A Review of Different Techniques for Improving the Performance of Amorphous Silicon based Solar Cells

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ABSTRACT

Hydrogeneted amorphous silicon (a-Si:H) based solar cells are promising candidates for future developments in the photovoltaic industry. In fact, amorphous silicon technology offers significant advantages including low cost fabrication and possibility to deposition on flexible substrat as well as low temperature fabrication. Much progress has been made since the first single junction cell in amorphous silicon made in 1976 by Carlson and Wronski. However, the performance of the solar cells based on a-Si:H is limited by the high defect density and degradation induced by exposure to light, or Staebler-Wronski effect. To become competitive, the performance of the solar cells based on a-Si:H must be improved. In order to improve the performance of a-Si:H solar cells, much research is directed to optimization techniques. The improvement in performance is therefore based on the optimization of the different layers of the solar cell, in particular, the window layer and the absorber layer (intrinsic). The aim of this work is to give an overview on the different techniques and strategies that is used to improve the performance of solar cell. This work is therefore focus in three main areas: first, optimization of window layer, in particular, the p/i interface using wide band gap alloys such as a-SiC:H, second development of high quality absorber layer using band gap engineering, and alloys such as a-SiGe:H. last, optimizing n-type layer and i/n interface.

I. Introduction

Since the discovery of the first a-Si:H solar cell by Carlson and Wronski in 1976, hydrogenated amorphous silicon (a-Si:H) received a lot of attention as enabled manufacturing of a-Si:H solar cells. Thin film silicon solar cells have the potential to be a low-cost alternative for crystalline silicon solar cells. Moreover, the fabrication technique requires less energy as they are processed at low temperature (150±C-300±C). Amorphous silicon (a-Si:H) becomes an interesting semiconductor for photovoltaic applications due to their high optical absorption coefficient, adjustable band-gap (from 1.6 to 1.8 eV) and low temperature of deposition [1]. Moreover, the optoelectronic properties of a-Si:H have been influenced by alloying with other materials like oxygen, carbon, germanium …etc. Alloying a-Si:H with germanium aims to have a narrow bandgap. So, the optical bandgap (Eg) can be adjusted from 1.7eV to 1.0eV by increasing the Ge content in the material. In contrast, Alloying with oxygen or carbon could be increased the bandgap. Furthermore, the photoluminescence and the line width of a-Si:H alloys increase as a function of the optical bandgap [1,2].

However, the performances of a-Si:H solar cells is limited by high defect density and light-induced degradation, hence, the efficiency can drop 10%-30% with respect to initial efficiency [2]. Infact, the disordered atomic structure and high defects density of a-Si:H influed on the physical limits and efficiency limits of the performance. According to Green [02], the performance of a-Si:H solar cells is well below fundamental conversion efficiency limits. Although Jsc and Voc have potential of improvement too, the FF contributes most to the difference between device performance and potential. While high-efficiency a-Si:H solar cells have a FF above 75% and an efficiency above 11% (initial), the FF and consequently the efficiency drop by typically 10–20% within the first few months of operation.

It is clear that the solar cell efficiency is determined by the three factors of Jsc, Voc, and FF. Their values are affected by many material properties and device structures.

Table 1. Theoretical limits and performance of laboratory-scale record-efficiency single-junction solar cells: short-circuit current density (**Jsc**), fill factor (FF), open-circuit voltage (**Voc**), and stability.

Performance	Limits	Record	Techniques
Voc (volt)	>1	0.8	Window layer and p/i interface optimization (wide band gap p-i interface layer.) n-type layer band gap optimization and i/n grading
Jsc (mA/cm^2)	20	15	light-management techniques High qualité Absorber layer (bandgap grading, using low band gap a-Si:H alloy)
FF (%)	76	72	Absorber layer (bandgap engineering) Optimizing p/i and i/n interface and doped layers

The stability of a-Si:H solar cells is strangly depend on the light-induced degradation (Staebler-Wronski effect SWE). So, SWE leads to a significant initial efficiency drop that is accounted for in advertised efficiencies; on long-term, the degradation of a-Si:H solar modules is linear and with about 1%/yr close to other solar technologies [3].

Several research of a-Si:H solar cells has conducted for 40 years and a significant progresses have been made by the international community. Because of the complexity of the material structure, a-Si:H material provides one of the best platforms for fundamental studies (such as the microscopic material structures, electronic structure and defect states, the carrier transport, and metastability) in order to enhance the performance of a-Si:H solar cells.

II. Optimization Areas

The p-i-n type diodes have been widely used in photovoltaic solar (PV) energy conversion. The designed amorphous solar cell includes three original parts. In the optical model, intrinsic amorphous silicon is sandwiched between p-doped and n-doped materials to the excellent separation of the carriers into free charges because of the electric field at the p-n junction. Incident light that falls on the diode is absorbed in the intrinsic layer and electron-hole (e-h) pairs are generated, producing the PV or electrical energy, while the p-type and n-type layers produce built-in electric field to separate the e-h pairs, created in the i-type layer.

II.1. Window Layer

Several possibilities exist to improve the conversion efficiency of a solar cell. The interfaces between the window materials and the intrinsic layer (active) must be of good quality. Thus, a p-type wide bandgap semiconductor material can be used as a window layer to improve light transmission. This same layer must be having a high conductivity to increase the electrical potential in the structure and reduce the effects of series resistance. This leads to a better concordance between the different layers of the structure.

- **p-type layer**

It is well known that the open circuit voltage (Voc) and the short circuit current density (Jsc) strongly depend upon the thickness of p-layer in a p-i-n a-Si solar cell. This dependency is caused by homogeneity and large optical absorption p-type a-Si:H. Amorphous silicon carbide has a large optical band gap than a-Si:H so that the photovoltaic performance dependence on the thickness of p-type a-SiC:H may be different from the case of a p-type a-Si:H [5]. It was demonstrated in the 1980s that application of the p-a-Si$_{1-X}$C$_X$:H alloy leads to improved performance of a solar cell with better blue response of its quantum efficiency (QE). There are few other well known wide band gap alloy materials available, however one interesting advantage of the p-a-Si$_{1-X}$C$_X$:H is that both the C and Si are four fold coordinated atoms, and hence a suitably prepared material may attain wider optical gap with good stability [2]. Furthermore, p-type a-SiCx:H and an i-a-SiCx:H buffer layer are used as wide-bandgap material in a-Si:H solar cells, providing a tunable bandgap in the order of 2 eV for higher Voc and reduced absorption at low wavelengths compared to a-Si:H layers without carbon, which leads to higher conversion efficiencies. It has been found that the best structure must have a thin window layer, and a doping higher than 10^{19} cm^{-3}. The considerable initial conversion efficiency reaches to 11.52% [7, 11].

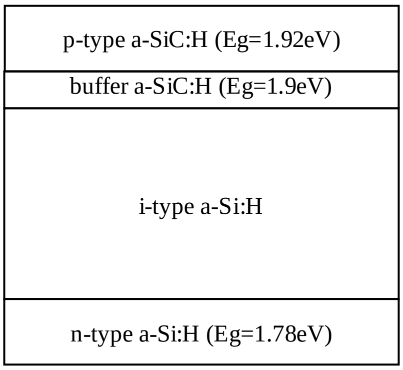

Fig. 1. Structure of p-i-n single-junction solar cell based on a-Si:H alloys: (a) a-SiC:H as window layer (p and buffer layer),

Because of the low mobility holes (about 1/10 th) compared to the electrons in a-Si:H material. Since the optical generation in the i-layer is larger on the light-entry side, the holes must traverse a shorter distance to the p-layer. Also the higher gap of a-SiC:H p-layer reduces the absorption of high energy blue wavelengths, allowing a light above blue to be absorbed into the active layer.

- **Optimizing the p/i junction**

As montionned above, The use of a-SiC:H alloy as buffer layer at p/i interface provide a built-in field to assist in hole collection and thereby achieve good performance for the solar cell. Moreover, the combination of a-SiC:H alloy as widow leads to a reduction in light induce degradation of the cell to ~10% as opposed to over 20% for a standard cell [3]. In fact, the problem of combination at p/i interface and the stability of amorphous silicon (a-Si:H) solar cells upon light soaking has been a major problem. Various methods have been used to reduce such degradation in a-Si:H solar cells, including the use of a-Si:H alloys [3]. In order to improve the performance of a-Si:H solar cells, much research is directed to light-management techniques. Improved p/i junction (interface) leads to a higher short-circuit current density. Another approach to improve the performance of a-Si:H solar cells is by increasing the Voc. The Voc depends on not only the bulk properties of the absorber layer but also the p-i interface region due to high recombination at this heterogeneous interface [3]. The p-i interface is a hetero-junction with band offsets between the valence and conduction bands of a wide band-gap p-type and an intrinsic a-Si:H layer. One strategy to reduce recombination in the p-i region is by optimizing the material properties of the p- and intrinsic layer. Hydrogenated amorphous silicon carbide (a-SiC:H), fluorinated microcrystalline silicon p-layers, and other materials have been investigated as p-type window layers. Some simulation works have already achieved a Voc of greater than 1 V for their n-i-p type a-Si:H solar cells [2,11,12].

The complexity of interfaces between the thin layers, often not more than a few nanometers thick, governs to a large extent the performance of a-Si:H solar cells. Further complexity is added by bi-phase materials such as microcrystalline/amorphous phases or mixed-compound materials such as silicon-oxides. In both cases, small changes in the deposition conditions or even substrate have a tremendous influence on the film, interface, and device properties. There has been huge effort in the understanding and improvement of interfaces between intrinsic a-Si:H, doped a-Si:H, and the contact layers on either side in the last years, and we estimate the potential for further improvement of solar cell efficiencies by interface modifications larger than that of bulk properties of a-Si:H, which are limited by the amorphous nature.

In addition, the insertion of non-doped a-SiC:H at the p/i interface (buffer layer) is important to enhance the absorption in p-i-n solar cell based a-Si:H, and reduction the recombination at p/i region. So, we focused in this section on a-SiC:H buffer layer at the p/i interface in order to improve the performance of p-i-n solar cells based on a-Si:H. The optimization of a-SiC:H buffer layer depends on their optoelectronic priorities and thickness. In order to optimize the effect of buffer layer on the solar cell performance, we tried to exhibits the effect of thickness variation on solar cell parameters [10].

Simulations show that a p-i interface layer reduces the concentration of electrons at the p-i interface. As a result the recombination rate at the p-i interface, which limits the Voc, is reduced and thus the open-circuit voltage is increased. In the case of an a-Si cell with a p/i buffer layer, however, the loss due to the p/i interface recombination is negligible , which means that the influence of p/i interface defects can be avoided successfully with the buffer layer and that it does not limit the cell performance.[11]. The increasing a-SiC:H buffer-layer thickness VOC and Jsc were almost constant while the fill factor and efficiency were decreased, where we notice a slight degradation. We note that 2 nm is optimum value for a-SiC:H buffer layer thickness [13-15].

We demonstrate in this section the importance of p/i interface in a-Si:H solar cells on the performance of solar cell. Although we focus on p/i interfaces in a-Si:H solar cells, different result presented in this section contribute to a better understanding and improvement of electronic transport in mixedphase materials and at interfaces in general which is useful for a variety of different devices..

II.2. Absorber Layer

Although there are techniques to access the quality of a-Si:H for the high performance of a-Si:H solar cells, the device architecture of a-Si:H solar cells with layer thicknesses in the nanometer range and multulayers p-i-n junction create a several combinations at interfaces. The solar cells are very sensitive to the absorber layer quality. Therefore, we focus in this section on the correlation between absorber layer design and device performance. Severals studies confirmed that the solar cells performance is directly related to the absorber layer a-Si:H quality [3, 24, 26]. Some of these research have been studied the correlation of the mobility-lifetime product the absorber layer with solar cell properties [14, 21]. In general, the optimization of absorber layer quality is based on its bandgap engineering and proprieté of material (alloys).

- **Bandgap Engineering:**

It is clear that the solar cell efficiency is determined by the three factors of Jsc, Voc, and FF. Their values are affected by many material properties and device structures. First, the bandgap of the intrinsic layer determines the Voc and Jsc. A wide bandgap of the i-layer allows a wide quasi-Fermi level split and hence a high Voc, but low Jsc because of low absorption for the long wavelength photons, therefore an optimized bandgap for the absorber layer is very important for a-Si:H solar cells, especially for single junction solar cells. To enhance the carrier transport across the absorber layer, there are severals bandgap engineering (bandgap profling).

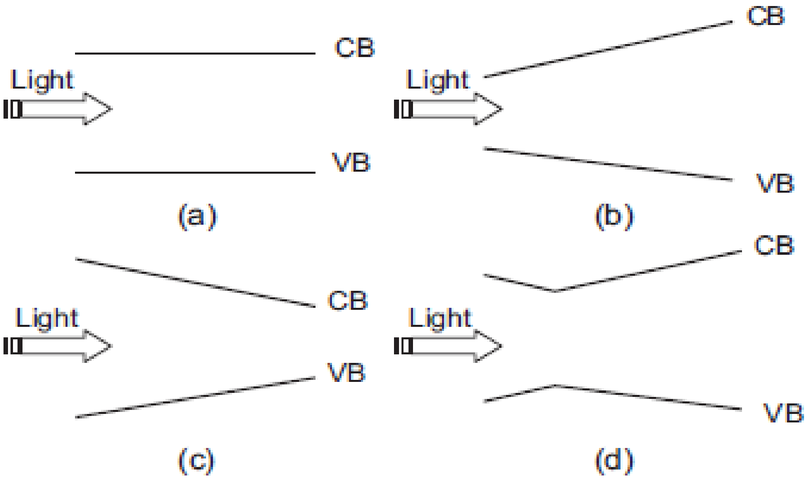

Figure 2: Schematics of bandgap Engineering in a-Si:H solar cells [18]

Figure 2 shows four different bandgap profiles: (a) a flatbandgap, (b) a profile of narrower bandgap in the p layer and wider in the n layer, (c) opposite to (b) with wider bandgap in the p-layer and narrower bandgap in the n layer, and (d) a profile with a small bandgap decreasing region from the p-layer and a large bandgap increase region from the minimum toward n-layer (called “V-shape profile”)[19].

Each configuration have its own advantages, the profile (b) have a high carrier transport compare to (a) because the narrower bandgap near the p side results in more photocarrier generation in this region, in which holes travels a short distance to reach the p-layer. In addition, the tilted bandgap provides additional force for hole transport and decelerates electrons, balancing the difference between hole mobility and electron mobility. On the other hand, the decreasing bandgap profiling (c) leads to a high Voc but poor FF. The high Voc results from the wide bandgap near the p/i interface. While the poor FF is caused by the low hole collection because of the enhanced generation near the n/i region. Furthermore, the profile (c) is better than (b) because high energy photons are absorbed in the shallow region with the wide bandgap and low energy ones are absorbed in the deep region with the narrow bandgap, but the hole transport faces a difficulty to travel longer distance with a decelerating force caused by the bandgap profile. Although (b) is favorable for hole transport, the narrower bandgap near the p-layer causes a large bandgap discontinuity at the p/i interface and results in a high density of interface states. To resolve this interface issue, the “V-shape profile” is designed as shown in (d) with a short opposite profile to compromise the hole transport and bandgap continuity at the p/i interface [17-19].

- **Using Narrow Bandgap a-Si:H alloys**

In this section, we proposed to replace the a-Si:H as absorber layer with the a-SiGe:H film for p-i-n single-junction solar cell. As mentioned above, the a-SiGe:H film was achieved by adding GeH4 to SiH4 gases. To optimize the intrinsic layer, both the germanium content (C_{Ge}) and the hydrogen dilution can be calculated from the measured optical band gap using equation 01 and 04 respectively. The same as in a-Si:H, the hole mobility-lifetime product is much lower than electron mobility-lifetime product in a-SiGe:H. The short hole collection length is the major limitation for a-SiGe:H solar cell efficiency.

The open circuit voltage (Voc) decreases with the increase of the intrinsic layer, which reflects the relationship between the electrical field and voltage. We find also that the short-circuit current is high because of the optical gap of a-SiGe:H is smaller than that of a-Si:H. There is more of absorbed photons so more pairs collected which explains a high current [21].

The FF takes into account the percentage of pairs collected relative to the created pairs. We can say that the a-SiGe:H presents many defects so many trapped pairs and fewer pairs collected. So more the thickness increases in a-SiGe:H, the recombination become more important. On the other hand, the series resistance increases with the increase of the intrinsic layer thickness which decreases the fill factor.

The main problem of a-Si:H solar cell is low fill factor FF owning to the low hole collection of a-Si:H material, and the interface recombination near p/i and i/n region. On one hand, we proposed an approach based on a-SiC:H alloy as buffer layer at the p/i interface for diminishing the band gap discontinuity and interface recombination near p/i region. On the other hand, we introduce the a-SiGe:H as absorber layer to enhance the solar cell parameters. This structure enhances the absorption of the short wavelength light in the p/i front region.

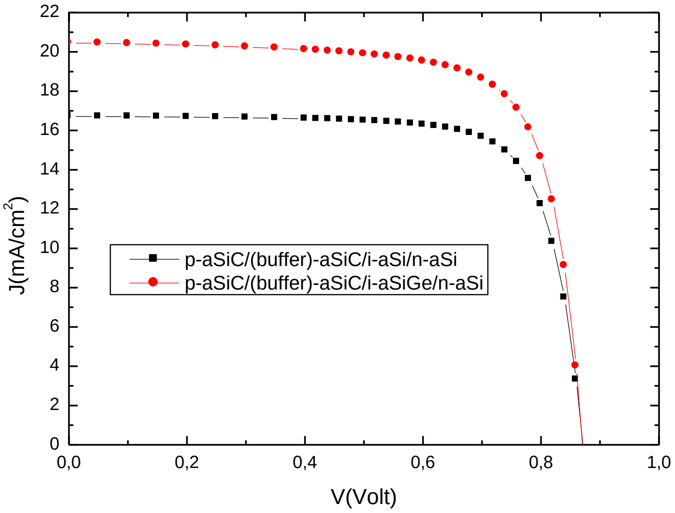

Figure 3: Simulated J–V characteristics of solar cells.

Fig 3 shows I-V characteristic of solar cell as a function of different structure. The results indicated a clear increase in the overall performance of p-aSiC/buffer-aSiC/i-aSiGe/n-aSi structure. Hence, using a-SiC:H as buffer layer can be enhanced V_{OC} and FF while using a-SiGe:H as absorber layer can be enhanced the output parameter of solar cell. As a result, the highest efficiency has been observed at 700 nm of absorber layer thickness which corresponds to the maximum efficiency of 13.12 % and then a significant drop in efficiency is due to the decline in VOC and FF when the thickness is over 800nm.

Table 2. Recent results obtained (experimental and simulation) of a-Si:H single-junction p-i-n solar cell.

Absorber	Method	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	η(%)	Ref
a-Si:H	Experiment	0.859	17.52	63.0	9.47	[6]
	Experiment	0.891	17.20	67.0	10.30	[11]
	Simulation	0.844	17.49	72.3	10.68	[12]
	Experiment	0.896	18.71	66	10.99	[14]
a-SiGe:H	Experiment	0.8709	16.71	76.10	12.08	[18]
	Simulation	0.7955	20.65	80.87	13.12	[20]

Table 2 listed the development of p-i-n solar cell structure based a-Si:H, the maximum efficiency of 13.12% has been achieved with an absorber layer bandgap of 1.66eV and thickness of 700nm for single junction solar cell. This highest efficiency is achieved due to the enhancement of FF and JSC, whereas a gradual decrease in VOC has marked. Comparing to other simulation and experimental realization [6, 11, 18, 19], one notes that p-aSiC/buffer-aSiC/i-aSiGe/n-aSi structure has achieved the highest efficiency [20].

II.3. N-type Layer

The doped layers influence the performance of a solar cell in several ways. First, the lifetime of photogenerated carriers in most doped layers is very short as a result of the high defect densities so that light absorbed in these layers does not contribute to the photocurrent. Thus, it is desirable to have doped layers with wide bandgaps, especially in the case of the front p-layer. Second, the doped layers determine the built-in potential of the solar cell and hence the photovoltage. In this case, it is desirable to have wide bandgap doped layers that should act as minority carrier mirrors and generate built-in potentials close to the bandgap. Finally, the doped layers must also be very conductive in order to assure that the losses associated with contact resistance are very small. The wide bandgap material like a-SiO:H is usually considered as a window layer for single junction and as absorber materials of the top cell for multi-junction. Their properties and applicability in solar cells based on a-Si:H has been studied and confirmed in [22]. In this context, a-SiO:H is an interesting material, which it can introduce as a doped layer for improving the performance of solar cell based on a-Si:H by increasing the built-in potential (Vbi) and minimizing the recombination losses at interlayers [19]. Some of the studies involving a-SiOx:H confirmed that the photoconductivity of a-SiO:H is important compared to a-SiC:H at similar optical bandgaps [21] . The objective of this work is to use a–SiO:H as an n-doped layer in a-Si:H solar cells and try to achieve both a higher JSC and Voc. With a simulation study and analysis method, we try to design n-doped and an ultrathin non-doped layer at n/i regions based on a–SiO:H.

The use of a-SiO:H as the n-type layer increases the use of light in the absorber layer and reduces the optic losses in the non-active regions of the cell. Furthermore, the a-SiO:H layer showed less light-induced degradation (LID) effect in comparison to the a-Si:H. In fact, several experimental and simulations studies reveal a difference in the LID of 5.7 % [23].

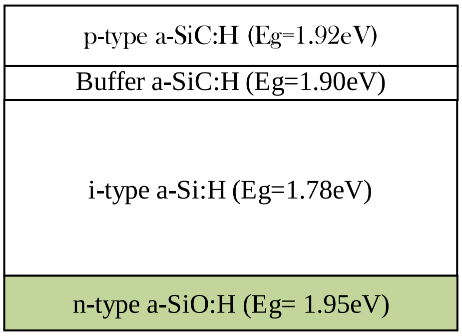

Figure 4. Design of a-Si:H p-i-n solar cell structure with n-type a-SiO:H layer

The effect of (n)a-SiO:H layer on the solar cell performance were investigated using simulation and expremental s method in [22-24]. The results show that the wide-bandgap a-SiO:H as an n-doped layer can improve the open-circuit voltage Voc as well as the fill factor. In addition, the use of a-SiO:H as a buffer layer minimizes the recombination at n/i region and increases the internal electric field in the solar cell.

III. Discussions

Amorphous silicon and its alloys has been the subject of investigation for more than three decades. Especially, the large band-gap a-Si:H alloys that contain carbon, oxygen or both. In practical a-Si:H alloy solar cells, a-SiCx:H and a-SiOx:H could be used as the wide bandgap i-layer for high Voc top cell and a-SiGe:H as the narrow bandgap i-layer for high current density in multijunction solar cells. Second, the Voc is also limited by the built-in potential, and therefore determined by Fermi level difference of the p and n layers. Optimized doped layers such as P-type and N-type a-SiCx:H, a-SiOx:H, nc-SiCx:H, and nc-SiOx:H are widely used in high efficiency solar cells. Third, the band tails in the i-layer and the deep level defects strongly affect the cell efficiency [3, 20, 24]. A wide band-tail state distribution limits the quasi-Fermi level split and therefore limits the Voc; it also reduces the carrier drift mobility, hence reduces the FF. A high defect density leads to a high recombination rate and reduces all three parameters of Jsc, Voc, and FF. Furthermore, the device design such as the thickness of each layer, the interface between the doped layer and the i-layer also have a significant impact on a-Si:H solar cell performance.

Several simulations and experimental results have been approved the interrelation between the performances of a-Si:H solar cell and the properties of p- and n-doped layers [3, 19]. In particular window layer (p-layer), thus any change of the window layer design can be affected significantly the performance of a-Si:H solar cell. But even so, the n-doped layer can be played a crucial role in optimizing the solar cell parameters.

The research of a-Si:H material and application has lasted over 40 years and significant progresses have been made by the international community. Because of the complexity of the material structure, a-Si:H material provides one of the best platforms for fundamental studies, such as the microscopic material structures, electronic structure and defect states, the carrier transport, and metastability.

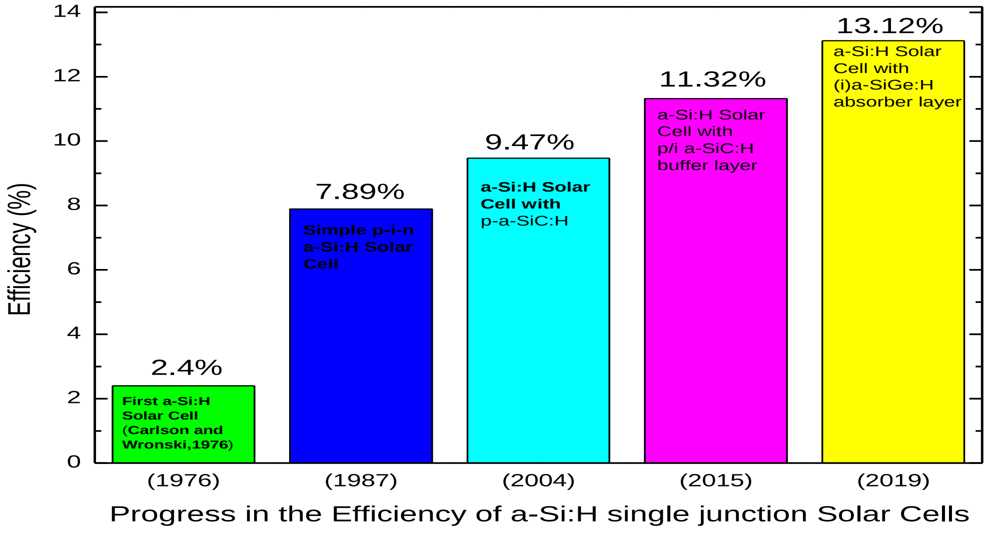

Figure 5: Progress in the efficiency of a-Si:H single junction solar cell since first solar cell 1976,

Although many optimisation techniques have been understood after the extensive studies, many others still need to be further investigated. The most important contribution is the invention of PECVD deposition to incorporate H in the materials, which significantly reduces the dangling bond defect density and makes the doping possible. Some studies built the foundation of electric structure and carrier transport in aSi:H alloys. A remarkable amount of material characterization works have been done and well documented in the literatures.

One big issue with a-Si:H is the light-induced degradation first observed by Staebler and Wronski, which is an intrinsic property of the materials. Light soaking reduces both dark and photoconductivity, and generates silicon dangling bond defects. The light-induced degradation can be annealed away at an elevated temperature. Reflected in a-Si:H solar cell, the energy conversion efficiency decreases with light soaking time and saturates after a few hundreds of hours. Although several mechanisms have been proposed, including the weak-bond breaking model, the charge transfer model, and the H collision model, no consensus has been made yet.

IV. Conclusion

From the above discussion, it is clear that the performance and stability of the a-Si:H solar cell needs to reduce the number of combination at p/i interface and also simultaneously improve the electric field in the middle of the intrinsic layer of the cell. The a-SiC:H buffer layer have been simulated as function of various band gap engineering to improve the performance of solar cell.

The research of a-Si:H solar cells has realized a significant progress by the international community. Because of the complexity of the material structure, a-Si:H material provides one of the best platforms for fundamental studies, such as the microscopic material structures, electronic structure and defect states, the carrier transport, and metastability. Although significant progresses have been acheived after the extensive studies, many studies and research still need to be further investigated.

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