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A REVIEW OF PHOTOVOLTAIC TECHNOLOGY FOR ELECTRICITY GENERATION

Abstract: *One of the most inexhaustible and the cleanest renewable energy resources is the solar energy. Photovoltaic (PV) technology is one of the finest ways for using the solar power. In the recent years, the world`s development of PV technology is growing very fast because of the technological development and government support for renewable energy. Photovoltaic is playing an important role to utilize solar energy for electricity production worldwide. The efficiency of solar cells is one of the important facts in PV technologies. This paper represents the review of the photovoltaic technology based upon the silicon solar cells. Also, the paper reviews the non-silicon photovoltaic technology, based upon Cadmium telluride (CdTe) and Cadmium sulphide (CdS), Copper indium gallium selenide/copper indium selenide (CIGS/CIS), Dye-sensitized solar cell (DSSC) and some new photovoltaic technology for PV cell production - Nanotechnology or ''third- generation PV''. Very important perspective of thin film PV technology is flexible modules, and this study will show that there is great perspective for development thin film building integrated PV products.*

Keywords: *Photovoltaic, Solar cells, Silicon technology, Non-silicon technology, New PV technology, building integrated photovoltaic*

1. INTRODUCTION

One of the most promising renewable energy technologies is photovoltaic (PV) energy conversion. PV energy conversion represents the direct conversion of sunlight into electricity. Commercial PV materials commonly used for PV systems include solar cells of silicium (Si), cadmium-telluride (CdTe), coper-indium-diselenide (CIS) and solar cells made of other thin layer materials. PV systems are still an expensive option for producing electricity compared to other energy sources, but many countries support this technology. Over the last five years, the global PV industry has grown more than 40 % each year [1].

PV is currently a technically and commercially mature technology able to generate and supply short/mid-term electricity using solar energy. However, the current PV installations are still small and provide only 0.1 % of world total electricity generation but through some market report indicated that PV installations are growing at 40 % average annual rate [2, 3]. Silicon is a leading technology in making solar cell, due to its high efficiency. But many researchers, due to its high cost, are trying to find new technology to reduce the material cost for production of solar cells and thin film technology can be seen as a suitable substitution.

However, the efficiency of this technology based solar cells is still low, and researchers are intensively making an effort to enhance the efficiency. [3,4]. Flexible modules are light-weight and suitable for applications where weight is important, and they offer a much faster payback than products based on conventional photovoltaics [5]. It is expected that they will play a very important role in the world PV market in the near future, especially for building integrated systems. In this paper the review of the photovoltaic technology based upon the silicon and non-silicon solar cells is given.

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Also the advantages and perspective of the flexible thin film photovoltaic technology for building integration are pointed out.

2. MATERIALS FOR SOLAR CELLS

2.1. Crystalline silicon

Silicon technology is the dominant one for the supply of power modules into photovoltaic applications. From all other solar cell materials, crystalline silicon based solar cell has the highest efficiency compared to others [6]. On top of that, silicon supply can be easily available since it is the second easiest raw material that can be found on earth. Crystalline silicon offers an improved efficiency when compared to amorphous silicon while still using only a small amount of material.
Most commercial Si solar cells have used boron-doped single-crystal wafers (around 400 lm thick) grown by the Czochralski (CZ) process. It is the standard process used for the needs of microelectronics. CZ Si is free from lattice defects; however, it contains residual impurities such as oxygen, carbon, and transition-metal ions. Oxygen introduced from a quartz crucible is beneficial for microelectronics, because the oxygen strengthens the wafers and can also be used for guttering defects from wafer surfaces. Oxygen reacts with the boron to form an electronically active defect that limits the quality of the material after illumination [7]. Magnetic confinement is used to reduce the amount of oxygen by transferring material from the crucible within the melt. Si grown by the float zone (FZ) process is the preferable method for solar cells of highest efficiencies because it has the lowest recombination losses.
Likely changes are an increasing proportion of multi-crystalline silicon and monocrystalline silicon being used for high-efficiency solar cells while thinner wafers and ribbon silicon technology continue to grow [8]. Braga et al. reviewed the recent advances in chemical and metallurgical routes for photovoltaic silicon production and found that production of (solar-grade silicon) SoGSi can be five times more energy efficient than the conventional Siemens process that uses more than 200 kWh/kg [9]. Keogh et al. suggested that testing of silicon solar cells under natural sunlight is simpler, cheaper, and more accurate than all but the most careful simulator measurements [10]. The brief overview of silicon crystalline materials is given below.

2.1.1. Monocrystalline silicon cells

In this process, high-purity, semi-conductor-grade silicon is melted in a crucible, usually made of quartz. Dopant impurity atoms such as boron or phosphorus are added to the molten silicon in precise amounts to dope the silicon, thus changing it into an n-type or p-type silicon. This influences the electronic properties of the silicon. A precisely oriented rod-mounted seed crystal is dipped into the molten silicon. The seed crystal’s rod is slowly pulled up ward sand rotated simultaneously. By precisely controlling the temperature gradients, rate of pulling and speed of rotation, it is possible to extract a large, single-crystal, cylindrical ingot from the melt. Occurrence of unwanted instabilities in the melt can be avoided by investigating and visualizing the temperature and velocity fields during the crystal growth process. This process is normally performed in an inert atmosphere, such as argon, or in an inert chamber, such as quartz [11].
This type of material has been widely used in developing PV cells due to its high efficiency compared to polycrystalline cells by 15%. Among other type of solar cell material, monocrystalline solar cell has highest efficiency with more than 20% but for commercialization, the efficiency claim from manufacturer are normally lies between 15 % and 17 %.

2.1.2. Polycrystalline silicon cells

Polycrystalline cell is a suitable material to reduce cost for developing PV module; however, its efficiency is low compared to monocrystalline cell sand other developing materials [12]. Even though, polycrystalline cell have low flaws in metal contamination and crystal structure compared to monocrystalline cell [13]. Polycrystalline silicon is produced by melting silicon and solidifying it to orient crystals in a fixed direction producing rectangular ingot of polycrystalline silicon to be sliced into blocks and lastly into thin wafer. However, final step can be abolished by cultivating ribbons of wafer thin ribbons of polycrystalline silicon. Polycrystalline manufacturing technology was developed by Evergreen Solar [14].

2.2. Amorphous silicon

Amorphous silicon is a non-crystalline form of silicon in disordered structure and has 40 times higher rate of light absorptivity compared to monocrystalline silicon [15]. Amorphous (uncrystallized) silicon is the most popular thin film technology with cell efficiencies of 5–7% and double- and triple-junction designs raising it to 8–10%. Some of the varieties of amorphous silicon are amorphous silicon carbide (a-SiC), amorphous silicon germanium (a-SiGe), microcrystalline silicon (mc-Si), and amorphous silicon-nitride (a-SiN). Tawada et al. developed a series of production technologies for stable 8% efficiency direct-super-straight-type modules along with large area a-Si deposition technique. Radue et al. [15] in their paper analyzed the degradation of three technologies of amorphous silicon which are single junction amorphous silicon, triple junction amorphous silicon and flexible triple junction amorphous silicon and found that each materials degrade by 45%, 22% and 27%, respectively.

2.3. Hybrid solar cells

Generally, the idea of hybrid solar cells is by combining crystalline silicon with non-crystalline silicon [16]. Higher ratio of performance to cost has been evaluated by the adopting amorphous silicon with crystalline silicon. One of the biggest solar cell manufacturers from Japan, Sanyo has developed a hybrid solar cell with 21 % efficiency. It is called as HIT (combination of Hetero junction and Intrinsic thin film layers solar cell). The base of this solar cell is n-type CZ silicon wafer that functions as a light absorber. Sanyo plans to commercialize this solar cell and plant production is on the way.

2.4. Cadmium telluride (CdTe) and cadmium sulphide (CdS) solar cells

This material can produce high efficiency, more than 15 % and is also known to give an ideal band-gap (1.45 eV) since the direct absorption coefficient is very high. A layer of cadmium sulphide is deposited from solution onto a glass sheet coated with a transparent conducting layer of thin oxide. This is followed by the deposition of the main cadmium telluride cell by variety of techniques including close-spaced sublimation, vapor transport, chemical spraying or electroplating [17]. CdTe solar cells have been used as low cost, high efficiency, thin-film photovoltaic applications since 1970. With the forbidden zone width of 1.5 eV and the coefficient of absorption 10^5 cm^{-1}, which means that a layer thickness of a few micrometers is sufficient to absorb 90 % of the incident photons, CdTe is almost an ideal material for solar cells manufacturing. CdTe solar cell is sensitive in the wave length of 0.3–0.95 mm and maximum of its sensitivity is in the wave length range of 0.7– 0.8 mm. Laboratory CdTe cells have the efficiency of 16 %, and commercial ones around 8 %. Great toxicity of tellure and its limited natural reserves diminish the prospective development and application of these cells. In order to improve CdTe solar cell characteristic, Soliman et al. [16] have conducted an experiment that prove the chemical heat treatment is needed to produce better cells.

2.5. Gallium arsenide (GaAs) solar cells

GaAs is a compound semiconductor form by gallium (Ga) and arsenic (As) that has similar structure as silicon. Compared to silicon based solar cells, GaAs has high efficiency and thickness is also less. Band gap energy for GaAs is 1.43 eV. Efficiency of GaAs solar cell can be increased by alloying it with certain materials such as aluminum, indium, phosphor and lead. Alloying process will result in formation of multi-junction devices and band gap values will also be increased [18]. GaAs is normally used for concentrator PV module and for space application since it has high heat resistance. In addition, GaAs is lighter compared to poly-and monocrystalline silicon. However, GaAs material and manufacturing can be costly [16].

2.6. Copper indium gallium selenide/copper indium selenide (CIGS/CIS) solar cells

This material is still in its developing phase since it is a new technology and is set to compete with other silicon solar cell. An efficiency of 13 % for modules and 20 % for cell has been recorded [15]. Its direct band gap can be as high as 1.68 eV with slight modification with Sulphur (S). Radue et al. [16] had conducted an experiment to asses CIGS solar cell performance and life time. The experiment had been conducted indoor (under STC) and outdoor for 4 months. It has been observed that the defects on the module will lead to a decrement in current collection. Meyer and van Dyk [19] also conducted an experiment to investigate the performance of CIS and other thin film material. The result from the experiment conducted is CIS only degrades by 10 % compared to other thin film material after an outdoor exposure of 130 kWh/m^2. Absorption coefficient of $CuInSe_2$ is greater than 10^5 cm^{-1}.

2.7. Dye-sensitized solar cell (DSSC)

Due to some problems with efficiency, production cost and environmental related issues of some solar cell materials, researchers have come up with ideas to produce new material technology call dye-sensitized solar cell. Generally, this type of material has five working principles which are (1) a mechanical support coated with transparent conductive oxides; (2) the semiconductor film, usually TiO_2; (3) a sensitizer adsorbed onto the surface of the semi conductor; (4) an electrolyte containing a redox mediator; (5) a counter electro de capable of regenerating the redox mediator like platinum [20]. Dye-sensitized solar cell will be a good competitor to the existing material technology in producing of solar cell.

2.8. New technology for PV solar cell

Other than searching for new material to improve solar cell output, new technology in processing PV solar cell has been ascertained. Nanotechnology or sometimes referred as ‘‘third- generation PV’’ is used in order to help increase conversion efficiency of solar cell since energy band-gap can be controlled by nanoscale components [21]. Nanotubes (CNT), quantum dots (QDs) and ‘‘hot carrier’’ (HC) solar cell are three devices used in nanotechnology for PV cell production. The advantages of using this technology are: (I) Enhance material mechanical characteristic, (II) Low cost, (III) Lightweight and (IV) Good electrical performances.

2.8.1. Carbon nanotubes (CNT)

Carbon nanotubes (CNT) are formed by hexagonal lattice carbon. One research team has invented photo diode solar cell from CNT and successfully improves efficiency and current output from that solar cell. Although the efficiency for solar cell is still low (3 – 4 %), many research will be carried out in this technology to improve the electrical output [13].

2.8.2 Quantum dots (QD)

Quantum dots (QD) can be described as a material that is built with many forms of material thus makes it a special semiconductor system with an ability to control band-gap of energy. Voltage output can be increased as band-gap energy size increases but on the other hand, smaller band-gap can also increase current output. As a solution, QDs are used since they can vary light absorption and emission spectra of light [22]. Efficiency of solar cells based on QD are easily influence by the defects on them.

2.8.3. Hot carrier solar cell (HC)

Hot carrier (HC) is a challenging method compared to CNT and QD because it needs selective energy contacts to convert light into electrical energy without producing heat. Its efficiency reaches 66% which is three times higher than existing cell made from silicon. But to this date, due to lack of suitable material that can decrease carrier cooling rates, HC has never been commercialized but remain an experimented technology [23, 24].

3. EFFICIENCY OF SOLAR CELLS

The efficiency of solar cell is one of the important parameter in order to establish this technology in the market. Presently, extensive research work is going for efficiency improvement of solar cells for commercial use. It is known that efficiency is a main parameter for establishment of PV technology in the market but some factors are affecting the PV efficiency. The main factors are (1) temperature of solar cell, (2) effect of dust on solar cells, (3) effect of humidity on solar cells [16].

Si cell efficiency can be divided into four stages, with each stage corresponding to new solutions in technology or cell structure. In the beginning of the "semiconductor era" (after the discovery of the bipolar transistor in 1948), the rapid progress of silicon technology allowed production of Si solar cells with 15% efficiency. In the second stage (1970s), 17% efficiency Si solar cells were fabricated due to achievements in microelectronics (e.g., photolithography). The most significant results have been obtained in the third (1980s) and fourth (2000+) stages, and Si cell efficiencies close to 25% have been achieved. These efficiencies were due to improved contact and surface passivation of the cell, along the front and rear surfaces, as well as an improved understanding of the significant role of light-trapping in Si devices [8].

The efficiency of monocrystalline silicon solar cell has showed a very good improvement year by year. It starts with only 15 % in 1950s and then increased to 17 % in 1970s and continuously to increase up to 28 % nowadays. According to [8], the role of light trapping in polycrystalline solar cell and improvement of contact and surface of solar cell help in increasing the efficiency. The polycrystalline solar cell also achieved 19.8 % efficiency to this date but the commercial efficiency of polycrystalline is coming in between 12 % and 15 %. Now-adays, GaAs has the highest efficiency among the all other solar cell materials with 40.7 % efficiency achieved in 2010. The new materials for solar cells i.e., dye-sensitized and organic base cells are still rated at low efficiency with only 5.4 % until 2010. The monocrystalline solar cell has 24.7 % efficiency, polycrystalline cells with 20.3 % and thin film technology with 19.9 % in 2010, respectively.

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Highly efficient plastic-substrate dye-sensitized solar cells (DSCs) by the press method were developed by Yamaguchi et al. [25]. The conversion efficiency of cell was improved by optimizing the press conditions, the thickness of the TiO2 layer and the surface treatment of the plastic-substrate. They achieved 8 % efficiency of such cells. Yamaguchi et al. also improved the efficiency of dye-sensitized solar cell to more than 10 % with the help of Series-connected tandem method. They optimized the dye combination, TiO_2 layer (structure and thickness), and electrolyte (TBP concentration) and successfully obtained an efficiency of 10.4 %, which was slightly higher than that of the black-dye single cell.

4. PERSPECTIVE FOR THIN FILM PV USE

The Building integrated Photovoltaics (BIPV) market, which got increased political support during the last years is still one of the big hopes for TF technologies. In this context, these modules have many advantages compared to c-Si ones: strongly reduced weight for the application to the building stock, see through property, adjustable optical transmittance, excellent building appearance, potential capability for applying flexible sub-strates, and less sensitivity to the degradation of light intensity and increasing temperature of the module [26].

4.1. Flexible solar cells

Very important perspective of thin-film PV technology is flexible modules with strategic space and military use, integration in roofs and buildings facades, and use in portable power sources, automobiles, and consumer electronics. Since they can be made in different shades, shapes, and sizes, these flexible a-Si solar cells are likely to be very popular and in demand for applications in the low to medium range of power.

The ultimate advantage of thin-film technology is roll-to-roll manufacturing to produce monolithically interconnected solar modules leading to low time for energy payback because of high-throughput processing and to low cost of the overall system. A large number of activities on highly efficient, stable, and flexible thin-film modules based on CIGS have recently drawn much interest for flexible solar cells on metal and plastic foils. Apart from the expected high efficiency and long-term stability for terrestrial applications, flexible CIGS has excellent potential for space application because of their tolerance to space radiation, being 2–4 times superior to conventional Si and GaAs cells. Flexible CIGS cells can be grown on polymide and on a variety of metals, e.g., stainless steel, Mo, and Ti, [26].

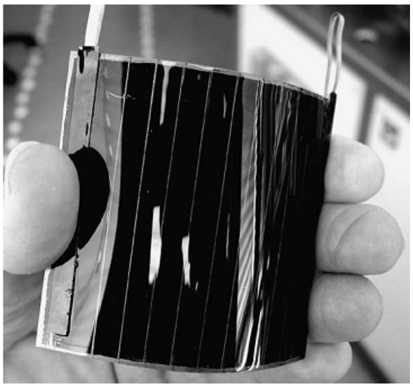

Figure 1. Monolithic integrated mini-module with 10 cells on Ti foil

On Fig. 1, a flexible prototype mini-module developed on polymer foil by ZSW and ETH (Zurich) within a European collaborative project is shown [5].

5. CONCLUSION

The worldwide energy consumption is increasing every year and different technologies are using to produce electricity to compete the energy demand. The environmental pollution is also a serious problem nowadays. Solar PV technology is growing rapidly in past decades and can play an important role to achieve the high energy demand worldwide. Huge amount of PV systems installed yearly shows the seriousness and the responsibility of every country about the issue to save the earth by using renewable energy. This paper illustrated about the worldwide status of crystalline and non-crystalline silicon PV technology for solar cells and their efficiency. Also the advantages and perspective of the flexible thin film photovoltaic technology for building integration are pointed out.

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