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## PHOTOVOLTAIC SOLAR CELL FROM LOW-COST THIN-FILM TECHNOLOGY

MOHAMMAD JAVAD OKHRAWI

*Department of Electrical Engineering, Faculty of Engineering  
Azarbaijan University of Tarbiat Moallem, Tabriz, Iran*

[mjokhrawi@yahoo.com](mailto:mjokhrawi@yahoo.com)

One of the main hindrances of using solar energy for electrical power supply is the high initial cost. Thin-film technologies hold considerable promise for substantial cost reduction for photovoltaic solar cells. The paper reviews the present state of the most advanced thin-film technologies. Amorphous silicon (*a-Si:H*) solar cells have surmounted the barrier to mass production. Pilot manufacturing lines are under construction for *CdTe* thin-film module. *Cu(In,Ga)Se<sub>2</sub>* has reached a record efficiency of 18.8% in the laboratory and pilot productions have been announced by various companies.

**KEYWORDS.** Thin-film technology, amorphous silicon, solar cell, microcrystalline silicon, cost reduction, efficiency, cadmium telluride, band gap, absorption

### 1. INTRODUCTION

Fossil energy sources will be depleted within the next few centuries, leaving only nuclear, direct and indirect solar energy sources to fulfill the energy needs of humanity. Renewable energy sources today cannot be competitively used in industrialized countries and the countries of the south as a rule do not have the economic resources, which would allow them to use renewable energy. If governments do not want to be centrally responsible for satisfying energy needs, they must create incentives, which will allow private business to invest into research, development and deployment of conversion systems, such as photovoltaic solar cells under the auspices of global competitiveness. The direct conversion of solar radiation to electricity by photovoltaics has a number of significant advantages as an electricity generator. That is, solar photovoltaic conversion systems tap an inexhaustible resource, which is free of charge and available anywhere in the world. In spite of various advantages in photovoltaic power generation, a big barrier impeding the expansion of large-scale power source application was the high price of solar cell module. Therefore, the cost reduction of the solar cell is of prime importance. To achieve this objective, worldwide efforts have been made in a wide variety of technical fields, from solar material, device structure, and mass production processes to photovoltaic over the past ten year. An improvement in cell efficiency is also directly connected to the cost-reduction in the photovoltaic systems [1]. A

series of technological efforts have been made on each step of the photovoltaic process, for example, anti-reflective coating and non-reflective texture surface [1].

### 2. THIN-FILM TECHNOLOGIES IN SOLAR CELL

The last years have seen a steady expansion of the production volume of PV modules and systems, which was accompanied by a considerable price reduction. The field is dominated by the traditional silicon wafer technology, which bases on single crystalline or multicrystalline wafers typically 200  $\mu\text{m}$  thick. In spite of reasonable progress, the barrier for further penetration of PV into the energy market is the high system price. A major cost factor of solar cells is the material itself. Therefore, there are strong efforts to reduce the sell thickness of Si-cells to values below 100  $\mu\text{m}$  and to avoid the sawing losses. Typical approaches in this direction are the use the EFG-material (Edge defined film Fed Growth), tricrystals or crystalline Si-thin-film cells. Considerable hops have been put on the use of thin-film semiconductors in a thickness in the order of 1 $\mu\text{m}$  [2,3,4]. The expectations from thin-film technologies are manifold:

- Reduction of material consumption and use of inexpensive substrate
- Simpler material and cell processing when the carrier collection length is short (typically 1 $\mu\text{m}$ )
- High productivity due to ability to large area deposition

- Monolithic cell integration
- New innovative cell structure such as multispectral cells or the use ultra thin absorbers
- Attractive new products e.g. applications in architecture

Thin-film solar cells require semiconductors which are able to absorb sun light effectively in a thickness of  $1\mu\text{m}$  or even less and which have band gaps as close to optimum value about 1.4 eV as possible. This lead to the well known direct semiconductors *CdTe* (1.45 eV).

Due to the indirect nature of the energy gap a thin-film cell of crystalline Si with an absorber thickness of a few  $\mu\text{m}$  requires excellent light trapping and back reflector structure. The development of these thin-film technologies started in the mid-seventies for *a-Si:H*, *CdTe* and *CuInSe<sub>2</sub>*. Meanwhile impressive efficiencies have been reported for laboratory cells: *a-Si:H* triple tandem 14.2% [5], *CdTe* 16.4% [6], *Cu(In,Ga)Se<sub>2</sub>* 18.8% [7].

These results underline the high potential of these techniques. In particular, it has to be emphasized that the CIS (Conductor-Insulator-Semiconductor) cell has penetrated into the range, which for a long time was only accessible to Si wafer technology. So far only the *a-Si:H* technology made it to mass production. Pilot and production line are planned or under construction for the *CdTe* and CIS technology by various companies. The crystalline Si thin-film solar cell is less far developed. Efficiencies of about 10% have been obtained both by using high-temperature CVD (chemical vapor deposition) and low-temperature plasma deposition [3,8].

### 3. AMORPHOUS SILICON (a-Si:H)

*a-Si:H* is most frequently deposited by plasma enhanced chemical vapor deposition (PECVD) using silane or gas mixture of silane and hydrogen with deposition rates of 0.1- 0.5 nm/s at deposition temperature of 150-200°C. The structure of the films is considered to be best described by a random network in which the tetrahedral short range order is maintained. The loss of long range order strongly affects the optical properties (Fig. 1). The absorption constant of *a-Si:H* is considerably larger than c-Si thus enabling effective absorption of sun light in a film of only  $1\mu\text{m}$  thickness. The films contain hydrogen in a concentration of 8-12%. This enables the growth of relaxed network and passivates deep defects. The most important defects are Si-dangling bonds, which act as effective recombination centers. In optimized undoped films the concentration of dangling bounds amounts to less than  $10^{16}\text{cm}^{-3}$ . Doping can easily be achieved by adding controlled amount of *B<sub>2</sub>H<sub>6</sub>* or *PH<sub>3</sub>* to the process gas [9].

Solar cells have been developed as both superstrate and substrate structure. In most commonly used superstrate cell the glass substrate is covered by a transparent conducting oxide (TCO) which leads to a structure (glass/TCO/P+-SiC/i-a-Si:H/n+-a-Si/metal). The substrate cell uses stainless steel (ss) with the inverted layer sequence (ss/Ag-ZnO/a-Si(n+)/a-Si(i)/a-Si(p+)/metal). In both cells the thickness of the active absorber layer, *a-Si:H(i)*, amounts to about  $0.5\mu\text{m}$  such that carrier collection occurs predominantly by drift

in the internal electric field. A major problem of the amorphous silicon technology has been the degradation of the amorphous films and devices under illumination. It is widely believed that the mechanism of defect formation is intrinsic to the material arising from disorder and the presence of hydrogen. Considerable progress has been made concerning increased stability of solar cells by proper device engineering. The strategy is to use stacks of two or three pin structures. It is important that the degradation of solar cells appears to saturate as a function of the exposure time (typically after 100h illumination with AM1). The use of stacks led to considerable reduction of this effect and to the ability to fabricate modules with a stable efficiency of 7.5% [5].

Fig. 2 shows the absorption spectra of various materials.

### 4. CRYSTALLINE SILICON THIN-FILM SOLAR SELL ON GLASS

The grain size of crystalline Si films deposited on foreign substrates is strongly determined by the process temperature. Using PECVD techniques at  $T < 300^\circ\text{C}$  one obtains microcrystalline Si ( *$\mu\text{c-Si:H}$* ) which is characterized by crystallites of 10-20 nm diameter. In a single-cell device structure, such material led to efficiencies of up to 8% [13]. A so-called micromorph tandem cell using  *$\mu\text{c-Si:H}$*  as bottom cell in a superstrate structure on glass has been developed with a stable efficiency of about 12% [13]. This concept makes use of the enhanced absorption of  *$\mu\text{c-Si}$*  at low photon energy Fig. 1.

Studies are underway to deposit material of larger grain size at higher temperature 350-650°C using laser- or solid phase crystallization, ion-assisted deposition techniques and deposition on precrytallized seed layers [3,8]. The best results obtained thus far is 10.1% on an area of  $1.2\text{cm}^2$  using a  $2\mu\text{m}$  thick absorbing layer [14]. This cell realizes efficient light trapping by surface texture that develops during the process and a textured multilayer back reflector. At present, the major issue is the deposition of material of reasonable electronic quality at a sufficiently high deposition rate.

### 5. CdTe THIN FILM SOLAR CELLS

From its basic physical-chemical properties *CdTe* is an optimum material for use in thin film solar cells mainly for two reasons:

1. The energy gap is direct and its value of  $E_G = 1.45\text{eV}$  has an optimum value for photovoltaic solar energy conversion.
2. It can be deposited with reasonable quality at high rate using various methods.

Above  $449^\circ\text{C}$  the stoichiometric compound is the stable solid [15]. Therefore the material condenses stoichiometrically as long as the substrate is held above this temperature. In this high temperature phase the films in general are p-type with a carrier concentration of  $p < 10^{15}\text{cm}^{-3}$  probably due to a slight Cd deficiency. The most commonly used solar cell structure consists of a *n-CdS/p-CdTe* heterojunction. The n-type *CdS* is

deposited using the same techniques as for *CdTe* onto glass which is coated with a TCO such as  $In_2O_3$  or  $SnO_2$ . The final step is the deposition of the back electrode. In this heterostructure *CdS* with its wider gap of 2.4 eV acts as window layer. Under illumination, the carriers are predominantly generated in the field zone and the carrier collection occurs by drift rather than by diffusion.

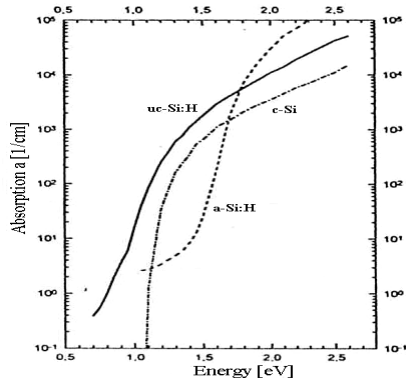


Fig. 1: Absorption spectra of a-Si:H,  $\mu$ c-Si and single crystalline Si [10]

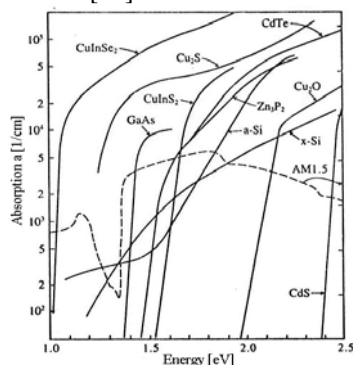


Fig. 2: Absorption spectra of various semiconductor material [12]

Various techniques have been used to prepare p-type *CdTe* films (1-6  $\mu$ m) of good quality:

- Sublimation/Condensation, modifications of this process namely CSS (Close Speed Sublimation) and vapor transport deposition
- Chemical spraying
- Electrodeposition
- Screen printing
- Chemical vapor deposition and sputtering

These processes have led to efficiencies in the range 10-16%. The world record of 16.4% has been obtained using the CSS technique at a substrate temperature of about 600°C which required the use of a borosilicate glass substrate [6]. Using less expensive soda-lime glass resulted at a lower efficiency of about 12% due to the lower deposition temperature [16]. Because of the high laboratory efficiencies and the high attainable deposition rates of up to 10  $\mu$ m/min the CSS technique appears to be well suited for production and in fact ANTEC GmbH (Germany) has announced to commercialize *CdTe*-solar cells (10MW/year) on basis of this technique [17]. In this process an extended carbon crucible contains granulated *CdTe* and is radiation-heated to about 700°C. The substrate is positioned or moved above the crucible and

kept at about 500°C. It is characteristic for this technique that the temperature difference and distance between source and substrate are kept small.

As *CdTe* is a direct semiconductor, a p-n junction generated inside a *CdTe* film would suffer from strong surface recombination. Furthermore, it is difficult to manufacture *CdTe* p-n junctions in polycrystalline thin films, as dopants would diffuse preferentially along grain boundaries. A heterojunction partner with wider band gap than *CdTe* allows light to enter the *CdTe* material more readily. This effect is called the "window effect". Around 1970 a new heterojunction was identified for *CdTe*, using *CdS* as n-type partner.

The *n-CdS/p-CdTe* heterojunction solar cell has to be illuminated through the *CdS* windows, so that the light is absorbed in the *CdTe* close to the junction. In the preferred fabrication procedure CSS – the *n-CdS* film is deposited onto a TCO (Transparent Conductive Oxide) film, typically  $In_2O_3$  and/or  $SnO_2$ . Next the *CdTe* is deposited onto the *CdS* and finally a low-resistance contact is made to the *CdTe* followed by a back electrode, which can be opaque [18]. Fig.3 shows the superstrate cell structure.

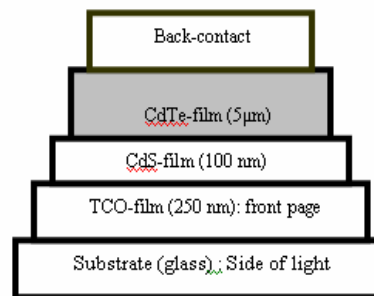


Fig. 3: Structure of the *CdTe/CdS* thin film solar cell

The production process consists of nine steps and the lamination process for hermetically sealing the thin film structures [18]:

1. Cleaning of the substrate (Float glass)
2. Deposition of the transparent contact ( $ITO + SnO_2$ )
3. Scribing of the TCO-film for cell definition and interconnection
4. Deposition of *CdS* and *CdTe* by CSS (Close Speed Sublimation)
5. Activation (improvement of junction by annealing in Cl-contacting atmosphere)
6. Etching for contact preparation
7. Scribing by mechanical tools for interconnection of cells
8. Deposition of back contact by sputtering
9. Scribing by mechanical tools for interconnection of cells

## 6. $Cu(In,Ga)(S,Se)_2$ THIN FILM SOLAR CELLS

These materials offering band gaps in the range (1.0-2.4)eV and high optical absorption have been particularly interesting for applications in solar cells. The most important and simple semiconductors among this family are  $CuInSe_2$  (1.0 eV),  $CuInS_2$  (1.4 eV) and  $CuGaSe_2$  (1.7 eV). Intermediate values of the band gap can be obtained by proper control of the film composition.

The most frequently studied and hence most advanced materials are  $CuInSe_2$  (CIS) and  $Cu(In,Ga)Se_2$  (CIGS) where some Ga-doping causes an increase in band gap.

Fig. 2 shows the most commonly used cell structure and the best results obtained in the laboratory so far.

The most advanced material is  $Cu(In,Ga)Se_2$  for which efficiencies above 15% have been obtained by various groups [2]. The highest efficiency ever obtained for a thin-film material of 18.8% [7].

A major breakthrough in device performance was the use of float glass (soda lime glass) instead of borosilicate or ceramic as substrate material. This led to the discovery of the beneficial effect of sodium doping which causes more pronounced p-type conduction and thus leads to a higher value of the open circuit voltage [19].

Ni,Al
ZnO:Al
ZnO
CdS
$Cu(In,Ga)Se_2$ :
18.8%; 678mV; 32.22 mA/cm <sup>2</sup> [7]
$CuInS_2$ :
12.8% ; 729mV ;24.3 mA/cm <sup>2</sup> [22]
$CuGaSe_2$ :
9.3%; 870mV; 14.8 mA/cm <sup>2</sup> [23]
Glass: A=0.3-0.4 cm <sup>2</sup>

Fig. 4: Scheme and device parameters ( $\eta, V_{OC}, I_{SC}$ ) of solar cell made of  $Cu(In,Ga)(S,Se)_2$

Fig. 4 shows the most commonly used cell structure and the best results obtained in the laboratory so far.

The development of the material with larger band gap opens new exciting perspectives. For instance,  $CuInS_2$  (1.5 eV) enables the fabrication of cells which are free of both toxic element Cd and Se. The wide range of energy gaps offers the chance to realize an inexpensive thin-film multispectral cell structure. A more efficient use of the sun light could in principle be obtained by combining cells of  $CuInSe_2$  and  $CuGaSe_2$  in a stack. Current work is focused on an improvement of the understanding of the complex materials, the development of the top cell and components of the tandem stack such as back contacts and tunnel junctions [20].

## 7. CONCLUSION

In spite of reasonable technological progress, thin-film technologies require intensive material research for a broader understanding of the growth processes, the material physics and the devices physics. Production lines are being set up which will answer the question whether the expectations of thin-film technologies can be fulfilled. The major question at the end is, as to whether such large area devices can be produced homogeneously on large area with high throughput. The competitiveness of any of the thin-film approaches at the end will be determined by the cost issue. In a recent study [21] it has been argued that thin-film technologies could drive the module manufacturing costs down to less than 1 ECU/Wp on a 60 MWp production level. It is particularly interesting that according to this study the costs appear to be very similar for *a-Si:H*, CIS and *CdTe*.

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