Current Status of Thin Film Silicon Solar Cells for High Efficiency

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ABSTRACT: The researches on the silicon-based thin films are being actively carried out. The silicon-based thin films can be made as amorphous, microcrystalline and mixed phase and it is known that the optical bandgap can be controlled accordingly. They are suitable materials for the fabrication of single junction, tandem and triple junction solar cells. It can be used as a doping layer through the bonding of boron and phosphorus. The carbon and oxygen can bond with silicon to form a wide range of optical gap. Also, The optical gap of hydrogenated amorphous silicon germanium can be lower than that of silicon. By controlling the optical gaps, it is possible to fabricate multi-junction thin film silicon solar cells with high efficiencies which can be promising photovoltaic devices.

Key words: Amorphous silicon, Microcrystalline silicon, Intrinsic layer, Doping layer, Triple solar cells

1. Introduction

Thin film amorphous silicon-based solar cells are one of the most promising low-cost photovoltaic technologies. Hydrogenated amorphous silicon (a-Si:H) and hydrogenated nanocrystalline silicon (nc-Si:H) thin film are commonly used for application of multi-junction solar cells because they can be deposited on various substrates. These reasons have made the a-Si:H and μc-Si:H become potential candidates for device technology with low price. Research and development of a-Si:H based solar cell are now in a new stage aiming at mass production and cost reduction[1,2].

Radio frequency (RF) plasma enhanced chemical vapor deposition (PECVD) is one of the most popular industrial methods for the production. Although a uniform layer thickness is usually obtained under low deposition temperature, the films deposited by conventional 13.56 MHz RF PECVD method have low conductivity, low deposition rate, and high hydrogen content[2]. To enhance the throughput of the PECVD process, a high deposition rate for thin films is required. The electrical and optical properties of thin films are known to be determined by its deposition conditions[2,3]. The growth of high-quality thin films requires deposition conditions of high hydrogen dilution of silane (SiH_4), sufficiently high discharge power and deposition temperature. An alternative deposition method is to use very high frequency (VHF) PECVD. The VHF PECVD offers the advantage of an enhanced gas dissociation rate, which results in the film deposition with a more stable phase. Additionally, during the VHF PECVD deposition, the self-bias, and therefore the ionic bombardment of the growing surface, are reduced as compared to the RF deposition, with a consequent reduction of structural damage and improvement of thin film quality[4].

The optical gap of a-Si:H is usually 1.72 eV whereas hydrogenated amorphous silicon oxide (a-SiO:H)[5-8] and carbide (a-SiC:H)[9-12] alloy, materials with carbon and oxygen bondings have optical gaps from 1.72 up to 1.87 eV. Hydrogenated amorphous silicon germanium (a-SiGe:H)[13] alloy which has bonding with germanium has a relatively lower optical gap.

For the a-SiO:H materials, the CO_2, H_2O, N_2O, O_2, etc. can be used as a source of oxygen, while CH_4, C_2H_2, etc. are found to be suitable for the a-SiC:H alloys. For the a-SiGe:H alloy, the GeH_4 source gas is generally used. Materials with various optical gaps are very useful in designing multi-junction solar cells. The multi-junction solar cells have various absorption layers with different optical gaps and the full spectrum can be used. In particular, layers made using Oxygen are suitable for obtaining high efficiency because of their excellent electrical and optical properties.

Worldwide, tandem and triple junction solar cells have been actively studied, and the triple junction solar cells have the

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world's highest efficiency with a stabilized efficiency of 13.6%[14].

The amorphous material has high optical band gap but has low conductivities and it seems that the microcrystalline material is more promising to have higher efficiency. Especially, the doped materials are being investigated extensively. The p-type materials use diborane (B_2H_6)[15,16] and trimethyl boron (TMB) source gas[17] and the n-type use phosphine (PH_3) as source gasses[15]. For the case of the p-type microcrystalline silicon, oxygen gas is used as a source to form p-type microcrystalline silicon oxide which has a high optical gap and high conductivity, and it is used as a window layer[18-24]. Also, since its refractive index can be controlled, it can be used as an anti-reflective layer[25]. By using the oxygen gas as a source the n-type microcrystalline silicon can be made to be n-type microcrystalline silicon oxide. Since it has a low refractive index, it can be used as a back refractor layer[26-30] and it is used as an intermediate reflector for multi-junction solar cells[31-35].

2. Current status of developing of p─type layer (silicon oxide) for thin film silicon solar cells

Materials with wide optical gap should be used as a window layer for the single, tandem and triple junction solar cells. The reason is that light should penetrate the window layer. Thus, a wide optical gap which has low absorption is used. Since the window layer is in contact with TCO, the conductivity which affects the fill factor is important.

For contact layers, boron doped amorphous and materials with microcrystalline structure are used. To get a wide optical gap, silicon oxide or silicon carbide should be made within the film using CO_2 or CH_4.

In this review, the focus will be on the silicon oxide. First, the amorphous silicon is deposited by the plasma-enhanced chemical vapor deposition (PECVD) technique. SiH_4 and H_2 gasses are mostly used. For the doping gas, diborane (B_2H_6) and trimethyl boron (TMB, $B(CH_3)_3$) are used. The SiH_4 is dissociated into SiH_3 and H, H_2 into H and H by electron and CO_2 is dissociated into CO and O by hydrogen. As a result, silicon (Si) bonds with oxygen (O) forming silicon-oxygen (Si-O) alloy. In 1993, Watanabe et al. proposed the two-phase structure model of the Si-O alloy[35]. The silicon-rich regions are surrounded by the oxygen-rich regions. The size of the silicon-rich regions and the relative contribution of the oxygen-rich regions depend on oxygen concentration. Various plasma parameters have been studied and they are applied to single, tandem and triple junction solar cells.

Table 1 shows the initial photovoltaic parameters of the best-achieved device performances and characteristics of p-type hydrogenated amorphous silicon oxide (p-type a-SiO$_x$:H) films. The optical bandgap increases with oxygen to silane gas flow ratio, while the electrical conductivity decreases. The optical bandgap changes easily as a function of gas-source ratio from 1.3 to 2.0 eV. Hydrogenated amorphous silicon solar cells have been fabricated using p-type a-SiOx:H with around 1.85 eV optical band gap and a conductivity greater than 1×10^{-7} Scm^{-1}. The V_{oc}, J_{sc} and conversion efficiency of the amorphous silicon solar cells are 0.84 V, 14.66 mA/cm^2 and 6.95%, respectively[36].

Sometimes silicon carbide is used as a wide band gap material. The band gap of the silicon oxide and silicon carbide are similar. However, the p-type a-SiO:H films having thickness $\geq$ 10 nm has photoconductivity (σ_{ph}) one order of magnitude higher than that of p-type hydrogenated amorphous silicon carbide (p-type a-SiC:H) films. For 10 nm thick required for the window layer, the σ_{ph} of p-type a-SiO:H film is ~10^2 times higher than that of p-type a-SiC:H film. Single junction p-i-n structure a-Si solar cells are fabricated. The fill factor (FF) is 10% higher when fabricated with p-type a-SiO:H compared

Table 1. Initial photovoltaic parameters of best achieved device performances and characteristic film using p-type a-SiOx:H films in different device structures

Year	Research	Characteristic [optical gap (eV), dark conductivity (Scm⁻¹)]	V_{oc} (V)	J_{sc} (mA/cm²)	FF (%)	Initial efficiency (%)	Classification of Cells	Ref.
1998	Y. Matsumoto et al.	1.85, 1×10^{-6}	0.84	14.7	56	6.95	a-Si	36)
2002	A. Sarker et al.	2.02, 3×10^{-6}	0.91	17.7	72	11.6	a-Si (p/i buffer layer)	37)
2016	D.-W. Kang et al.	2.20, 1×10^{-7}	0.89	17.0	71	10.7	a-Si (p-type a-SiO$_x$C$_y$: H, p/i buffer layer)	38)

with p-type a-SiC:H. The efficiency is 11.6%, open-circuit voltage (V_{oc}) is 0.91 V and current density (J_{sc}) is 17.7 mA/cm² [37].

p-type a-SiO$_x$C$_y$:H films are fabricated by adding Trimethylboron (TMB, B(CH$_3$)$_3$) doping gas to p-type a-SiO$_x$:H films. The band gap is between 2.14 to 2.20 eV without electrical conductivity deterioration. The response in short wavelength regions is increased improving J_{sc} while maintaining FF and the efficiency improved from 10.4 to 10.7% [38].

Table 2 shows the initial photovoltaic parameters of best-achieved device performances and characteristics of the film using p-type nanocrystalline silicon oxide (p-type nc-SiO$_x$:H) films. Although there are a number of ways to deposit nanocrystalline silicon (nc-Si:H) films, the material properties of the nano nc-Si:H thin films obtained using different deposition methods are close to each other. There have been two mechanisms of p-type nc-Si:H thin films. The two mechanisms of deposition of plasma from SiH$_4$ gas are surface diffusion, [58,59] and selective etching [60-62]. Both have been proposed to explain the deposition of nc-Si:H thin films. The surface diffusion was considered to improve the mobility of the deposition precursors, by the many hydrogen atoms that impinge on the surface. For selective etching, amorphous and crystalline phases are assumed to be deposited simultaneously; atomic hydrogen impinges on the film surface, and the amorphous material is selectively etched, leaving behind a crystal film. The chemical approach states that hydrogen atoms annihilate the strained Si-Si bonds in a-Si:H, and promote the crystallization [63-66]. The concentration of hydrogen in silicon network, and within the film, is dependent on the chemical potential of the hydrogen in the plasma state. When the hydrogen chemical potential is low, the weak Si-Si bonds break while the strong bonds remain. The concentration of hydrogen increases with the chemical potential, but the hydrogen concentration within the a-Si:H films decreases, while the hydrogen is being added to plasma [67]. Reconstruction of the silicon network occurs by replacing the weak bonds by strong ones when the chemical potential reaches a certain level. Some structural defects, which have not been reconstructed, remain at the interface of amorphous and crystalline regions. The insertion of hydrogen to the Si-Si bond causes the formation of a Si-H-Si configuration [68,69]. The structure, which is in the transition amorphous-to-crystalline, gets mediated by relaxation of the strained Si-Si bonds. The hydrogen atoms that left the bond-centered location break or relax the strained Si-Si bonds. Next, local structural rearrangements yield c-Si like bond lengths and angles [70]. The CO$_2$/SiH$_4$ gas ratio is the main process condition influencing the proportion of oxygen in nc-SiO$_x$:H films. When H$_2$/SiH$_4$ the gas ratio is increased, the hydrogen atoms cause the CO$_2$ gas to break into C-O and O-O bonds. This results in the silicon-oxygen (Si-O) bonds in nc-SiO$_x$:H. The p-type nc-SiO$_x$:H is fabricated with the B$_2$H$_6$ source gas.

There are several critical requirements for a promising p-doped material as window layer: (1) good ohmic contact with front TCO layer; (2) high band gap to achieve high build-in voltage (V_{bi}) and thus high open-circuit voltage (V_{oc}); (3) good conductivity to obtain high fill factor (FF); and (4) low absorption loss over the short wavelengths range (300−600 nm) [46]. The materials that have these four advantages are p-type nc-SiO$_x$:H films. In addition, the function as a nucleation layer for nanocrystalline silicon growth might be desired. (1) The electrical conductivity depends strongly on the crystalline volume fraction and (2) the band gap depends strongly on the oxygen content. The introduction of oxygen suppresses the nucleation of Si nanocrystallites. Therefore, p-type nc-SiO$_x$:H film with low oxygen content should be used for the contact

Table 2. Initial photovoltaic parameters of best achieved device performances and characteristic film using p-type nc-SiO$_x$:H films in different device structures

Year	Research	Characteristic [optical gap (eV), dark conductivity (Scm⁻¹)]	V_{oc} (V)	J_{sc} (mA/cm²)	FF (%)	Initial efficiency (%)	Classification of cells	Ref.
2000	T. Jana and S. Ray	1.95, 0.22	-	-	-	-	-	39)
2008	Y. Matsumoto et al.	1.98, 3×10⁻⁴	-	-	-	-	-	40)
2010	P. Cuony et al.	0.1~1×10⁻⁹, -	1.39	13.9	70	13.5	a-Si/nc-Si	24)
2011	K. Sriprapha et al.	2.09, 1.65×10⁻¹	0.90	14.3	66	8.5	a-Si	41)
2012	A. Lambertz et al.	2.30, 1×10⁻²	-	-	-	-	-	42)
2012	T. Krajangsanga et al.	2.22, 3.7×10⁻³	0.52	22.3	65	7.5	nc-Si	43)
2013	J. H. Shim et al.	1.99, 1.3×10⁻³	1.686	9.0	75	11.5	a-Si/a-SiGe	44)
2014	V. Smirnov et al.	2.25, 1×10⁻³	1.33	13.9	71	13.1	a-Si/nc-Si	45)
2015	H. Tan et al.	2.30, 1×10⁻¹²	1.44	12.8	73.8	13.6	a-Si/nc-Si	46)

layer, to guarantee growth of highly conductive Si nano-crystallites in the initial few nanometers. With p-type nc-SiO$_x$:H as p-layer, the optimal p-type nc-SiO$_x$:H film has high oxygen content and thus high band gap, resulting in higher V$_{oc}$ and better spectral response than the standard p-type amorphous silicon carbide alloys (p-SiC) based window layer. Although the optimal p-type nc-SiO$_x$:H film has very low planar conductivity (in the order of 10^{-12} S/cm), the filament-like Si nanocrystallites which grow perpendicular to the substrate enable the adequate transverse conduction for the solar cells. Consequently, a-Si:H solar cells with V$_{oc}$ > 1 V and FF > 70% have been obtained. Finally, the p-type nc-SiO$_x$:H window layers were successfully applied to thin-film silicon multi-junction solar cells. A higher initial efficiency has been achieved in a-Si:H/nc-Si:H tandem solar cells[24,39,42-46].

3. Current status of developing of i−type layer (silicon oxide) for thin film silicon solar cells

A multi-junction structure is essential for high-efficiency silicon-based thin-film solar cells owing to the efficient use of the solar spectrum. Triple-junction tandem solar cells with hydrogenated amorphous silicon (a-Si:H), hydrogenated amorphous silicon germanium (a-SiGe$_x$:H), and hydrogenated nanocrystalline silicon (nc-Si:H) absorber layers have been intensively studied and an efficiency of 16.3% has been achieved so far[71]. The band gap of the top, middle, and bottom cells are 1.8, 1.45, and 1.1 eV, respectively. However, the theoretical analysis performed by Yunaz et al.[72] suggests that increasing the band gap of the top cell up to 2.0 eV increases efficiency owing to the increase in V$_{oc}$. Therefore, new wide band gap amorphous silicon-based materials should be developed for the top cell.

Table 3 shows initial photovoltaic parameters of best achieved device performances and characteristic film using i-type a-SiOx:H films in different device structures. The effect of H$_2$ on the intrinsic a-SiO$_x$:H (i-type a-SiO$_x$:H) films has been investigated using the mixture of SiH$_4$, H$_2$, and CO$_2$. H$_2$ dilution strongly affected the electrical and optical properties as well as structural properties. Photo and dark conductivity measurements revealed that the photosensitivity of the films increased with increasing H$_2$ dilution until the phase transition from the amorphous phase to the microcrystalline phase. a-SiO$_x$:H solar cells fabricated in the phase transition region showed a high V$_{oc}$ of 1.04 V. This high V$_{oc}$ in the phase transition region is attributed to the high photosensitivity of the a-Si$_{1-x}$O$_x$:H films. The solar cells also showed a slightly higher light-induced degradation ratio than with standard a-Si:H solar cells[47]. The temperature coefficient (TC) of solar cells indicated that the values of TC for conversion efficiency (η) of the double-junction solar cells were inversely proportional to the initial V$_{oc}$, which corresponds to the band gap of the top cells. The TC for η of typical a-SiO:H/nc-Si:H was -0.32%/°C, lower than the value of conventional a-Si:H/nc-Si:H solar cell. Both the a-SiO:H/nc-Si:H solar cell and the conventional solar cell showed the same light induced degradation ratio of about 20%[48]. The effect of plasma power density on the defect density of the i-type a-SiO$_x$:H films has been investigated. The defect density is a critical parameter for estimating the thin film silicon-based quality. The defect density was increased with increasing plasma power density. Plasma power density strongly affected i-type a-SiO:H film properties. The best a-SiO:H based solar cell showed a conversion efficiency of 7.3% (V$_{oc}$ = 0.95 V, J$_{sc}$ = 12.6 mA/cm^2, and FF = 0.61). The superior of the spectral response in short wavelength showed the potential of i-type a-SiO:H layer for the use as an absorber layer in a top cell of multi-junction solar cells[49]. For a-SiO:H/a-Si:H double-junction solar cells, studies are carried out about a high V$_{oc}$, a low TC for

Table 3. Initial photovoltaic parameters of best achieved device performances and characteristic film using i-type a-SiOx:H films in different device structures

Year	Research	p−type layer	Characteristic [optical gap (eV)]	V$_{oc}$ (V)	J$_{sc}$ (mA/cm^2)	FF (%)	Initial efficiency (%)	Classification of cells	Ref.
2009	S. Inthisang et al.	a-SiC:H	1.88	1.04	7.92	64	5.2	a-Si	47)
2011	K. Sriprapha et al.	nc-SiO:H	1.80	1.47	10.6	67	10.5	a-Si/nc-Si	48)
2011	J. Sritharathikhun et al.	nc-SiO:H	1.85	0.95	12.6	61	7.3	a-Si	49)
2013	K. Sriprapha et al.	nc-SiO:H	1.83	1.87	7.44	68	9.51	a-Si/a-Si	50)
2015	D. Y. Kim et al.	a-SiO:H	2.07	2.37	7.27	73	12.58	a-Si/a-Si/nc-Si	51)

η as well as a low degradation ratio. The trade-off between the band gap and the photo gain of the i-type a-SiO:H films. The highest initial η of 10.2% with a high V_{oc} of 1.88 V was obtained from the a-SiO:H/a-Si:H double-junction solar cell, compared to the conventional a-Si:H/a-Si:H solar cell. The a-SiO:H/a-Si:H solar cell exhibits a higher η, better temperature dependent behavior, and a lower degradation ratio. These advantages are due to the enhancement of the V_{oc}, which is caused by using the wide band gap a-SiO:H films. These results have verified that i-type a-SiO:H films have a great potential for use as absorption layers of the top cell of multi-junction silicon-based thin-film solar cells, which are more attractive for operating in a high-temperature environment or a tropical climate. The a-SiO:H based solar cells with low TC together with low degradation rate are attractive for use in a high-temperature environment or a tropical climate[50].

4. Current status of developing of n–type layer (silicon oxide) for thin film silicon solar cells

A multi-junction solar cell consists of a high-gap a-Si:H top cell and a low-gap μc-Si:H bottom cell stacked on top of each other. The thickness of the a-Si:H cell should be as thin as possible to minimize the impact of light-induced degradation and thus, its current generally limits the current of the multi-junction device. To overcome this issue, an intermediate reflecting layer (IRL) can be introduced between the two cells to increase the current of the top cell. The refractive index (n) of the intermediate layer which acts as a reflector should be lower than that of silicon. The layer which serves as IRL is required to be sufficiently conductive to avoid blocking current and as transparent as possible to minimize the current losses due to

absorption of light outside the active layers[52]. Table 4 shows initial photovoltaic parameters of best achieved device performances and characteristic film using n-type nc-SiOx:H films in different device structures. (Intermediate reflector : IR, back reflector : BR). The n-type nc-SiOx:H which is based on the silicon oxide has optical and electrical properties suitable to serve as intermediate reflectors. Using the n-type nc-SiOx:H film, initial micromorph cell efficiency of 12.2% (V_{oc}=1.40 V, FF=71.9%, and J_{sc}=12.1 mA/cm^2) is obtained[52].

By increasing the oxygen content, it is possible to get a high band gap and low n but the electrical property is insufficient. To improve the property, CO_2 and H_2 have been investigated. Tuning the trade-off between a highly conductive μc-Si:H fraction and an a-SiOx:H phase with high oxygen content (O) yields a material with a combination of low refractive index and high band gap at sufficient conductivity (E_{04}=2.4 eV, n=2.1 at σ=10^{-5} S/cm). Using this IRL, a-Si:H/μc-Si:H tandem solar cells are fabricated and an efficiency of 11.5% is achieved[34].

To improve the light management of silicon thin-film solar cells, the n-type nc-SiOx:H films are used as IRL. The effects of O on optical, electrical and structural properties of n-type nc-SiOx:H films have been investigated. With increasing O in n-type nc-SiOx:H film, the optical band gap is widened due to the increased amount of Si-O bonds, while the conductivity decreases accordingly. A similar trend is found in the case of bi-phase n-type nc-SiOx:H comprising wide-band gap a-SiOx:H phase and conductive μc-Si:H phase. For a-Si:H/a-Si$_{1-x}$Ge$_x$:H tandem cell, employing n-type μc-SiOx:H as IRL increases the current density of the top cell. The a-Si:H/a-Si$_{1-x}$Ge$_x$:H tandem cell with efficiency of 9.2%, V_{oc} = 1.58 V, J_{sc} = 8.43 mA/cm^2, and FF = 68.4% is obtained[56].

To achieve more efficient light trapping and higher current density for nc-Si:H solar cells, the parasitic absorption losses occurring at the back and front electrodes should be minimized

Table 4. Initial photovoltaic parameters of best achieved device performances and characteristic film using n-type nc-SiOx:H films in different device structures. (Intermediate reflector : IR, back reflector : BR)

Year	Research	Application of reflector	Characteristic [refractive index, conductivity (Scm^{-1})]	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Initial efficiency (%)	Classification of cells	Ref.
2007	P. Buehlmann et al.	IR	< 2.20, > 1×10^{-5}	1.40	12.1	71.9	12.2	a-Si/nc-Si	52)
2011	A. Lambertz et al.	IR	2.25, > 1×10^{-3}	1.37	11.3	74.0	11.5	a-Si/nc-Si	34)
2012	S. Kim et al.	BR	< 2.00, > 1×10^{-5}	0.50	27.4	68.0	9.3	nc-Si	53)
2012	P. Babal et al.	BR	< 2.60, -	0.84	16.3	72.4	9.95	a-Si	54)
2013	L.V. Mercaldo et al.	IR	< 2.00, > 1×10^{-5}	1.29	11.2	71.9	10.4	a-Si/a-SiGe/nc-Si	55)
2016	P.-W. Chen et al.	IR	3.4, -	0.92	13.7	67.5	8.5	a-Si	56)

Table 5. Present status of conversion efficiency of thin film silicon solar cells [57]

Classification	Eff. (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF(%)	Test Centre (date)	Description
a-Si	10.2±0.3	1.001	0.896	16.36	69.8	AIST (7/14)	AIST
nc-Si	11.8±0.3	1.044	0.548	29.39	73.1	AIST (10/14)	AIST
a-Si/nc-Si (Tandem)	12.7±0.4	1.000	1.342	13.45	70.2	AIST (10/14)	AIST
a-Si/nc-Si/nc-Si (Triple)	14.0±0.4	1.045	1.922	9.94	73.4	AIST (5/16)	AIST

by optimizing the back reflector configuration and/or the front electrode material such as TCO.

To improve the reflection performance of the back reflector (BR), the refractive index of the BR material should be minimized for total reflection. The promising material satisfying this condition is an n-type nc-SiO$_x$ film which is composed of amorphous SiO$_x$ and conductive n-type microcrystalline Si. The n-type nc-SiO$_x$ film with high reflectivity and high transparency is a novel BR material. The n-type nc-SiO$_x$ films have a lower refractive index and lower absorption spectra at long wavelengths of >700 nm compared to the conventional ZnO:Al back reflector materials. The n-type nc-SiO$_x$ layer was applied as a back reflector for µc-Si:H solar cells, boosting not only the J_{sc} but also the V_{oc} and the FF. This result suggests that the anisotropic characteristics of the microstructure and the electrical conductivity of the n-type nc-SiO$_x$ layer may reduce the shunt current at the back contacts of thin-film Si solar cells[53,54].

5. Current status of high−efficiency thin film solar cell

Table 5 shows the present status of the conversion efficiency of thin film silicon solar cells. The quality of undoped a-Si:H layers deposited either by triode or diode PECVD is high and a p−i−n device in a superstrate configuration is fabricated at AIST. As a front TCO substrate, a commercially available SnO$_2$-coated glass (Asahi-VU) was used. For the p-layer, a very thin a-SiC:H is used. An a-Si:H p−i buffer layer is effective in reducing light-induced degradation while keeping V_{oc} reasonably high. The optimized a-Si:H single-junction solar cells have stabilized efficiency of 10.1-10.2% and for a-Si:H/µc-Si:H tandem solar cells, the stabilized efficiency of 12.69% is obtained[73].

Substrate-type n-i-p nc-Si:H cells are fabricated using honeycomb textures at AIST. The structure of the solar cell consists of honeycomb-textured substrate/Ag/ZnO/nc-Si:H n-i-p layers/In$_2$O$_3$:Sn (ITO, 70 nm)/Ag grid.

To reduce the absorption loss, wide-gap nanocrystalline silicon oxides (nc-SiO$_x$:H) are used for the n-type and p-type nc-Si:H. When the textures had moderate aspect ratios, we could find the optimum period to get high J_{sc}. Based on these findings, we have fabricated optimized µc-Si:H cells achieving a high efficiency exceeding 10% and a J_{sc} of 30 mA/cm^2 [74].

Using the honeycomb textures mentioned above, a-Si:H/nc-Si:H/nc-Si:H triple-junction cells are fabricated at AIST. In a single-junction µc-Si:H cell with IOH front contact, a high J_{sc} of approximately 33 mA/cm^2 is achieved. For the case of multi-junction cells, the growth of µc-Si:H layers is interrupted by doped layers or intermediate reflectors, such as nc-SiO$_x$:H film. The investigation on the film stacks of nc-Si:H/nc-SiO$_x$:H layers has been carried out. These technologies were also combined into a-Si:H/nc-Si:H/nc-Si:H triple-junction cells and a world record stabilized efficiency of 13.6% was achieved[75].

6. Conclusions

The phase of silicon-based thin films can be controlled variously and the electrical and optical properties can be optimized by plasma parameters for application to photovoltaic devices. To get high efficiency, new materials are needed. One of the promising materials is the silicon oxide (SiO$_x$). The technologies on fabricating a-SiO$_x$:H phase with wide bad gap, µc-Si:H phase with high conductivity and nc-SiO$_x$:H with bi-phase have been studied. Using these technologies, it has been possible to obtain a wold record stabilized efficiency.

Acknowledgments

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