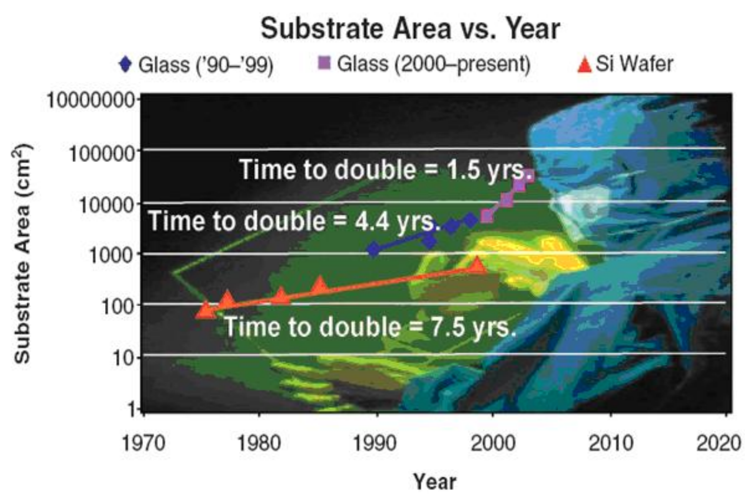

Fig. 4. As compared to the semiconductor industry, the use of a larger substrate is being adopted at a faster pace by the display industry (*Courtesy of P.L. Bocko, Corning East Asia*).

The experiences of both the semiconductor and display industries can be exploited by the photovoltaic industry. Adoption of manufacturing process similar to the display industry and the use of larger glass substrate will provide a major reduction in the cost of photovoltaic modules. There is no other renewable energy technology with the potential of cost reduction at the same magnitude that is possible with PV technology based upon large area substrates.

Other than the efficiency of PV modules, energy consumed in the manufacturing process, materials, gases and substrates cost, automation and throughput and yield are very important factors in the overall cost. Of course, factors such as low labor costs and low-costs of electricity also affect the cost of PV modules. The typical manufacturing cost relationship should be used to size the appropriate production capacity of the manufacturing process. An absolute control on the supply-chain and ultra large scale volume manufacturing are the principal requirements in reducing PV installed system cost to a level where generation of electricity is cheaper than other energy sources

2.4 Prospects for further cost reduction

Other than increasing the efficiency of the PV module, the manufacturing process should be capable of further cost reduction. For cost reduction of the PV modules, the change of substrate size with time by the semiconductor and display industries is the perfect choice for the PV industry. Currently, some amorphous silicon manufacturers are using glass substrates of the size of 5.7 m^2. Similar to the LCD industry, these manufacturers can increase the glass size to Gen 10 substrates with the area equal 8.7 m^2. Without inventing any new processes, the Gen 10 substrate size will provide further cost reductions similar to the LCD industry.

2.5 Environmental safety and health Issues (ESH) and green manufacturing

As compared to other methods of electricity generation, PV technologies have distinct environmental advantages for generating electricity over conventional technologies. Electricity generation by PV systems does not produce any noise, toxic-gas emissions, or greenhouse gases. Not only can photovoltaic energy help meet the growing worldwide demand for electricity, but it can do it economically and without any environmental concerns. Compared to burning coal, every gigawatt-hour of electricity generated by photovoltaics would prevent the emission of about 10 ton of sulfur dioxide, 4 ton of nitrogen oxides, 0.7 ton of particulates, and up to 1,000 ton of carbon dioxide.

The techniques used in PV manufacturing are quite similar to the $350-billion semiconductor industry. During the past 50 years, and despite the use of hazardous chemicals and tools, the semiconductor industry has developed processes for the safe handling of such chemicals, materials and gases. The PV industry has adopted handling of materials chemicals and gases in a way that is similar to the semiconductor industry. Thus from an environmental, occupational health and safety point there is no concern. The only material that poses a real concern is the use of Cd in CdTe based solar cells.

According to the Occupational Safety and Health Administration (OSHA) of USA, Cadmium is considered to be both toxic and a lung carcinogen. OSHA considers all Cd compounds (including CdTe) to be toxic. The efficiency of material utilization in CdTe solar cell formation ranges from a high of 90% for electrodeposition, to a low of 5% to 10% for spray pyrolysis. In addition to concerns about worker health and safety, public health may be affected by Cadmium. Chronic exposure to Cd compounds can occur when they are released to the environment as a by-product of different manufacturing steps or as a waste from the uncontrolled disposal of spent photovoltaic modules.

The seriousness of adverse effects of Cd can be judged from a recent study in China in which 58 villagers were diagnosed with high levels of cadmium. The Cd resulted from runoff from the factory razed by the government in 2004, which had contaminated the farmland and entered the food supply. The government study found that rice grown in the village contained amounts of Cd 20 times that of permitted levels [14]. Furthermore, in 2006, the European Union implemented a restriction of hazardous substances (RoHS) through a directive which limits the use of Cd less than 100 ppm by weight of homogeneous materials in electronic components [15]. Based on history of numerous lawsuits, businesses can be sued for adverse health effects years after workers left work due to illness. Therefore, serious health concerns must always constrain any use of CdTe solar cells.

Green energy must be generated using environment friendly materials and processes. Energy required for production of PV should be as low as possible, so that the energy payback time of PV systems would be less. Also manufacturing process should not produce any pollutants. For example, while nuclear energy produces no carbon emission during energy production, the storage of the Plutonium by-product remains a great threat to the environment. Therefore after the use of a solar module in the field, no harmful waste should remain.

3 NANOSTRUCTURES FOR SOLAR CELL APPLICATIONS

The nanostructures involve length scale of approximately 1 - 100 nm range. In this paper we will not differentiate between the approaches used in the fabrication of these structures. The issue of "bottom up" (atom by atom approach to build the required <100nm dimension) or "top down" (current lithography techniques used to reduce material dimension < 100 nm) approach will be dictated by throughput and cost related manufacturing issues. It has long been known that the properties of ultra-thin films differ from the bulk values. The invention of the scanning tunneling microscope in 1981 and the advancements in the silicon integrated circuits as well as other related semiconductor products (e.g. improved detectors with high signal-to-noise ratio) have accelerated the development of instruments with the ability to manipulate and analyze material on the atomic scale. Research in the nano-dimension material in the last decade has established the difference of properties of nano-dimension material from corresponding thin film materials. As shown in Fig. 5, at nanoscales the properties of material depend on the quantum-confinements.

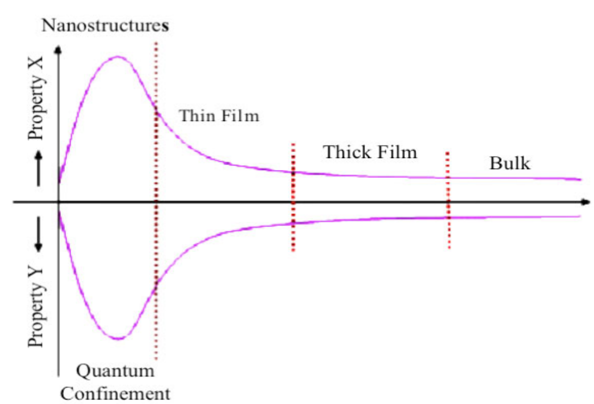

Fig. 5. Change in properties of any material due to its physical size.

The one-to-three dimensional nanomaterials provide unique opportunities to optimize a number of physical, chemical, biological, mechanical, electrical, optical and thermal properties of interest for future photovoltaic devices. The challenge is to integrate these unique properties of nanostructures and enhance the performance, reliability and yield of photovoltaic devices for manufacturing next generation of ultra low-cost photovoltaic modules.

4 CONCENTRATION SOLAR CELLS

We will use the technical and economical issues discussed in Section II to judge the suitability of concentrator solar cells. Benign solar density (about 75-100 mW/cm^2) prevents the reliable function of the PV system over 25 years. Due to the limitations of a number of currently available materials, the concentration systems have not provided a reliable cost-effective solution for terrestrial applications. For concentration systems, silicon solar cells can be used for low concentration (~1 to 5 suns). However, to date no one has provided an ultra-low cost concentrator system. For higher concentration (> 400 suns) GaAs solar cells are used. The typical cost of a GaAs based PV module is \$50,000/m^2. Also, to date, the economics of concentration cells for terrestrial applications has not been proven. Indeed, a number of concentration cell systems for large scale applications have failed (system complexity resulting in a number of unsolved materials and engineering issues). While the low concentrator silicon solar cells lack fundamental problems, the very high concentration of these solar cells results in cost related issues. Because of the myriad of engineering problems associated with high concentration solar cells yet to be resolved, the supply issue of Ga remains a serious problem [7, 10].

5 ORGANIC SOLAR CELLS

Organic solar cells are solution processed PV devices and are attractive due to a low processing temperature and simple fabrication techniques. After nearly three decades, organic solar cells have yet to become commercially viable. Poor electrical and structural properties and fast degradation under solar radiation are the fundamental problems preventing the widespread use of current organic solar cells. The major material problems with these cells are charge generation, geminate recombination, electric and magnetic field effects on charge separation and recombination, carrier mobility, polaronic effects, charge collection efficiency, organic semiconductors with optical gap in the near-infrared spectral range to better match the solar energy spectrum, interpenetrating morphologies, exciton range, and dependence upon film morphology [16].

To date, the best efficiency achieved for organic solar cells using a tandem cell structure for solar intensity of 20 mW cm^{-2} and 200 mW cm^{-2} are 6.7% and 6.1% respectively [17]. The device area was not mentioned in Ref. 17 and there are a number of issues related to manufacturing of these devices. However, the fundamental problem is reliability. After 100 hours of continuous exposure under one sun (AM 1.5), the solar cell efficiency degrades by 40% [17].

In 2001 [18] we critically examined the prospects of manufacturing organic semiconductor based integrated circuits and concluded that that there is no appropriate technology that can be implemented for a pilot-line production, eventually leading to mass-scale manufacturing. Fundamentally, the low thermal conductivity of polymer–semiconductor is a serious problem. Low-cost polymer deposition techniques (e.g. coating, electrodeposition etc.) have not provided the desired microstructural properties. With the present approaches under investigation, it is difficult to imagine the possibility of controlling the surface defects and voids which are detrimental to the performance device performance [18]. Similar arguments apply to organic solar cells. As we mentioned in Sec. 2.2, the low-cost film deposition techniques (e.g. roll-to-roll process) are quite attractive from a capital expenditures perspective. However the high defect density, makes the cost of ownership of manufacturing organic solar cells also quite high. Unless a new polymer is invented, manufacturing requirements discussed in Sec. 2 are met and reliability problems are solved, it is highly unlikely that organic solar cells will play any significant role in the future manufacturing of photovoltaic modules.

6 DISCUSSION

Other than manufacturing related issues, reliability is the main concern for organic and dye sensitized (DSC) solar cells. It is worth mentioning that the public and or private investment in a company does not mean that the investment will bring a product to the market and generate revenue. Due to a lack of knowledge in manufacturing challenges, investors often think of mass scale manufacturing as a trivial exercise and the company gets venture funding. Even for well established companies, the lack of necessary and sufficient data of defects, yield and cost of ownership can result in failure. Based on their research on such manufacturing processes, Motorola formed a subsidiary called Thoughtbeam in November 2001. The purpose of Thoughtbeam was to develop, sell and license its GaAs-on-silicon technology with applications to less-expensive optical communications, high-frequency radio devices and high-speed microprocessor-based systems. Due to the fundamental nature of defects densities at the interface of GaAs and silicon and an inability to deliver the desired device and circuit performance, Thoughtbeam closed it doors in January 2003 [19]. Lack of manufacturing experience also leads to wastage of millions of dollars. With an investment of at least $322 million, Optisolar also shut down operations due to manufacturing difficulties [20].

From the technical and manufacturing issues discussed in this paper, it is obvious that only silicon based PV manufacturing can provide sustained growth of the PV industry and can emerge as a low-cost viable source of electricity generation for the 21st century. The supposition is supported by four silicon PV technologies currently in manufacturing use (i) ultra high efficiency single crystal technology, (ii) medium efficiency poly- or multi-crystalline technology, (iii) amorphous silicon thin film technology based on the use of larger glass substrates (~5.2 m^2) and (iv) amorphous silicon technology based on flexible substrates. To control capital and manufacturing costs, large scale manufacturing (~ GW manufacturing at a single location) is a must. Thus, from the aspect of expense only amorphous silicon thin film solar cells based on the use of large glass substrates have the potential to reach the near-term goal of $3/Wp installed PV system cost. This will open a huge market for grid connected PV systems and related markets. Similar to cell phones, power generated by PV systems can reach over two billion people worldwide who have no access to clean energy. Further research and development of this approach can provide a cost of $2/Wp installed PV system in the next few years. The ultra high efficiency single crystal silicon PV modules will find a small niche market (in which small size PV modules are necessary due to the area available for installation). The amorphous silicon technology based on flexible substrates may find a niche market for consumer products. The medium efficiency poly- or multi-crystalline silicon PV modules (limited size of silicon wafer) will not be cost-effective as compared to large area glass based amorphous silicon thin film PV modules.

7 CONCLUDING REMARKS

In this paper we have presented the system level criterion for selecting semiconductor material for PV devices with the potential role of large scale green energy conversion. Only silicon based PV devices meet the criterion of manufacturing low-cost clean energy conversion (abundance of raw material and no environmental, health and safety issues) systems. With the use of large area glass substrates and using large scale (~ 1 GW per year at the same location) manufacturing technology similar to the LCD industry, installed costs of amorphous thin film solar cells based PV systems can be as low as $3/Wp without any new breakthrough in technology, thereby opening huge markets. Silicon based PV manufacturing will continue to provide sustained growth of the PV industry and will emerge as a low-cost viable source of electricity generation for the 21st century.

Acknowledgments

The author thanks Rupangini Singh for assistance in the preparation of this article. Thanks are due also to Godfrey Kimball for formatting and final editing of the manuscript.

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