# Present Status and Prospects of Thin Film Silicon Solar Cells

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**ABSTRACT:** Extensive investigation on silicon based thin film reveals a wide range of film characteristics, from low optical gap to high optical gap, from amorphous to micro-crystalline silicon etc. Fabrication of single junction, tandem and triple junction solar cell with suitable materials, indicate that fabrication of solar cell of a relatively moderate efficiency is possible with a better light induced stability. Due to these investigations, various competing materials like wide band gap silicon carbide and silicon oxide, low band gap micro-crystalline silicon and silicon germanium etc were also prepared and applied to the solar cells. Such a multi-junction solar cell can be a technologically promising photo-voltaic device, as the external quantum efficiency of such a cell covers a wider spectral range.

Key words: Amorphous silicon, Microcrystalline silicon, Tandem, Triple solar cells, Conversion efficiency

## 1. Introduction

Thin film amorphous silicon based solar cells are one of the most promising low cost photovoltaic technologies. The hydrogenated amorphous silicon (a-Si:H) based alloy can easily be prepared by vacuum deposition under 13.56 MHz radio frequency (RF)[1-3] or very high frequency (VHF) plasma in plasma enhanced chemical vapor deposition (PECVD) system[4-6] with silane ($SiH_4$) and hydrogen ($H_2$) gas mixture. The a-Si:H alloy shows optical gap in the range of 1.72 to 1.85 eV. Alloying it with other suitable materials like oxygen, carbon, or germanium can create hydrogenated amorphous silicon oxide (a-SiO:H)[7-15], carbide (a-SiC:H)[16-20], germanium (a-SiGe:H)[21,22] alloys, where the first two are higher optical gap and the last one is lower optical gap materials respectively. For the a-SiO:H materials, the $CO_2$[7-10], $H_2O$[11,12], $N_2O$[13,14], $O_2$[15], etc can be used as source of oxygen, while $CH_4$[16-18], $C_2H_2$[19,20] etc source gases were found suitable for the a-SiC:H alloys. For the a-SiGe:H alloy, the $GeH_4$ source gas is generally used[21,22]. The variations in optical gap in these materials are helpful to design multi junction solar cell. In a multijunction cell, each of the component cells absorb a specific band of solar spectra. Double and triple junction solar cells were extensively investigated[23-26]. It is known that the light induced

degradation (LID) or the Staebler Wronski effect[27,28] in the intrinsic layer of amorphous silicon solar cell (or isolated thin film material) has been a challenge. There have been sustained investigation in reducing the effect of the LID as well and a considerable progress has been made in this direction[26,29]. It was suggested that a suitably fabricated high quality thin film can show considerably low LID[29].

Furthermore, as the amorphous materials have low conductivities, its micro-crystalline version shows better promise in that respect. Doped and undoped versions of these materials have also been extensively investigated. The p-type materials are fabricated with diborane ($B_2H_6$) source gas[30,31] while the phosphine ($PH_3$) is used for the source of the n-type dopant P[30].

## 2. History and present status of developing thin film silicon solar cells

Work on the amorphous silicon solar cells started decades back, and literature can be found on as early as 1961. The amorphous silicon based solar cells are of p-i-n type structure, where a thin intrinsic layer is inserted between two oppositely doped layers, in order to create an artificial depletion region, just like that in a p-n junction diode. However, the device efficiency was not significant even in 1976, around 2.4%[32]. Later on it was found that mid-gap defects in the material were the primary reason for the observed low efficiency in the solar cell. Due to the mid-gap defect states, most of the photo generated charge

carriers are lost by recombination. Nowadays, it is perceived that these defects may also accelerate the degradation of the material under illumination. These light induced metastable defects can be removed by thermal annealing. However, in case of a p-type a-SiO:H film, an UV light soaking shows an improvement in film properties[33].

It was also noticed that a single p-i-n solar cell can utilize only a part of the solar spectra, photon energy of which is higher than optical gap of the material. However, above band gap photons create hot electrons in the conduction band that thermalizes by releasing heat to the material and thereby significant loss of energy of the high energy photons. Furthermore, high energy (above band gap) photons have very short decay length within the material, for which observed external quantum efficiency (EQE) of the cell is also low. Long wavelength lights have insufficient absorption. So the EQE at the short and long wavelength range is low. A solution to this situation is multi band gap multi junction solar cell. Otherwise, in order to utilize long wavelength radiation a very thick solar cell was needed, but the LID of such devices was not favorable[29]. So series connected tandem and triple junction solar cells were preferred. Theoretical and experimental results showed that such a multi junction solar cell can perform better than its single junction counterpart, with wider EQE spectra and higher open circuit voltage[26]. Light induced stability of such solar cells was found to improve when the cell thickness is reduced. Thus splitting the wide frequency range solar spectra into two or three bands was found to be a useful approach. The top cell of a triple junction cell can utilize short wavelength radiation, the middle cell can use intermediate wavelength radiation and bottom cell of a triple junction cell can utilize low frequency radiation. The cut-off frequency of the solar spectra can be determined by optical band gap of the materials used in these component cells. Thus a need for wide band gap and narrow band gap materials were felt. The a-SiC:H[16-20], a-SiO:H alloys[7-15] were extensively investigated as wide band gap materials. In 1982, a report on the a-SiC:H based solar cell shows a high efficiency device can be fabricated with p-type and i-type a-SiC:H alloy[16]. For the same reason the a-SiO:H based alloys were also investigated extensively. In a p-i-n cell structure, the p-layer is deposited prior to i-layer and then the n-layer. Light enters through the p-type doped window layer. So, at the p-layer, the optical absorption should be low, thus wider optical gap p-type silicon oxide and carbide is suitable for solar cell.

Long wavelength light is less absorbed and less utilized in photovoltaic energy production. The standard AM1.5 solar spectra have considerable intensity at longer wavelength range. In order to effectively absorb this radiation, multi junction solar cells were proposed[23-26], where good quality thick micro-crystalline silicon can be used at the bottom cell[23]. But, the micro-crystalline silicon films are more expensive to fabricate than a-SiGe:H materials. The a-SiGe:H has lower optical gap and it was found suitable for the bottom cell of a triple junction solar cell. The optical gap of the a-SiGe:H can vary from 0.5 eV to 1.7 eV, depending on the Ge content within the film[21,22]. The solar cell with the a-SiGe:H is expected to have a lower cost and can effectively absorb wider band of solar spectra, thereby can show a broader EQE spectra.

For lower cost and better stability, thickness reduction of amorphous silicon solar cell is one of the important design requirements. However, this thickness reduction can also be associated to insufficient absorption of the sun light. Generally, a longer wavelength radiation has lower absorption coefficient, so it is the longer wavelength part of the radiation where EQE improves with light trapping. Theoretical analysis and experimental results show that the long wavelength response of the EQE can be enhanced by light trapping scheme[34-37,39]. The light trapping scheme is a specialized design in which the light is made to pass longer distance across the active layer of the cell making it more probable to get absorbed. This can be achieved with textured front surface, back reflection of the un-absorbed light to the cell with the help of a mirror or back reflector (BR) at the back of the cell[38-40] and back surface texturing. Most commonly, a textured front TCO is used as a superstrate in p-i-n type solar cell fabrication. Higher diffused transmission through such a TCO shows a better performance of the solar cell. However, surface texture may also lead to texture induced surface defects[37], so a special care may be necessary. The BR is usually fabricated with AZO/Ag/Al layer combination[41], where AZO is aluminum doped zinc oxide. However, it appeared difficult to texturize the back surface of the cell after the thin amorphous silicon layers were fabricated. So an alternate cell design was proposed, in which the n-layer is deposited first on a textured substrate and the p-layer at last, which is known as n-i-p structure of the solar cell[39,42,43]. The advantage of such a solar cell is that it can be deposited on a textured substrate where the BR is already fabricated. Thus, the problem of texturing the back surface can be overcome. If the size of the texture of the substrate is large then the cell surface structure gets modulated by the texture of

the substrate, whereby the front surface also gets texturized. The solar cell with light trapping scheme, shows better red response of the EQE and with this technology, the thickness of the cells can further be reduced.

## 2.1 Amorphous silicon solar cells

The schematic diagram of a single junction amorphous silicon solar cell is shown in Fig. 1. The a-Si:H based solar cell is one of the oldest of the thin film solar cells. The advantage with this cell is that it has high optical absorption coefficient, hence a thin a-Si:H layer may be enough for absorption of solar spectrum. The doped p-type and n-type layers create the built-in electric field across i-type layer. The photo-generated electron-hole (e-h) pairs are collected by the doped layers. However, some inevitable optical absorption at these layer take place, most significant of which is at the p-type window layer. In order to reduce such an absorption loss wide band gap p-type a-SiC:H and p-a-SiO:H layers were used in solar cell fabrication and improvement in cell characteristics were observed[8,9,16,26,31,33]. There are some fabrication related issues like defects at the interface that can be reduced to a great extent by using suitable buffer layers. Buffer layers are also used at the TCO/p, p/i, i/n interface[8,9,11-15,18-20]. Band gap gradient is also a useful technique to utilize wide band gap solar spectra, however, because of larger film thickness light induced stability of such cells may not be high.

## 2.2 Microcrystalline silicon solar cells

Micro-crystalline, or nano-crystalline silicon films can be deposited at a certain deposition condition, like high hydrogen flow rate[23,44,45], high plasma power[46] etc. It is believed that, for good quality films, mainly the $SiH_3$ type radicals should take part in the film deposition. The $SiH_3$ are the most favorable type precursors that have high surface mobility, which is favorable for deposition of a good quality films with low defect density.
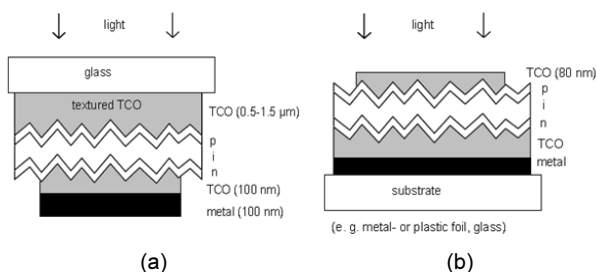
Presence of a large number of H radicals help to remove the defective sites at the film growing surface either by filling up the dangling bonds by Si-H bond formation or by removing the defective Si atoms from the film growing surface[47].

However, the micro-crystalline films show higher defect density, mainly because of micro-crystallite grain boundary[23]. These films have higher conductivity, so a thicker micro-crystalline layer may not degrade the cell performance, where fill factor may remain high. In tandem and triple junction solar cell, the micro-crystalline silicon layers have been used at the back[23-25].

Alternative to the wide band gap p-a-SiC:H and p-a-SiO:H layers was p-type micro-crystalline silicon. Such layers show its promising role in solar cells.

## 2.3 Tandem/Triple solar cells

A schematic diagram of a tandem and a triple junction solar cell is shown in Fig. 2. Structure of a solar cell gets complicated with increasing the number of component cells. Tandem solar cell consists of two series connected thin film solar cells made of materials with different optical gaps of absorption layer. Typical optical gap of the absorption layers of a tandem solar cell are 1.75 eV and 1.1 eV[48], while that of the triple junction cell are 1.75 eV, 1.45 eV and 1.1 eV[48]. One major requirement in a tandem and triple junction solar cell is the tunneling-recombination junction (TRJ) at the p/n interface (s). Because of p-i-n/p-i-n stacking in tandem and p-i-n/p-i-n/ p-i-n in triple
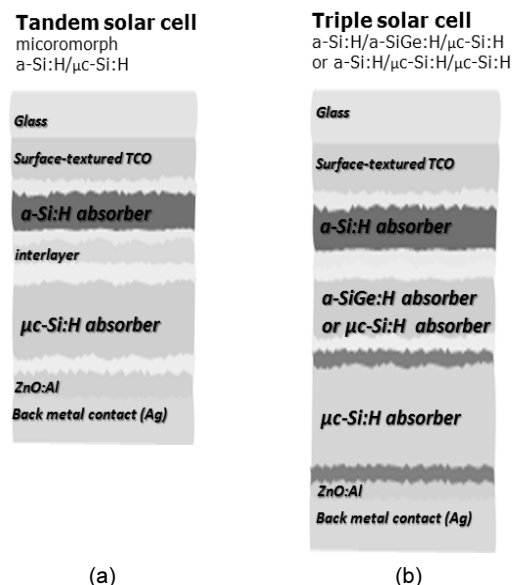


**Fig. 1.** The schematic diagram of single junction amorphous silicon solar cells (a) superstrate (p-i-n) structure and (b) substarate (n-i-p) structure



**Fig. 2.** The schematic diagram of (a) tandem junction silicon solar cell and (b) triple junction silicon solar cell

**Table 1.** Present status of conversion efficiency of thin film silicon solar cells

| Classification | Eff. (%) | Area (cm$^2$) | $V_{oc}$ (V) | $J_{sc}$ (mA/cm$^2$) | FF (%) | Test Centre (DATE) | Description |
|---|---|---|---|---|---|---|---|
| a-Si | 10.1±0.3 | 1.036 | 0.886 | 16.75 | 67 | NREL (2009/07) | Oerlikon Solar Lab. Neuchatel |
| nc-Si | 10.1±0.2 | 1.199 | 0.539 | 24.4 | 76.6 | JQA (1997/12) | Kaneka (2μm on glass) |
| a-Si/μc-Si (Tandem) | 11.9±0.8 | 1.227 | 1.346 | 12.92 | 68.5 | NREL (2010/08) | Oerlikon Solar Lab. |
| a-Si/μc-Si/μc-Si (Triple) | 13.4 | 1.006 | 1.963 | 9.52 | 71.9 | NREL (2012/07) | LG Elec. |

Source: Solar & Energy, July 2011 and NREL PV efficiency chart

junction cell, there is one and two p/n junctions inside the tandem and triple junction cells respectively. It is necessary to make the p/TRJ/n as Ohmic contact, so that the component solar cells acts in series. If improper TRJ is used, only one of cells may show its characteristic current voltage (I-V) curve, or an 'S' shape in the I-V curve[49].

## 3. Technologies for improving conversion efficiency of thin film silicon solar cells

There have been various technologies developed to improve performance of thin film solar cell[23-25,50,51], one most important of them in multi-junction structure of the device. In addition to the device structure, the a-Si:H based materials also needs to be improved with lower defect density, lower Urbach tail, and wide variation in activation energy of the doped and undoped layers. The VHF PECVD is very useful in that respect. Materials prepared in this technique show lower defect density. Micro-crystalline material can also be easily prepared in this plasma condition as well[3-6]. Hot wire CVD is also found to be promising because there is no ion bombardment damage of the film growing surface[18-20].

Advanced light trapping scheme, reduction of interface defects by using a suitable buffer layer, and low temperature deposition are few important aspects necessary for further improvement in device performance. In a n-i-p type solar cell structure the front as well as the back surface of the cells can be textured[39,42,43], with better properties at the p/i interface or reduced boron diffusion out of the p-layer.

## 4. Development of innovative thin film solar cells

There has been further innovative structure of the solar cells proposed, of which solar cells using Si nanostructures, such as

Si quantum dots and Si nanowires, have recently been attracting attention. A typical example of such a structure is a Si quantum dot superlattice (Si-QDSL). In the Si-QDSL, Si quantum dots are periodically arranged with an interval of 2-3 nm or less in a material with a band gap wider than that of Si. When several Si-QDSL thin films with different sizes of Si quantum dots are stacked, a wider wavelength range of the solar spectrum can be absorbed, and a marked increase in conversion efficiency of 40% or higher is expected to be achieved by using a multi-junction structure[52,53]. The various mechanisms have been proposed for quantum dot solar cells, such as quantum size effect, intermediate band, and multi-exciton generation[54-56].

Si nanowires (SiNWs) were first fabricated in 1964 by Wagner et al. at Bell Laboratories in the US using a vapor-liquid-solid mechanism[57]. Research on the application of SiNWs to solar cells has also been reported in recent years. The advantages of using SiNWs in solar cell structures are that the effect of light confinement due to light scattering can be obtained and that the band gap can also be controlled by the quantum size effect. A key issue to be addressed in this is the development of highly efficient surface passivation technology because SiNWs have a large surface area[58-60] and hence surface defects.

## 5. Conclusions

Hydrogenated amorphous silicon technology is continuously developing and it shows promise to become one of the most popular solar cell technology. Once a good quality, low cost, widely tunable optical gap of the amorphous silicon layer is used to stable solar cell structure, a concentrated radiation can be useful to produce higher energy with small sized solar cells.

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