REVIEW ARTICLE

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Progress of amorphous and nanocrystalline thin film silicon solar cell: a brief review

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Abstract

Crystalline-silicon (c-Si) solar cell dominates solar photovoltaic modules (PV) and acquires nearly 80% of total PV market due to its high conversion efficiency. But high production cost for fabrication of crystalline silicon solar cell forcible to think about its alternative substitute. Thin film technology for production amorphous-silicon solar cell for its low cost and ability of large area deposition made it suitable for large scale applications. However production of thin film hydrogenated amorphous-silicon (a-Si:H) solar cell is being commercialized and it takes up nearly 10% of PV market. But in single junction cells initial conversion efficiency cannot raise above 10% and its stabilized efficiency is again degraded by 25% from its initial efficiency. The light induced degradation of amorphous silicon thin film solar cell reduces the efficiency of the cell performance, hindrances large scale commercialization. To achieve the goal of high performance of conversion efficiency people are trying to combine amorphous silicon with its nano-crystalline/micro-crystalline counterpart. Solar cell based on a-Si:H and nc-Si:H have been the subject of interest. Current article is a brief review focuses on the significant advancement of thin film amorphous silicon solar cell technology by incorporating nano-crystalline silicon (nc-Si:H) in single and multi-junction a-Si;H thin film. Hydrogeneted nanocrystalline silicon thin film is composed of amorphous phase with few nanometer size crystalline Si grains. This nano crystalline/microcrstalline form of Si solar cell has been achieved significant performance in the efficiency than the conventional hydrogenated amorphous silicon solar cell. Incorporating nano form of si crystallites in amorphous silicon matrix opens up a new hope in solar cell industries. Though there is certain limitations by optimizing the device design and cell parameters researchers expect that nano crystalline thin film silicon solar cell may be the possible substitute of high cost crystalline silicon (c-Si) solar cell.

Keywords: thin film amorphous silicon solar cell, nanocrystalline solar cell, single junction, multijunction, cell performance.

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Introduction

To generate electricity from solar power photovoltaic devices have been developed. Different generations of solar cell devices also have been evolved. Among them hydrogeneted amorphous silicon solar cell (a-Si:H) has been extensively investigated for use as low cost solar cell and the thin film technology is mostly acceptable due to its cheap production cost. The low cost thin film amorphous hydrogenated silicon solar cell (a:Si:H) is very light, can be deposited on large area suitable for large scale application. This article have discussed about the performance of thin film amorphous silicon solar cell in combination with nanocrystalline silicon. Improved performance of modified thin film hydrogenated amorphous silicon (a-Si:H) with the incorporation of nanocrystalline form, in case of single junction, multijuntion solar cell has been reviewed in this article. Both initial and stabilized efficiencies of single/multijunction solar cell have been modified with the incorporation of nano crystallites form of silicon.

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Materials and Methods

Among thin film silicon solar cell only hydrogenated amorphous silicon solar cell (a-si:H) have been accepted for commercialization as the defects states in amorphous silicon can be passivated by hydrogen doping. Due to doping of hydrogen the dangling bond concentration decreases to values around~ 10^{15} to 10^{16} cm^{-3}.[1,2] But the main disadvantage is that the thin film hydrogenated amorphous

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solar cell suffers from light induced degradation. This material degrades under prolonged light soaking, which is the so called Staebler Wronski effect.[3] So its stabilized efficiency is of more interest than the initial efficiency. Due to its low conversion efficiency it is still remain far from large scale commercialization. A major challenge was face to develop a high quality thin film materials with low defect density.

Thin film hydrogenated amorphous silicon solar cell

Solar cell is a specially designed p-n junction diode which converts light into electrical power. But In case of thin film solar cell technology, an intrinsic layer (i-layer) with relatively low defect density is introduced between p and n type thin film form pin structure. The simplest type of single junction a-Si:H has the structure of glass/TCO/p-type a-Si: H/intrinsic a-Si;H/n-type a-Si:H/Al or Ag contact. The first amorphous silicon solar cells were made by Carlson D.E. and Wronsky C.R., 1976[4] with 2.4% initial efficiency. This cell had a simple pin diode structure, with the i-a-Si:H layer thickness~ 1 μm and doped layers of several tens of nanometers. This achievement initiated a period of increased interest in a-Si:H with rapidly increasing conversion efficiency. Matsui et al[5] demonstrates a record conversion stabilized efficiency 10.22% for single junction a-Si:H solar cell. The superstrate type structure of thin film amorphous silicon solar cell is depicted in Figure 1,

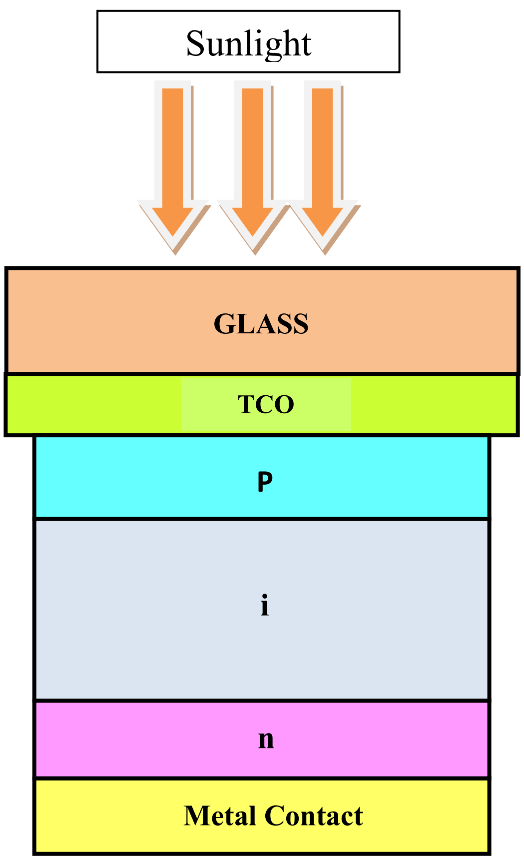

Figure 1: Single junction amorphous hydrogenated silicon (p-i-n) solar cell (superstrate type)

where Transparent conducting oxide (TCO) layer is deposited on glass through which light enters into the cell. TCO must be transparent like glass and conductive like metals .Tco layer act as the optically transparent front surface electrode allows photons into the solar cell and transports the photo generated electrons to the external device terminals. Mostly Indium Tin Oxide (ITO), zinc oxide (ZnO) is used as TCO in solar cell.

The light induced degradation can be partly solved in multi junction solar cell, which is made up of two or more sub cells with thin intrinsic layers of different band gaps to absorb light from different regions of the solar spectrum. To obtain high efficiency in a multijunction cell structure, some parameters are responsible. These are (1) high quality intrinsic layers of different band gaps, (2) doped layers with high conductivity and low optical loss (3) high conductivity and transparency of antireflection coating or window layers (4) proper current matching of component cells (5) High quality back reflection for efficient light trapping (6) low resistance tunnel junctions etc. So to obtain high efficiency different components of a cell have to upgrade its quality. Scientists are continuously trying to fulfill their requirements by modifying the component cells. But there are some limitations of stacking the several no of layers in formation of multijunction structure. Current mismatching between the component cells and losses in the junction cell restricts the choice of maximum no of cells that can be used without affecting the cell performance.

Small area with high stabilized efficiency of 13% in triple junction solar cells had been fabricated by the group of Yang J. et al.[6] Initial efficiency 15.2% of multi-junction a-Si:H based solar cells had also been fabricated by Yang J. et al, 1998[7] on

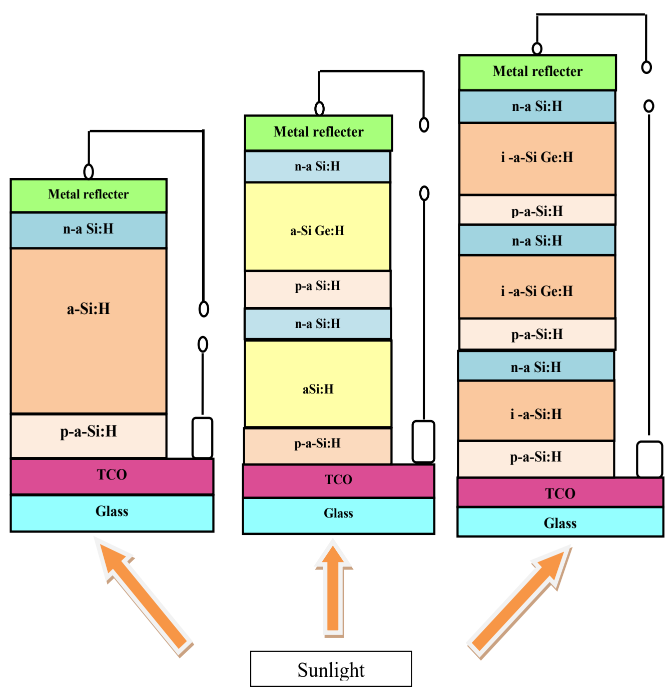

Figure 2: Various type of amorphous solar cell, single junction, double junction, triple junction (superstrate type) where light enters through Glass.

small areas.. Conversion efficiency of 13% was also obtained in tandem and triple junction solar cells [Green at al 2008].[8] Triple junction structure has been depicted in Figure 2.

These are superstrate type structure, where light enters through Glass. TCO (Transperent conducting oxide) is used as antireflection coating and also gives the low resistance contact to the doped layer. In triple junction the different intrinsic layers must be chosen with different bandgap. The top intrinsic layer a-Si:H(i-layer) has an optical bandgap of about 1.8 eV and captures the blue light. Intrinsic layer of middle cell is made up in combination of about 10% Ge with amorphous silicon (a-SiGe:H) lowers the bandgap of about 1.6 eV which is suitable for absorbing green photons. The i-layer of bottom cell is formed with combination of about 40% Ge with amorphous silicon. This reduces the bandgap (1.4 eV) and very much suitable to absorb red light.But device performance of thin film silicon solar cell is still low compared to other technologies. Matsui et al developed a novel deposition technique and has been able to achieve a record efficiency in single junction and multijunction solar cell.[9] Matsui concluded that fabrication of a perfectly stable a-Si:H with high efficiency is quite impossible as light induced degradation is still unavoidable.

Nanocrystalline silicon solar cell

Hydrogeneted microcrystalline silicon (μc-Si:H) or hydrogenated nanocrystallline silicon[10] has been evolved as a new light absorbing material exhibits better light sensitivity for longer wavelength (Wang and Lucovsky, 1990, Meier et al.,1994)[11,12] compared to hydrogenated amorphous silicon. The solar cell performance depends on the structural optical and electronic properties of the nanocrystalline material. Actually the nanocrystalline material consists of nanometer size crystallites clusters to form large grain size of micrometer embedded in amorphous silicon matrix. It is inhomogeneous materials comprised of an amorphous phase, crystalline grain and grain boundaries with a large range of crystalline volume fraction. With increase in hydrogen dilution the amorphous material become more ordered and beyond a certain critical dilution nanocrystallites (grain size 10-30 nm) are formed. Kondo et al (2005)[13] have systematically studied the nc-Si:H material properties at various deposition parameters such as high pressure, high power and high depletion regime. They reported that they have been able to get the efficiency of nc- Si:H single junction solar cell of 9.4 % at deposition rate 15 Å S^{-1} and 9.1 % at 23 Å S^{-1}

To improve the efficiency of hydrogenated amorphous silicon (a-Si:H) n-i-p solar cell in 2011 Zhangou Wang et al[14] fabricated a double layer p-type hydrogenated nanocrystalline silicon structure. A low hydrogen dilution buffer layer (i/p) and high hydrogen dilution p-layer formed a double p-layer structure. They observed that the thin film contains nanocrystallites of grain size 3-5 nm are embedded in amorphous silicon matrix. By inserting a buffer layer at i/ p interface the overall performance of the solar cell was improved significantly compared to the buffer less cell.

But light induced degradation is still present in nc-Si:H single junction solar cell reduced the cell efficiency. It is expected that multijunction structure can improve the stable efficiency. Due to difference in band gap between hydrogenated amorphous silicon (1.7 eV) and hydrogenated nanocrystalline silicon (1.1 ev) it has been used in multijunction solar cell. Combination of amorphous silicon with microcrystalline/ nanocrystalline form of thin film hybrid solar cell called micro morph. Micromorph is another possibility to offer better performance as the band gap between each component cell can be properly adjusted. Micro morph is a tandem device structure combining with a-si:H top cells and hydrogenated nanocrystalline silicon as bottom cell depicted in Figure 3. For lower band gap (1.1 eV) and higher absorption coefficient of longer wavelength of light it can also be used as a bottom layer of a multijunction solar cell. Unlike amorphous silicon solar cell microcrystalline/ nanocrystalline thin film has low light induced degradation also. Fischer et al., 1996,[15] Yamamoto et al., 2004[16] had been able to develop a double junction solar cell. Saito et al., 2005[17] and Kim et al., 2013[18] fabricated triple junction solar cell. Quadruple-junction silicon solar cells had been developed by Si et al., 2014.[19] Schüttauf et al., 2015 [20], Kirner et al, 2015.[21]

The maximum stabilized efficiency for micro morph was 12.69% obtained by [Matsui et al 2015[22] and 12.6% over large (1.43 m^2) area achieved by TEL solar trubbach Labs [A. Braga et al, 2016.[23] S. Guha[24] reported a revolutionary progress on hydrogenated nanocrystalline silicon solar cells fabricated at different deposition rates.. Yan et al 2006, achieved 14.1% initial and 13.2% stable active area efficiencies in a-Si:H/nc-S:H/nc-Si:H triple-junction structure. However their performance is still low compared to other technologies.

Deposition condition is also an important parameter for fabrication. An initial active-area efficiency of 10.2% was

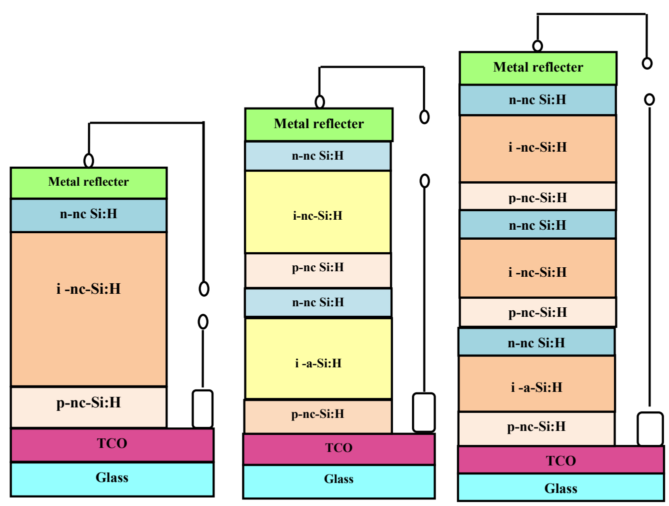

Figure 3: Represents (a) Single p-i-n junction nanocrystalline solar cell, (b) Double junction p-i-n solar cell, where bottom layer is of amorphous type and bottom layer is nanocrystalline (c) Tripple junction of intrinsic layer a-Si:H/nc-Si:H/nc-Si:H

achieved in a nc-Si:H single-junction cell deposited at ~ 5 Å /s. By changing the deposition rate at 10 Å /s; using same combination they obtained stabilized total area efficiency of 12.5%

A transparent and conductive p-layer based on nanocrystalline silicon oxide (p-nc-SiOx:H) is also widely used as p-layer for solar cell. For its highly crystalline fraction it reduces the optical parasitic absorption at shorter wavelengths results higher value of V_{OC} compared to conventional p-layer (p-a-Sic;H, p-aSiOx:H) and p-nc Si:H also. Abbas Belfar[25] 2021, showed that by using double p-type window layers based on nanocrystalline silicon oxide performance of single junction a-Si:H solar cell has been improved (simulated efficiency 10.21%).

Recently in 2019 a research team (Promad M. Rajanna et al)[26] declared a new film fabrication technique with 8.8% conversion efficiency (1 cm^2) by using newly developed p type transparent conducting film. They introduced a rational designed p type material which is appropriate alternative of conventional p type material. For hybrid thin film solar cells the conventional p-type layer was replaced by p type transparent conducting film. Here the modified p layer is constructed by a single-walled carbon nanotubes (SWCNTs) in combination with poly (3,4) ethylenedioxythiophene-polystyrene sulfonate (PEDOT:PSS), molybdenum oxide and SWCNT fibers. The single-walled carbon nanotubes (SWCNTs) are used as p-type transparent conductors with greater optical and electrical properties and the film is produced under room temperature. SWCNTs combined with MoO_3-PEDOT:PSS and SWCNT fibres forms a composite layer which acts as a window layer as well as front electrode to form hybrid thin film solar cells with amorphous silicon as active layer is described by the figure depicted below.

Light trapping plays an important role to increase the efficiency of nanocrystalline silicon solar cell by enhancing the weakly absorbed infrared light in thin film μc-Si:H layer. Textured front surface with pyramid structure of anti reflection coating layer reduces the reflection of the incident light so maximum light can be trapped. But excessively steep textures may produce crack on the nanocrystalline solar cell and reduces the conversion efficiency (Python et al 2008,[27] Python et al 2009,[28] Li et al 2009.[29]) To reduce the crack V shaped structure of textured surface was replaced by the U shaped structure, but still the crack is observed with increase the absorber layer thickness. Sai et al 2012[30] fabricated a honeycomb shaped periodic pattern of textured surface and applied to the nanocrystalline n-i-p solar cell. Effective light trapping of infrared light was possible by preserving the high quality crack less absorber layer. S. Guha et al 2009[31] studied the effect of texture in Ag/Zno back reflectors (BRs) on the performance of hydrogenated nanocrystalline silicon solar cells (nc-Si:H). By optimizing the texture design, the deposition of absorber layer, TCO, p/i interface layer, Matsui et al 2018[32] developed a better solar cell performance. While a larger texture provides a maximum light trapping, it also deteriorates the cell quality. Using optimized back reflector

Table 1: Performance of amorphous, nanocrystalline/ microcrystalline single junction, double junction and triple junction Solar Cell

Device configuration/ junction type	*VOC (Volt)*	*JSC (mA/ sq-cm)*	*FF*	*Initial Efficiency (%)*	*Stabilized Efficiency (%)*
a-Si:H	0.896	16.36	69.8	10.22	10
a-Si:H/ a-SiGe:H/ a-SiGe:H	2.357	7.721	74.3	14.5	13
nc –Si:H	0.548	29.39	73.1	11.8	10.2
a-Si:H/ nc –Si:H	1.342	13.45	70.2	12.69	9
a-Si:H/ nc –Si:H/ nc –Si:H	1.965	9.11	79.0	14.1	13.2

they had been able to get initial active area cell efficiency 10.2% in nc-Si:H single junction cell and a stable total area efficiency of 12.5% in a hydrogenated amorphous silicon/ nc-Si:H/nc-Si:H triple-junction cell.

Nanowire arrays and nano particles are emerging as alternative to the anti reflection coating layers (ARC) in enhancing the light absorption. Compared with pyramid type textured structure for Si solar cell, vertical aligned Si nanowires array has reached low front reflection (about 2%) along with efficiency 16.5% (Chen et al., 2010).[33] Using silver nano particle (Ag NP effective trapping of light can be made by creating oscillating dipole. Plasmonic effect hikes the value of short circuit current (J_{SC}) (Zolfhaghari Borra. et. al., 2014.[34])

Results and Discussions

Table 1 summarizes the J-V characteristics of several solar cell (single junction, double junction and triple junction solar cells in the initial and light degradation states where light soaked state was reached by light soaking under -100 Mw/ cm^2 of white light at 50^0C for over 1000 hours.

Single junction stabilized efficiency for hydrogenated amorphous silicon is 10% whereas using nanocrystalline silicon as active layer, efficiency increases to 11.8%. But still the stabilized efficiency of nanocrystalline solar cell is 10.2%. In case of double junction, combination with nanocrystalline and amorphous silicon solar cell, though there is increase in efficiency up to 12.69%, but there is no significant improvement in stabilized efficiency. In case of triple junction solar cell there is a significant improvement in stabilized frequency. A stable active area efficiency 13.2% was achieved with a-Si:H/ nc –Si:H/ nc –Si:H cell structure replacing conventional intrinsic middle layer (a-SiGe:H) and bottom layer (a-SiGe:H) by nanocrystalline silicon structure.

Conclusion

The production of practical alternative power source will demand highly efficient and inexpensive device to generate electrical power from solar irradiation, i.e. a green energy conversion device. The high defect density of a-Si:H film and its degradation under solar illumination still is a great impediment to increase the efficiency of the hydrogenated amorphous silicon solar cells and hence it faces a great challenge to the market dominance. By proper deposition condition that is applying low pressure and high hydrogen dilution deposition of nanocrystalline thin film of silicon is made possible. But for single junction solar cell, there is no significant improvement in the cell performance between amorphous and nanocrystalline silicon thin film solar cell. In case of multijuncition solar cell nanocrystalline film has been successfully used in either top layer or bottom layer or both the top and middle layers results a good performance. Again adopting an improved light trapping technique, weak absorption of infrared light in case of nanocrystalline silicon solar cell can be resolved. It is expected that attempt taken by the researcher to develop technologies to combine nanocrystalline with amorphous material (a-Si:H) will achieve a better performance in upcoming future. A thorough research is necessary for further progress. By optimizing the device design or by using nano-structured materials instead of conventional transparent conducting oxide in amorphous /nanocrystalline solar cell thin film technology will play a significant role.

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