EVOLUTION OF PHOTOVOLTAIC MATERIALS FOR RENEWABLE ENERGY DEVELOPMENT

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Keywords: solar cells, silicon, CIGS, CdTe, polymers, nanomaterials, photovoltaic

Contents

Summary

This article reviews the present status and possible future developments of photovoltaic (PV) materials for terrestrial applications. The principle of the photovoltaic conversion is first recalled. Then the physical and technical limitations of crystalline silicon and inorganic thin films (a-Si, μc-Si, pc-Si, Cu(In,Ga)(Se,S), CdTe) serving as absorbing materials for solar cell devices are described. Other potential materials to be used in

dye-sensitized solar cells and organic solar cells are also mentioned. Finally, advanced nanomaterials and concepts that can offer potential to high absorption, large carrier generation, and efficient separation towards very high efficiency solar cells are considered.

1. General Introduction

Photovoltaic technology (PV) exploits the most abundant source of free power from the Sun and has the potential to meet almost all of mankind's energy needs. Unlike other sources of energy, PV has a negligible environmental footprint, can be deployed almost anywhere and utilises existing technologies and manufacturing processes, making it cheap and efficient to implement. A Photovoltaic system contains individual cells connected in series or parallel to make a module that converts sunlight into electricity. Each cell (figure 1) is composed of a semi-conducting material (silicon Si, Gallium-Arsenide GaAs, Cadium-Teluride CdTe, Copper-Indium-Gallium-Selenide CIGS, polymers, molecules…), dielectrics and metal contacts. Light falling on the cell creates electron-hole pairs than are separated and flow towards opposite contacts, thanks to an internal electric field across the semiconductor. The intensity of the light determines the amount of electrical current each cell generates. The voltage is determined by the specific semiconductor material and its quality. The product of the current and voltage is the power output (quantum efficiency) from the cell.

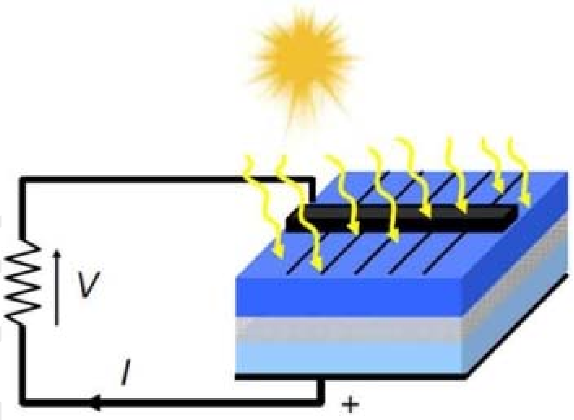

Figure 1: Schema of an illuminated solar cell

The maximum thermodynamic efficiency for the conversion of unconcentrated solar irradiance into electrical free energy in the radiative limit assuming detailed balance and a single threshold absorber was calculated by Shockley and Queisser in 1961 (Shockley et al., 1961) to be about 31%. For comparison, the efficiency of a system based on mineral resources is thermodynamically limited to about 30-35% at best, i.e. in the range of what can be produced by photovoltaic conversion now. There are many losses in single bandgap solar cells (Figure 2) but the two most important power loss mechanisms are the inability to absorb photons with energy less than the bandgap (5 in Figure 2) and thermalisation of photon energies exceeding the bandgap (1 in Fig. 2). These two mechanisms alone amount to the loss of about half of the incident solar energy in solar cell conversion to electricity.

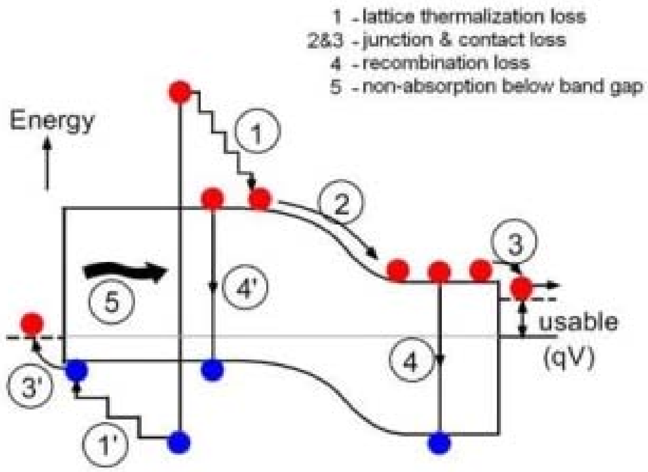

Figure 2: Loss processes in a standard solar cell: (1) lattice thermalisation loss of carriers generated by above band gap photons; (2) and (3) junction and contact voltage losses; (4) recombination loss (radiative recombination is unavoidable); and (5). non-absorption of photons below the bandgap.

Green (Green, 2003) proposed to distinguish among 3 generations of photovoltaic technologies (Figure 3). The “first generation” and currently dominating technology based on the fabrication of high quality and hence low defect single crystal photovoltaic devices (silicon wafers based), which have high efficiencies that are approaching the limiting efficiencies for single band gap devices but which use energy and time intensive techniques.

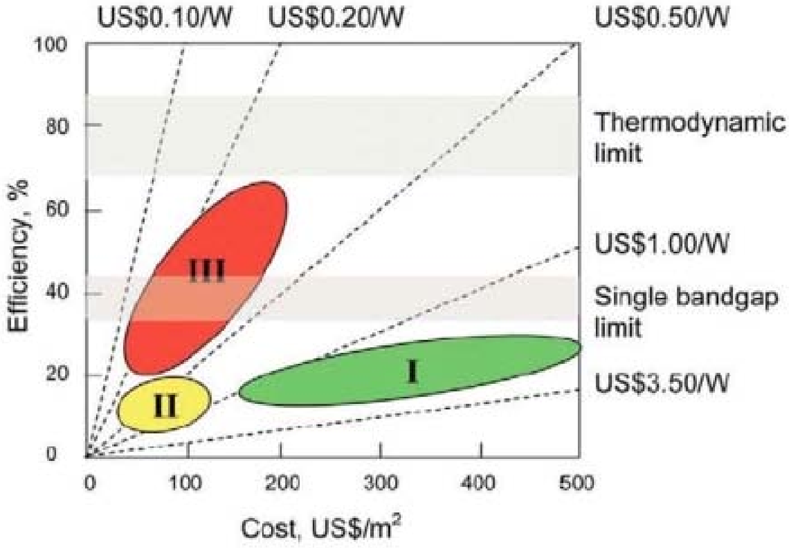

Figure 3: Efficiency and cost projections for first (I), second (II) and third-generation (III) PV technologies (wafer-based, thin films, and advanced thin films, respectively).

The generation II which uses thin films semiconductor materials and appropriate fabrication technologies that offer low materials consumption and large area modules.

This results in moderate efficiencies but low costs. Finally, the “third generation” approaches aim to achieve high efficiency for photovoltaic (PV) devices by circumventing the Shockley-Queisser limit for single-bandgap devices.

The concept is to do this with only a small increase in areal costs and hence reduce the cost per Watt peak. Also, in common with the silicon and CZTS based second generation thin film technologies, these will use abundant and non-toxic materials. Thus these “third generation” technologies will be compatible with large scale implementation of photovoltaics, and aims to decrease costs to well below the $1/W level of second generation towards US$0.20/W or better, by significantly increasing efficiencies but maintaining the economic and environmental cost advantages of thin film deposition techniques (see Figure 3 of the three PV generations, Green, 2003).

Before giving details about materials and technologies used for the photovoltaic conversion, let us start with some history: The first photoelectric effect was reported by Antoine Becquerel in 1839 who demonstrated the production of an electric current upon illumination of a cell composed of two electrodes from platinium and copper oxide and immersed in an electrolytic acid solution. In 1877 Adam and Day discovered the photovoltaic effect in selenium, and C. Fritts produced the first photovoltaic solar panel using such material. But it was only in 1905 that Albert Einstein published a paper to explain the mechanisms behind the photoelectric effect. He got the Nobel price in 1921 for this discovery.

Much later, in 1940, Ohl described the fabrication of the first p-n junction on silicon. But the tipping point of this solar–electric technology occurred in 1954 when D.M. Chapin, G.L. Pearson, and C.S. Fuller from Bell Telephone Laboratories announced a conversion efficiency of about 6% using crystalline silicon as a base material, thus demonstrating a strong potential for these solar-powered devices as real electrical power sources. Since then progress in materials quality, technology and quantum efficiency has been substantial and steady, thanks to the strong research in microelectronics and optoelectronics.

Figure 4 presents the research progress over the past 30–35 years of the best laboratory cell efficiencies for different materials and associated technologies as will be described below. The observed positive trend is a result of a progression of substantial and creative research and development improvement in materials, devices, fabrication, characterization, and processing, leading to better device performance and reliability. Some additional information can be drawn from figure 4:

- Almost a decade was necessary to approach the efficiency limit for a single bandgap material such as silicon, CIGS and CdTe.
- Multijunction cells such as InGaP/InGaAsP/Ge device grown using epitaxial techniques allow much higher efficiencies
- New devices such as dye sensitized cells (DSC), polymer based cells and copper zinc tin sulphide (CZTS) emerged recently and are progressing very fast, due to a huge effort deployed by research institutes and industry.

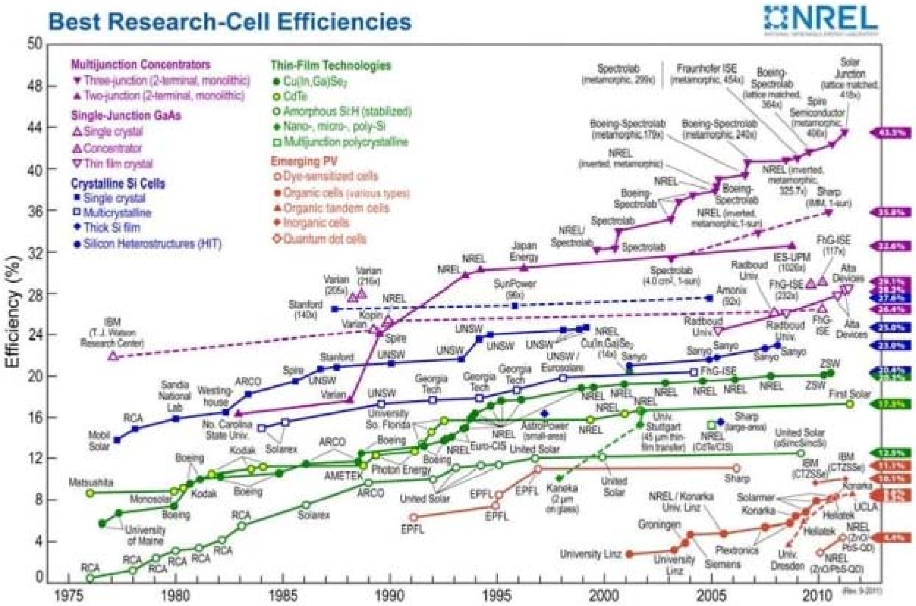

Figure 4. Efficiency evolution of best research cells by technology type. This table identifies those cells that have been measured under standard conditions and confirmed at one of the world's accepted centers for standard solar-cell measurements [source Kasmerski et al, National Renewable Energy Laboratory].

From the production point of view, Figure 5 presents the worldwide module shipments for the last decade. Since 1990, photovoltaic module production has increased more than 500-fold from 46MW to 23.5 GW of installed generating capacity in 2010, which makes photovoltaics the fastest-growing industry at present. In 2010, the world-wide photovoltaic production more than doubled, driven by major increases in installation in Europe. Thus the annual market volume of newly-installed solar photovoltaic electricity systems for 2010 varies between 17 and 19 GW, depending on estimates. This represents mostly the grid-connected photovoltaic market, as there are no reliable data available for the non grid-connected market. With a cumulative installed capacity of over 29 GW, the European Union is leading in PV installations. By the end of 2010, European photovoltaic installations provided more than 70% of the total world-wide solar photovoltaic electricity generation capacity. It can be noticed also from Figure 5 that the photovoltaic industry has changed dramatically over the last few years. China has recently taken over from Germany as the major manufacturing centre for solar cells and modules followed by Taiwan, Germany and Japan.

Another very important feature is the dramatic price reduction for solar modules by almost 50% since 2007. This can be explained by the evolution from a supply to a demand-driven market and the resulting over-capacity for solar modules. Business analysts predict that investments in PV technology could double from € 35-40 billion in 2010 to over € 70 billion in 2015, while they expect prices for consumers to continuously decrease. Though, the photovoltaic electricity price, of about 15–20 EU cents/kWh, is still too high for many grid-tied applications, it is approaching or has reached retail parity in some markets which have both large solar resources and relatively high electricity prices, these include south of Italy and some parts of

Australia. The price is still however for wholesale (central utility) generation, although one of the attractive aspects of photovoltaics is its modularity and appropriateness for distributed generation markets, helping to ensure continuity of supply for weak gridlines. Nonetheless continued price decrease and efficiency increase is needed to drive the competitiveness of PV technology to truly large scale implementation on the multi terra W scale. Intense effort is being employed by researchers and PV manufacturers to enhance significantly the efficiency at cell and module levels and to increase the throughput at the production level. The building of multi-GW markets moving toward the terawatt levels, and manufacturing plants to hundreds of megawatts are becoming more and more feasible.

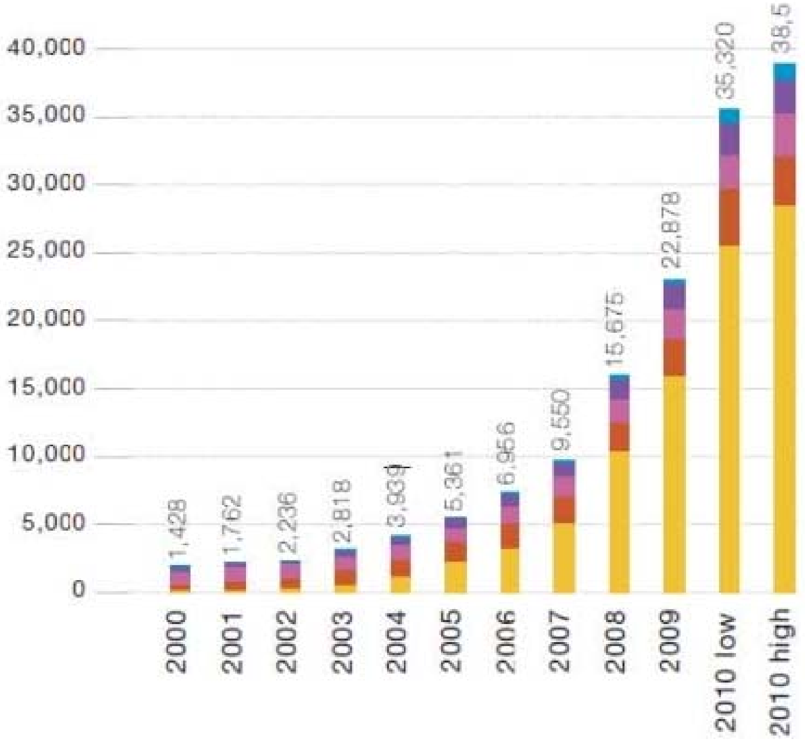

Figure 5. Global evolution of Photovoltaic installed capacity (in MW); from “Global Market Outlook for Photovoltaics until 2014”, EPIA, May 2010.

In order to maintain the high growth rate of the photovoltaic industry, different pathways have to be pursued. There is a need to reduce the material consumption per silicon solar cell because the cost of silicon is one of the main price factors of such devices. In parallel, the manufacturing of thin-film solar cells should be increased and the introduction of concentrated photovoltaics (CPVs) should be accelerated, including the use of cheaper concentrating lenses, typically made of plastic. For the long term, new compounds and advanced cell designs should be developed to produce very high efficiency solar cells.

This paper describes succinctly the current PV technology status with an emphasis on R&D needs and directions. Also future generation PV materials and concepts will be presented.

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Gavin CONIBEER received his BSc degree from Queen Mary College, London University in Materials Science; MSc from the University of North London in Polymer Science; and PhD from Southampton University, UK, in III-V semiconductors for tandem PV cells. Conibeer has held research positions at Monash, Southampton, Cranfield and Oxford Universities and has worked on III-V, II-VI, group IV and nanostructure materials for solar cells as well as PV systems and policy. He moved to his current location at the University of New South Wales, Sydney in 2002, where he is currently Deputy Director of the Photovoltaics Centre of Excellence and leads the Third Generation Photovoltaics group. Conibeer has authored 4 book chapters and more than 120 peer reviewed papers, which have been cited in excess of 800 times. Conibeer has been appointed a Future Fellow by the Australian Research Council (2012-2016).