

Current-Voltage Characteristics of ITO/p-Si and ITO/n-Si Contact Interfaces

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ABSTRACT

We investigated the electrical contact characteristics of indium tin oxide (ITO)/doped hydrogenated amorphous silicon (a-Si:H) junctions. For efficient collection of photo-generated carriers, photovoltaic and photodetector devices require good ohmic contacts with transparent electrodes. The amorphous-Si thin films were sputter deposited on ITO coated glass substrates. As-deposited p-type a-Si:H on ITO formed nearly ohmic type contacts and further annealing did not improve the contact characteristics. On the other hand, as-deposited n-type a-Si:H on ITO formed an ohmic contact, while further annealing resulted in a Schottky type contact. The ITO contact with p-type silicon semiconductor is a robust ohmic contact for Si based optoelectronic devices.

Keywords: Sputtered Amorphous Silicon; Electrical Contact Characteristics; ITO/Si Contact

1. Introduction

Indium tin oxide (ITO) layers are frequently used as front contacts in thin film optoelectronic devices such as solar cells, light emitting diodes, laser diodes, and photodetectors due to their high conductivity and transparency in the visible range of the solar spectrum [1,2]. In the case of thin film solar cells, the ITO contact is necessary to allow photons to reach the absorber layer and improve the photo-generated carrier collection [3]. Solar cells based on amorphous silicon consist of several layers of different chemical composition and hence different optical and electronic properties [4]. The growth of amorphous silicon on transparent conductive oxides such as ITO will undergo an interfacial reaction and the initial stage of growth will be different from the deposition of bulk materials [5]. The reduction of tin oxide (SnO₂) in hydrogen plasma may influence the contact resistance of the ITO/Si junction [6]. In order to achieve high performance devices, it is required to have ohmic contact with low contact resistance.

The deposition of thin film solar cell structures on low cost and flexible substrates like plastic foil has necessitated the deposition of the thin films at relatively low temperature. Various low temperature schemes have been adapted to prepare a-Si:H films. They include low-power radio frequency (RF), direct current, electron cyclotron

resonance and very high frequency—plasma-enhanced chemical vapor deposition [7,8]. However, these methods yield low growth rate. For inexpensive photovoltaic (PV) devices, high growth rate is required for depositing 0.5 μm thick absorber layers. Sputtering is a low cost, high deposition rate method that yields high purity films. Sputter deposited ITO on Si wafers or on Si films has been studied by various research groups [5,9], but there is not much work on the contact characteristics of the junction between ITO and sputter deposited amorphous Si films. In this article, we report on the electrical contact properties of ITO on p- and n-type a-Si:H films. Our results shows that the ITO/p-type a-Si:H contact interface is better for silicon based optoelectronic device applications.

2. Experimental Procedure

P-type and n-type Si:H films were deposited by a AJA Orion 1800F RF magnetron Sputter System (13.56 MHz) equipped with a load lock. The sputter deposition were carried out in an ultra pure argon (Ar) + hydrogen (H₂) atmosphere, on commercially procured fluorinated indium tin oxide coated glass substrates. Four-inch diameter boron-doped Si and phosphorus-doped Si targets were used for depositing n-type Si and p-type Si films respectively. The substrates were cleaned using acetone, methanol, isopropanol and de-ionized water before loading into the depo-

sition chamber for plasma cleaning before deposition of the Si film. The system base vacuum was approximately 1×10^{-7} Torr, while the process pressure was 3 m Torr. A fixed RF power of 150 W was used for a 5 cm distance between the target and the sample. The substrates were kept at 200°C during film deposition. The Ar and H_2 flow rate was maintained at 10 and 1 sccm respectively. **Figure 1** shows the schematic of the AJA Orion 1800 F RF/DC Sputter deposition system used for the sample preparation. For contact resistance studies, Al/Si/ITO test structures were formed by depositing Al on Si/ITO samples. Post deposition annealing of test structures were carried out at 300°C in vacuum.

Raman spectroscopy of the films was carried out using a Renishaw inVia confocal Raman spectrometer equipped with a research-grade Leica microscope, $20\times$ objective (numerical aperture of 0.40), and WiRE 2.0 software. A 785 nm laser light was utilized for excitation. The laser power on the sample was approximately 115 mW.

Cross-sectional transmission electron microscopy (TEM) specimens were prepared from the ITO/p-type a-Si:H/Al sample using a conventional ex-situ lift-out technique in a FEI Nova Nanolab 600 Dualbeam. The specimens were characterized by using a JEOL 2010F operated at 200 kV, equipped with an EDAX Si-Li energy dispersive X-ray spectroscopy detector. Current-voltage (I - V) measurements were performed for ITO/p-Si and ITO/n-Si hetero-structures at room temperature using a Keithly 2400 SourceMeter. The contacts were made using Signatone 1160 series probe station.

3. Results and Discussion

All deposited films in this work were thoroughly characterized by Raman spectroscopy and TEM. Raman spectroscopy observation indicated that as-deposited films are amorphous silicon. **Figure 2** shows a Raman spectrum taken on as-deposited p-Si films. Si-Si vibrational peaks can be seen around 160 and 480 cm^{-1} . The Raman spectrum of amorphous silicon consists of two distinct bands,

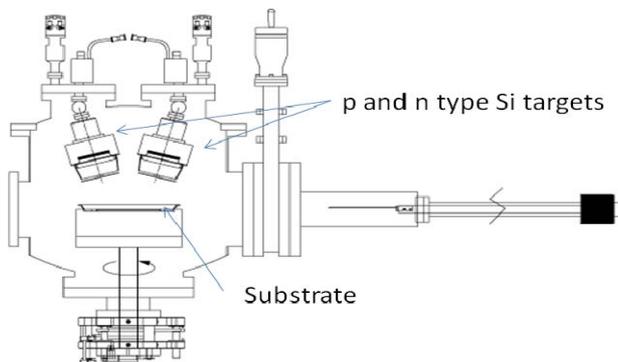


Figure 1. Schematic of the AJA Orion 1800F RF/DC Sputter deposition system used to deposit thin films of p- and n-type a-Si:H on ITO/Glass substrates.

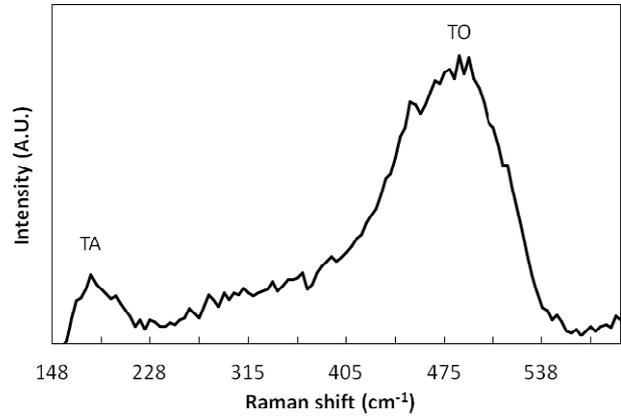


Figure 2. Raman spectroscopy scan of as-deposited p-type a-Si:H film. The peaks at 160 and 480 cm^{-1} correspond to amorphous Si-Si transverse acoustic (TA) and transverse optic (TO) vibrational modes, respectively.

near 160 cm^{-1} and 480 cm^{-1} , associated with transverse acoustic (TA) and transverse optic (TO) vibrational modes, respectively [10]. The appearance of the TA-like phonon mode is associated with the network formation of a-Si or the onset of layer growth. Similar results were observed for n type a-Si:H films. Hence, the sputter deposited silicon films processed for this study are in an amorphous phase.

TEM analysis also confirms amorphous nature of the as-deposited p-type and n-type Si films and the as-deposited films are around 50 nm thick. **Figure 3** shows cross-sectional TEM micrograph of ITO/p-Si/Al interface. No grains are seen in the Si layer, confirming the Raman spectroscopy result of an amorphous phase. It also shows that the interface between ITO and Si is rough. The p-type Si layer thickness measured from this micrograph is around 50 nm .

Figure 4 shows the current-voltage characteristics of ITO/p-Si junctions before and after annealing. The I - V characteristics show nearly linear behavior except for a slight deviation in the range of -0.5 to 0.5 volts. The contact resistance at voltages above 0.5 V is around 15 ohms , while the resistance in the -0.5 to 0.5 V range is around 30 ohms . This indicates that there is an interfacial Schottky barrier that requires 0.5 volt to overcome the barrier. The Schottky contact barrier height at the metal and p-type semiconductor interface is given below:

$$\phi_B = E_g - (\phi_M - \chi_S)$$

where E_g is the bandgap of the semiconductor, ϕ_M is the metal work function and χ_S is the semiconductor electron affinity. The work function for ITO is 4.7 eV , while the electron affinity for p-type a-Si:H is roughly 3.4 eV and its band gap is 1.8 eV . Hence, the calculated barrier height at the ITO/p-Si interface is around 0.5 eV . In addition, interface mixing also influences the contact properties. It is known, for instance that the sputter deposition of ITO on

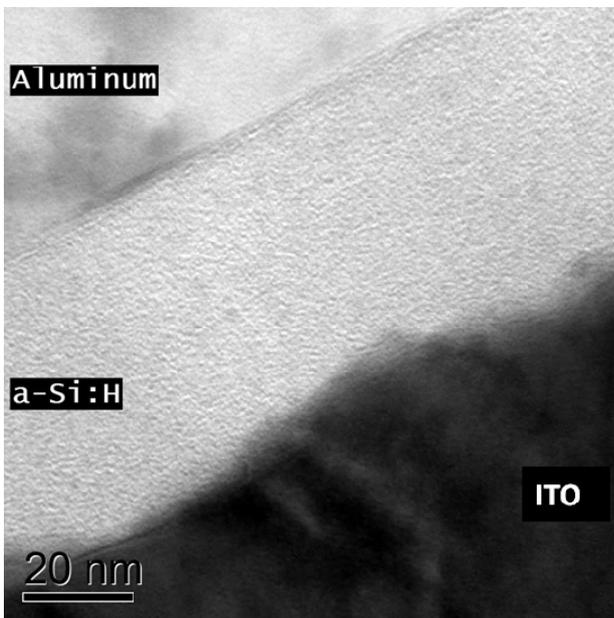


Figure 3. Transmission electron micrograph of the Glass/ITO/p-type Si:H/Al sample. The silicon film has an amorphous structure and the layer thickness is around 50 nm.

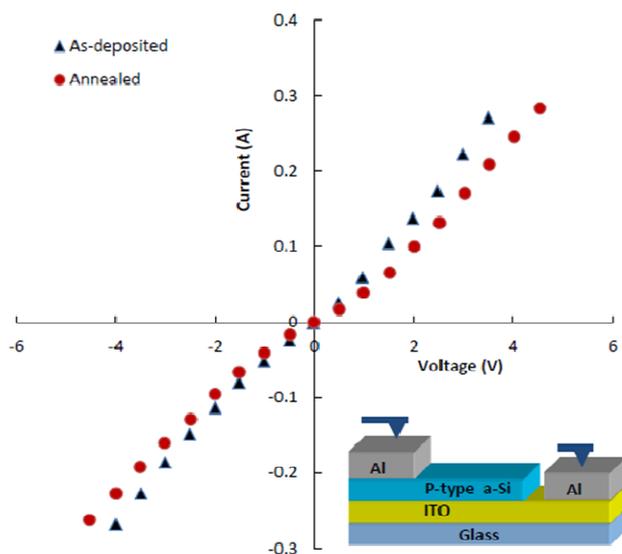


Figure 4. Current-voltage characteristics of ITO/p-type a-Si:H thin film junctions after deposition and annealing. The inset shows the schematic of the sample used for the measurement. The nearly linear current-voltage curve indicates the formation of ohmic contact between ITO and p-type silicon.

Si can create an intermixed damaged layer to a depth of 2 - 3 nm even at room temperature [11]. In our case, during sputter deposition of Si on ITO, energetic Si atoms deposited on ITO can lead to formation of an interfacial oxide layer. The free energy of formation for SiO_2 , In_2O_3 and SnO_2 are -193 , -207 and -124 kcal/mole respectively [12]. Thus, In_2O_3 and indium rich oxides may be

expected to yield a stable interface with silicon, but the diffusion of oxygen from SnO_2 into the silicon layer may form an interfacial oxide layer. On the other hand, ITO substrates with an indium oxide rich top surface layer could minimize the formation of an interfacial oxide layer. Thus, the I - V behavior of the as-deposited structure can be attributed to the presence of the interfacial oxide layer. Annealing does not improve the I - V curves. It is also known that during PECVD growth of Si, the hydrogen plasma reduces the ITO surface layer that leads to metallic interface layer. But in sputtered Si deposition, the hydrogen plasma interacts with Si at the target, not at the substrate. The high energetic neutral Si atoms that deposit on ITO are more favorable to form a thin interfacial oxide layer.

Figure 5 shows the current-voltage characteristics of ITO/n-Si junction before and after annealing. The as-deposited junction shows a linear current-voltage characteristics indicating ohmic contact with a contact resistance of approximately 9 ohms at the junction. After annealing, non-linear, Schottky diode like current-voltage characteristics with a contact resistance of approximately 100 M ohms is observed. N-type silicon layer is expected to form a Schottky contact with ITO due to its work function. The Schottky barrier height at the metal and n-type semiconductor interface is given below:

$$\phi_B = \phi_M - \chi_S$$

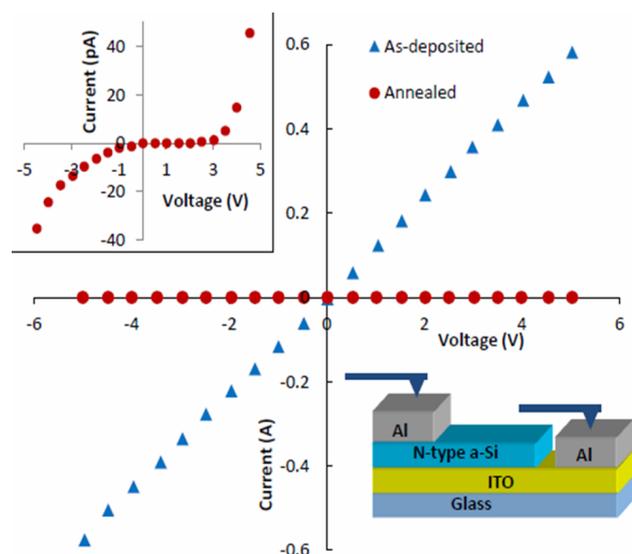


Figure 5. Current-voltage characteristics of ITO/n-type a-Si:H thin film junctions after deposition and annealing. The as-deposited n-type Si film shows ohmic contact with ITO. After annealing, the contact deteriorates to a Schottky type contact with increased contact resistance. The top inset shows the current-voltage characteristics of the annealed sample. The bottom inset shows the schematic of the sample used for the measurement.

where ϕ_M is the metal work function and χ_S is the semiconductor electron affinity. The work function for ITO is 4.7 eV and the electron affinity for n-type a-Si:H is approximately 3.8 eV. Hence the barrier height at the ITO/n-Si interface is approximately 0.9 eV. The ohmic contact behavior of as-deposited ITO/n-Si interface is due to formation of interface defects. During post deposition thermal treatment, these defects are annealed out and the formation of an interfacial oxide takes place [13]. The ITO serves as an oxygen source for the formation of the interfacial oxide. Hence, the annealed ITO/n-Si junction shows Schottky type contact behavior with higher resistance compare to the as-deposited interface.

4. Summary

Amorphous Si films were fabricated by sputter deposition on ITO/glass substrates in an ultra high vacuum chamber. The electrical contact properties of ITO/p-Si and ITO/n-Si were characterized. P-type silicon film on ITO forms a nearly ohmic type contact, while n-type silicon on ITO forms a Schottky type contact. P-type Si/ITO contacts are a promising, robust ohmic contact for silicon-based optoelectronic devices.

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