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Morphological and electrical properties of ATSP/*p*-Si photodiode

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ABSTRACT

Aromatic thermosetting copolyester (ATSP) has been recently introduced, which exhibits promising thermal, mechanical, and adhesive properties to address broad range of industrial applications. However, the ATSP resin has not been well described in terms of electronic properties. Hence, we used a thin film of ATSP as an interfacial layer between a metal and a semiconductor to control the properties of the metal-semiconductor contacts. In this study, ATSP oligomers were dissolved in tetrahydrofuran (THF) and multiple layers were deposited on a *p*-type Si wafer in thin film form by spin-coating technique. To obtain the metal and semiconductor device (Al/ATSP/*p*-type Si), Al was sputtered on the back surface of Si wafer as an Ohmic contact and the front surface as a rectifying contact. Morphological properties of the ATSP thin film were characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM). Transmittance and band gap values of the ATSP thin film were determined by ultraviolet-visible (UV–Vis) spectrometry. Al/ATSP/*p*-type Si devices were characterized with *I-V* measurements under dark condition and with light illumination. These devices can potentially be developed for use as rectifiers and photodiodes.

1. Introduction

When a metal contacts with a semiconductor, there are two distinct behaviors that can be observed. Depending on the band alignment of the metal and the semiconductor, these two behaviors are Ohmic contact (non-rectifying) and Schottky (rectifying) contact [1]. Metal-semiconductor structures are well-developed devices for electronics, and can be used to form the basis of solar cells, field-effect transistors, and microwave amplifier transistors [2–4]. Generally, the metal-semiconductor contacts do not possess intimate contact themselves but rather are enabled by an insulative layer in the interface. [5]. It is possible to improve the performance of the Schottky barrier diode (SBD) by introducing interfacial metal oxides, organic layers such as polymers or high dielectric insulators [6–9]. Such improvements in the performance of the SBD are enabled due to the space charge region of the semiconductor which is shaped by the interfacial layer [10]. By changing the material of the interfacial layer, continuous tuning of some of the electrical properties can be accomplished [11,12].

Recently, the importance of the polymers in the electronics and optics industry has been highlighted [13–16]. Organic solar cells [17], organic light-emitting devices (OLED) [18] and organic field-effect transistors (OFET) [19] are the most prominent examples of electronic devices made out of polymers. Compared to their inorganic counterparts, polymers offer several advantages of facile processing (such as spin-coating or spray pyrolysis), cost effectiveness, and conformal flexible structures [20,21]. Previous works have focused on inserting a polymer interfacial layer to modify the characteristics of metal-semiconductor contacts, and the polymers used in those studies include poly (methyl methacrylate) [22], polystyrene [23], poly(vinyl alcohol) [24].

Aromatic thermosetting copolyester has striking features such as excellent specific strength, stiffness, and dimensional stability [25]. With a glass transition temperature up to 310 °C, it also shows excellent performance as an adhesive [26], outstanding wear resistance, and promising dielectric properties (reported dielectric constant of ATSP as 4.5 for non-foam form) for microelectronics [27,28]. These positive features of ATSP lead us to study this material as an interfacial layer in metal-semiconductor contacts. The aim of this study is to use ATSP as an interfacial layer between the metal and semiconductor, and to characterize its morphological properties as a thin film.

2. Experimental details

Aromatic thermosetting copolyester oligomers, in powder form, were received from ATSP Innovations, LLC, Champaign, IL. Matching

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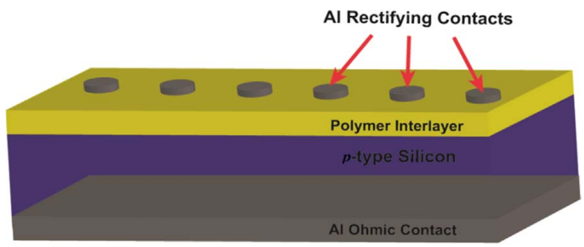

Fig. 1. Schematic diagram of Al/ATSP/*p*-Si device.

carboxylic acid and acetoxy functional group constituent oligomers were synthesized using hydroquinone diacetate (HQDA), 4-acetoxybenzoic acid (ABA), isophthalic acid (IPA), and trimesic acid (TMA) (Sigma-Aldrich Co., USA) as outlined in the prior literature [25,29,30].

To obtain Al/ATSP/*p*-type Si devices, *p*-type Si wafer which has (100) direction and 7.3×10^{15} cm^{-3} carrier concentration was used as the main structure. A large piece of Si wafer was cut into 15 mm × 10 mm pieces, and these pieces were cleaned with acetone, water, and isopropanol in an ultrasonic cleaner. After that, these pieces were placed into HF:H_2O (1:1) solution to remove native oxide layers and impurities from the surface of the wafers. A 100 nm Al layer was sputtered on the back surface of the wafers, and wafers were then annealed in an N_2 atmosphere for 5 min at 500 °C. One, two, and three layers of ATSP oligomers which, were dissolved in THF (0.005 g/ml dilute solution), were deposited on the front surface of the Si wafer by using a spin coater. The ATSP on Si wafers were cured on a hot plate at 300 °C inside Ar-filled glovebox. Finally, Al rectifying contacts were sputtered on the ATSP surfaces again using a mask. A schematic diagram of the Al/ATSP/*p*-type Si devices is shown in Fig. 1. In these devices, *p*-Si/ATSP/Al part works as rectifying contact, Al/*p*-Si part works as Ohmic contact. The devices were characterized using AFM, SEM, *I-V* and photovoltaic measurements. UV–Vis spectroscopy was performed to determine transmissivity and band gap of the ATSP thin films on a glass substrate. Asylum Research MFP-3D was used to obtain AFM images. SEM images were taken with Hitachi 4800. *I-V* and the photovoltaic measurements were performed using Keithley 2400 Picoammeter/Voltage Source, and Newport Solar Simulator (10 mW/cm^2 power density and 400–1100 nm wavelength range), respectively. Shimadzu UV-2450 was used for UV–Vis spectroscopy studies.

3. Results and discussion

ATSP film surfaces were studied using AFM to investigate surface morphology. Two different size images were acquired: 1 µm × 1 µm and the 10 µm × 10 µm scanning areas. 2D and 3D AFM images of Al/ATSP/*p*-Si devices for 1 µm × 1 µm and 10 µm × 10 µm maps are shown in Fig. 2a-d. The surface of the ATSP on Si is very smooth, and RMS surface roughness values for 1 µm × 1 µm scanning area is 0.22 nm and for 10 µm × 10 µm scanning area is 0.28 nm. Even for images as large as 25 µm × 25 µm, the RMS surface roughness is only 0.6 nm. These results have revealed that the ATSP surfaces are very suitable to use as an interface between the metal and the semiconductor as a smooth interfacial layer for the metal-semiconductor devices, which has an important role in controlling the properties of these devices [31,32].

SEM images of Al/ATSP/*p*-Si device are shown in Fig. 3. While Fig. 3a and b show SEM images of Al rectifier contact, Fig. 3c and d show SEM images of ATSP surface at different magnifications, and Fig. 3e is a cross sectional image of the device. In Fig. 3a and b, it is observed that the Al rectifier contact was successfully deposited forming a homogeneous layer on the Si surfaces by sputtering. Fig. 3c and d indicate that ATSP has a very smooth surface. This result confirms that ATSP can be used in metal/semiconductor interfaces [33]. The

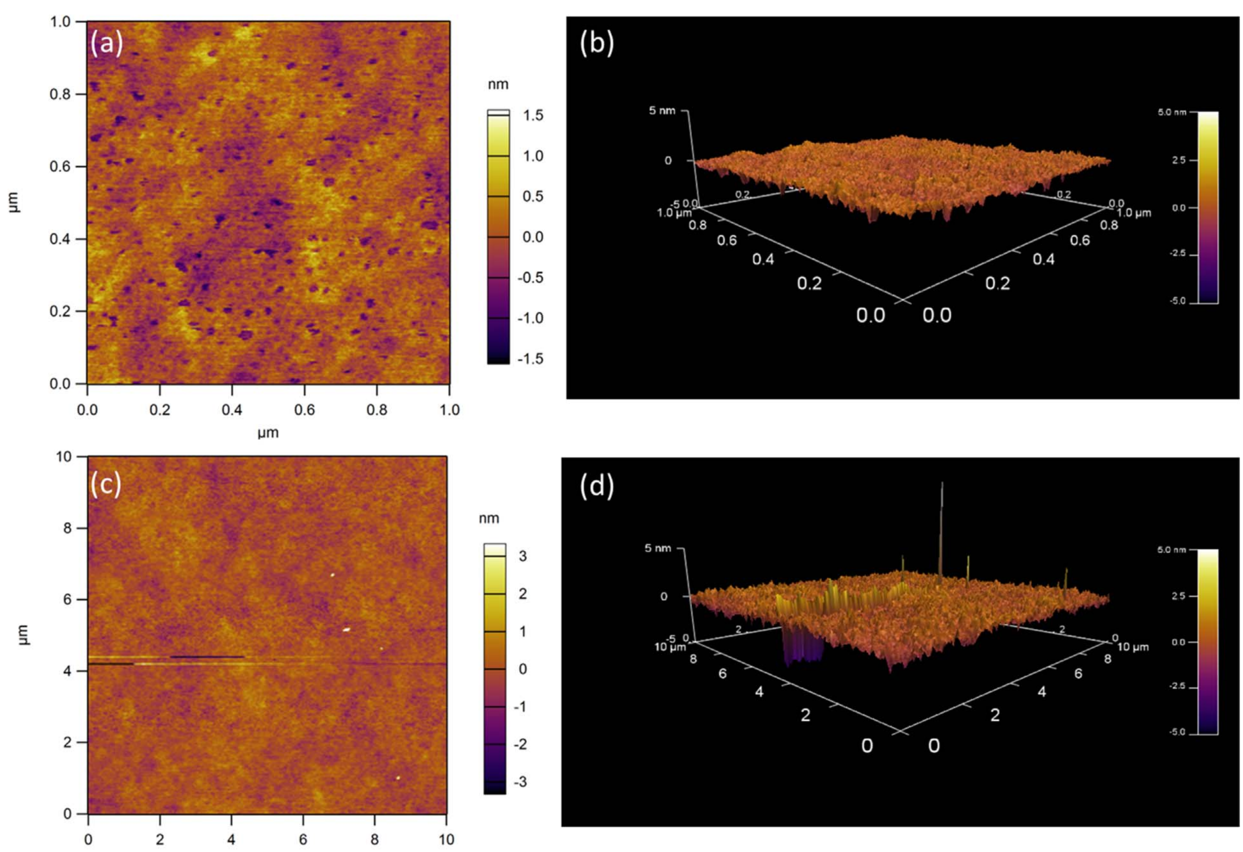

Fig. 2. AFM images of Al/ATSP/*p*-Si in 2D and 3D for 1 µm × 1 µm (a, b) and for 10 µm × 10 µm scanning areas (c, d).