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# Effect of p-type a-SiO:H buffer layer at the interface of TCO and p-type layer in hydrogenated amorphous silicon solar cells

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Wide band gap p-type hydrogenated amorphous silicon oxide (a-SiO:H) buffer layer has been used at the interface of transparent conductive oxide (TCO) and hydrogenated amorphous silicon (a-Si:H) p-type layer of a p-i-n type a-Si:H solar cell. Introduction of 5 nm thick buffer layer improves in blue response of the cell along with 0.5% enhancement of photovoltaic conversion efficiency ( $\eta$ ). The cells with buffer layer show higher open circuit voltage ( $V_{oc}$ ), fill factor (FF), short circuit current density ( $J_{sc}$ ) and improved blue response with respect to the cell without buffer layer.

Key words: Hydrogenated amorphous silicon solar cell, RF PECVD, Quantum efficiency, Buffer layer, Silicon oxide.

#### Introduction

The role of a buffer layer at an interface is to reduce certain abrupt differences between the adjoining layers. Thus a successful buffer layer can improve interface characteristics. It is known that the interfaces in a-Si:H thin film solar cells have a key role in the device performance under illumination. The operation of the solar cell fundamentally relies on the junction formation with extrinsic (p-&n-type) and intrinsic (i-type) semiconductor, the creation of a built-in potential, and the separation of photo-generated electron-hole pairs. Therefore, if the junction formation or interface becomes defective, the charge collection and the cell performance will be reduced. The parameters that play significant role in solar cell performance include the interface defects, energy band mismatch, carrier mobility etc. Interface defects and energy band mismatch hinders carrier diffusion and enhances electron-hole recombination at the interface. It is generally known that such a problem can be overcome by the introduction of a buffer layer between two such mismatching layers. A 10 nm thick graded band gap silicon carbide buffer layer at the p/i interface improves cell performance [1]. Recently it has been found that the introduction of a-SiO:H buffer layer at the interface of n-layer and TCO improves cell performance primarily due to the reduced lateral conductivity at the interface [2]. The a-SiO:H thin film is known to have microscopic Si-rich and O-rich regions [3, 4], where electrically less conductive O-rich regions help to enhance the optical gap and the electrically conductive Si-rich regions contribute to the electrical conduction. Therefore, a-SiO:H can exhibit an enhanced transverse conductivity even at higher optical gap and lower lateral conductivity. It is generally known in a solar cell that the characteristics of the TCO/p-layer interface is a crucial factor for the device performance because of electrical surface barrier potential and optical mismatches at the interface [5-7] etc. There have been many attempts to solve these problems with various ways. For example, the use of higher band gap p-type hydrogenated amorphous silicon carbide (a-SiC:H) layer [8] improves the solar cell performance, which may be because it compensates the band gap mismatch of adjacent layers. However, at a higher optical gap  $(E_g)$ , the electrical conductivity of a-SiC:H is lower. There are some reports on the use of high conductivity nanocrystalline (nc) p-type a-Si:H thin layers [5, 9] as buffer layers. Although the electrical conductivity of nc-Si is higher but the midgap defect density of such material also remains high. It should also be noted that the deposition condition of the first layer over TCO, in which a higher hydrogen flow is required, the higher hydrogen flow may lead to the chemical reduction at the top surface of the TCO material and the top surface of TCO may become more defective.

In such a situation a-SiO:H can be a better alternative buffer layer because of its optoelectronic and chemical characteristics. Opto-electronically p-type a-SiO:H material shows higher conductivity at a higher optical gap [8, 10], while the chemical nature of the existing oxygen in a-SiO:H deposition can help to prevent greatly the reduction at the top surface of TCO.

Therefore, we deposited boron doped thin amorphous silicon oxide buffer layers on the TCO first, before depositing the usual a-Si:H single junction solar cells, and estimated the solar cell performance. We obtained

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N <sub>2</sub> O gas flow	Gas flow (sccm) SiH <sub>4</sub> : H <sub>2</sub> : B <sub>2</sub> H <sub>6</sub> : N <sub>2</sub> O	Pressure (Torr)	Power density (mW/cm <sup>2</sup> )	Ts (°C)	Electrode distance (mm)
1.5	10:195:0.05:1.5	0.7	42	175	40
3.0	10:195:0.05:3.0	0.7	42	175	40
5.0	10:195:0.05:5.0	0.7	42	175	40

**Table 1.** Deposition conditions for the buffer layer

the promising improvement in the solar cell performance, compared with that of our reference cell which does not contain the silicon oxide buffer layer. This work is mainly focused on the effect on solar cell parameters due to the presence of a-SiO:H buffer layer at the interface between TCO and p-type a-Si:H layer and its effect on the device performance.

# **Experimental**

Boron doped a-SiO:H films have been deposited at a relatively low temperature (175 °C) by a radio-frequency (13.56 MHz) plasma enhanced chemical vapor deposition (RF PECVD) method with the mixture of silane  $(SiH_4)$ , hydrogen (H<sub>2</sub>), diborane (B<sub>2</sub>H<sub>6</sub>) and nitrous oxide (N<sub>2</sub>O), where the N<sub>2</sub>O gas is 90% diluted with helium (N<sub>2</sub>O:He = 10:90). In order to control the  $E_g$  and dark conductivity of the films, the SiH<sub>4</sub>, H<sub>2</sub>, B<sub>2</sub>H<sub>6</sub> gas flow rates were kept constant and only N2O gas flow rate was changed during the preparation of buffer layers (Table 1).  $B_2H_6$  flow rate was kept constant at 0.5 vol % with respect to SiH<sub>4</sub> flow rate. All the other conditions such as plasma power, pressure, temperature and separation between cathode and anode electrodes of the RF PECVD system were kept constant. Thickness and optical absorption coefficients were measured by a spectroscopic ellipsometry (SE), while optical band gap was deduced following Tauc's relation,

$$(\alpha h\nu)^{1/2} = B^{1/2}(h\nu - E_g)$$
(1)

where B is a constant, h is Plank's constant. Dark conductivity of the films were measured in a coplanar electrode structure. Oxygen content of the films has been estimated from the FT-IR spectroscopic analysis.

Amorphous silicon single junction solar cell was fabricated on a fluorine doped tin oxide (SnO<sub>2</sub>:F) coated glass substrate, at a substrate temperature of 175 °C. The p- and n-type layers were deposited by a RF PECVD technique and the intrinsic layers were grown using a very high frequency (VHF, at 60 MHz) PECVD technique. Photovoltaic conversion efficiency of the cells have been measured under AM 1.5 illumination while the spectral quantum efficiency of the cells were measured in the spectral range of white light (Xe lamp).

# **Results and discussion**

Several p-type a-SiO:H films have been deposited and some of the p-type materials with reasonable



Fig. 1. Properties of a-SiO:H buffer layers. (a) The variation in optical bandgap ( $E_g$ ) and refractive indices and (b) dark conductivity and activation energy of the films prepared with various N<sub>2</sub>O flow rates.

electrical and optical properties have been chosen for the investigation as a buffer layer. These a-SiO:H lavers were inserted into the TCO/p interface of the cell and the cell characteristics were measured. The thickness of the buffer layers were kept fixed at about 5 nm by controlling the deposition time. Fig. 1(a) shows the optical gap and refractive index of the buffer layers prepared at various N2O gas flow rates. For N2O flow rates of 0.5, 1.5, 3.0 and 5.0 sccm, the Eg of a-SiO:H films are 1.71, 1.82, 1.94 and 2.00 eV, respectively and the refractive indices are 4.32, 4.12, 3.84 and 3.53, respectively. Therefore, higher N2O flow rate results in silicon oxide material having favorable optical properties. Theoretically, such a buffer layer may result in lower reflection (R) of incident light from the TCO/ p-interface, as coefficient of reflection at normal incidence depends on the difference in refractive index of two layers,  $R = [(n_1 - n_2) / (n_1 + n_2)]^2$ , where  $n_1$  and  $n_2$  are refractive indices of the two layers. Thus, a-SiO:H buffer layer has advantages over the cells without buffer layer, respecting the higher transmission through the interface due to lower refractive index mismatch and lower band gap mismatch.

Fig. 1(b) shows that the lateral conductivity of the silicon oxide films, which measured in the co-planar electrode configuration, that reduces with increase in  $E_g$ . Transverse conductivity of these films are expected to be few orders higher than this value. The co-planar electrodes were deposited on the surface of the film at a separation of 150 µm.

The boron content of the buffer layers are assumed to be unchanged as the diborane flow rate was kept constant at 0.05 sccm for all the deposited films. However, for samples with higher oxygen content, the silicon oxide films may not be efficiently doped with boron [11], which may also be a reason for the lower dark conductivity at higher oxygen content of the films.

Fig. 2 shows the oxygen content of the films measured by the FT-IR spectroscopy. The number density of oxygen was estimated by following Lucovsky's proposal [12],

$$C(O) = A(O)I(940 \sim 1080) \tag{2}$$

where C(O) is the oxygen contents in at.%), A(O) = 0.156 at.%/eVcm<sup>-1</sup> is a calibration constant and  $I(940 \sim 1080)$  is the integrated absorption intensity in the wave number band from 940 to 1080 cm<sup>-1</sup>. For N<sub>2</sub>O flow rate of 0.5, 1.5, 3.0 and 5.0 sccm, the oxygen content of the film were 4.29 at.%, 9.07 at.%, 14.59 at.% and 26.91 at.%, respectively.

The solar cell deposition conditions and thicknesses



Fig. 2. IR absorption spectra for the films due to oxygen stretching vibration in Si-O-Si mode.

Table 2. Deposition conditions of the cell without buffer layer

of the different layers are shown in Table 2. Using one of the buffer layers, prepared with 3 sccm N<sub>2</sub>O flow rate, results in a nearly 5% improvement in the external quantum efficiency (EQE) of the cell in the shorter wavelength range. Fig. 3 shows such an improvement in the EQE in the spectral range from 400 to 600 nm for the solar cell with buffer layer, compared to the a-Si reference cell which contains no buffer layer. Fig. 3 also shows that the EQE remains low for the buffer layers prepared with the lower (1.5 sccm) or higher  $(5.0 \text{ sccm}) \text{ N}_2\text{O}$  flow rates. The current voltage (I-V) characteristics shows a similar trend for N<sub>2</sub>O flow rate of 3 sccm, where, Voc, Jsc and FF show improvement for the solar cell parameters as compared to the cells with other buffer layer conditions (Figs. 4 and 5). Fig. 5 shows the variation of the solar cell parameters  $(\eta, \eta)$ Voc, Jsc and FF) with the different buffer layers. Here the best performance of the solar cell was observed for the buffer layer which was prepared with 3 sccm of N<sub>2</sub>O flow rate. It is known that when an increased number of surface defects and higher barrier potential at the interface exist, much more charge carriers will be lost which is attributed to the increase in undesired local currents [2]. The presence of a-SiO:H buffer layer seems to hinder such a loss mechanism. The reduced conductivity due to higher oxygen incorporation, as shown in Fig. 1, also supports this hypothesis.

The electric bias dependence of the quantum efficiency (BQE) spectra provides some information concerning the field-dependent carrier transport and collection, which mainly reflects the magnitude of carrier recombination at the interface [15, 16]. For the field



Fig. 3. Externals quantum efficiency of the cells with/without buffer layers.

Cell layer (thickness)	Gas Ratio	Pressure (Torr)	Power density (mW/cm <sup>2</sup> )	Ts (°C)	Electrode distance (mm)
p (15 nm)	$\begin{array}{c} SiH_4:H_2:B_2H_6\\ 30:147:0.3 \end{array}$	0.2	70	175	40
i (350 nm)	SiH <sub>4</sub> : H <sub>2</sub> 50 : 50 (1 : 1)	0.2	42	175	20
n (25 nm)	SiH <sub>4</sub> : H <sub>2</sub> : PH <sub>3</sub> 30 : 120 : 0.3	0.2	70	175	40



Fig. 4. I-V characteristics of the cells with/without buffer layers.



Fig. 5. Variation of solar cell parameters for the cells with/without buffer layers. The various  $N_2O$  flow rates indicate various buffer layers.



Fig. 6. Normalized quantum efficiency, QE(-1V) / QE(0V), for the cells with/without buffer layers.

dependant QE measurement, we applied -1 Volt bias to the cell. Normalized QE spectra (QE(-1V) / QE(0V)) of the cells is shown in Fig. 6. The increase in the normalized BQE in the shorter wavelength regime of 400-500 nm may be attributed to the reduced surface recombination loss of charge carriers at the TCO/p interface after the buffer layer was introduced. It is believed that the deterioration of blue response of our cells, prepared at  $N_2O$  gas flow of 1.5 and 5.0 sccm, may be due to the higher defects in these two materials and therefore higher defects in the buffer layers of the solar cells. Therefore, the film prepared with 3.0 sccm  $N_2O$  flow rate seems to be the optimized buffer layer. Although the reference solar cell is not optimized for best performance, however the improved device performance due to the presence of a buffer layer shows that p-type a-SiO:H buffer layer may play a significant role in improving the solar cell device characteristics.

### Conclusions

The effect of 5 nm thick a-SiO:H buffer layer introduced between TCO and the p-type a-Si:H layer of a p-i-n type solar cell has been investigated. At an intermediate O-content improvement in solar cell parameters were observed in  $V_{oc}$ , FF and  $J_{sc}$  as compared to the cells without buffer layer. The improvement may be due to the reduced leakage current at the interfaces and reduced barrier height between the adjacent TCO and p-type layers along with better bandgap matching at the interface.

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