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Rectified Schottky diodes based on PEDOT:PSS/InGaZnO junctions

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ABSTRACT

We report the successful use of the high-work-function, high-conductivity transparent conducting polymer PEDOT:PSS as the Schottky contact to form the Schottky junction (and thus Schottky diode) with the n-type semiconductor a-IGZO. The Schottky didoes exhibited a low apparent turn-on voltage, a high rectification ratio of $>10^5$ at ± 1 V, and a decent ideality factor of ~1.5–1.6. Detailed junction properties were systematically analyzed from J-V and C-V characteristics of the diodes. We also demonstrated the applications of PEDOT:PSS/a-IGZO Schottky junctions to various types of Schottky diodes, including the flexible, the transparent, and the flexible transparent PEDOT:PSS/a-IGZO Schottky diodes, by using different substrates and different counter electrodes.

1. Introduction

In recent years, the amorphous oxide semiconductor, amorphous indium-gallium-zinc-oxide (a-IGZO), has attracted considerable attention due to its various merits, such as high carrier mobility (>10 cm^2 V^{-1} s^{-1}) in the amorphous phase, optical transparency, and relatively low processing temperatures [1–6]. It has thus been widely adopted to realize high-performance thin-film transistors for applications ranging from displays, large-area electronics, flexible electronics/displays, to transparent electronics/displays [1–6].

In addition to thin-film transistors, rectified diodes are also an essential circuit element for realizing functional circuits in displays, large-area electronics, flexible electronics, and transparent electronics [7–11]. There had been a few reports of IGZO-based Schottky diodes in which Schottky junctions were formed between the n-type a-IGZO semiconductor (with a conduction band edge E_C around ~4.1–4.4 eV) and some high-work-function metals such as Pt, Pd, Ag, and Au etc. [12–16] Yet, these reported devices generally required noble metals (e.g., Pt, Au, Pd, Ag etc.) and relatively higher post-annealing temperatures (e.g., 200 °C) to form well-behaved rectified Schottky diodes. In addition, due to the optically opaque nature of these metal contacts, these Schottky diodes could not be made transparent for applications in transparent electronics.

In view of these, the transparent conducting polymer poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) [17–21], which typically has a high work function (~5.1 eV), appears to be a potential contact for forming the transparent Schottky junction with a-IGZO, not to mention its other merits such as excellent mechanical flexibility, solution processing capability, low processing temperature, and low cost. In addition, the conductivity of PEDOT:PSS had been substantially enhanced by various methods in recent years [17–21], so that high-conductivity PEDOT:PSS can now be successfully used as transparent electrodes alone for various electronic or optoelectronic devices [17–21]. Yet, so far there have been no reports of using high-conductivity PEDOT:PSS to form the Schottky contact with a-IGZO.

In this work, we report the use of the high-work-function transparent conductor PEDOT:PSS as the Schottky contact to form the Schottky junction (and thus Schottky diode) with a-IGZO. We first investigate the PEDOT:PSS/IGZO junction and diode characteristics on glass substrates. Then, applications of the PEDOT:PSS/a-IGZO Schottky junctions to various types of Schottky diodes, e.g., the flexible, the transparent, and the flexible transparent PEDOT:PSS/a-IGZO Schottky diodes, will also be demonstrated by using different substrates and different counter electrodes.

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2. Experiments

PEDOT:PSS/a-IGZO Schottky diodes were fabricated on glass substrates or transparent plastic substrates (e.g., cyclic olefin copolymer, COC). Fig. 1 shows the schematic structure of devices on either glass or plastic substrates. A ~75-nm-thick high-conductivity PEDOT:PSS layer was first coated onto the substrate as the bottom anode contact, which formed the Schottky contact to the a-IGZO deposited above. Then a-IGZO films were deposited by RF magnetron sputtering through shadow masks without intentional substrate heating. Finally, 50-nm-thick Mo (or 50-nm-thick indium tin oxide, ITO) was deposited by e-beam evaporation (or by RF magnetron sputtering) through shadow masks to serve as the top ohmic cathode contact (counter electrode) to a-IGZO or as the contact pad to the PEDOT:PSS contact/electrode. The actual active area of PEDOT:PSS/a-IGZO Schottky diodes was 0.4×0.4 mm^2 as defined by the overlap of the top contact area (i.e., Mo or ITO) and the bottom contact area (i.e., PEDOT:PSS). Devices adopting Mo top contacts were then tested without further post-annealing, while devices adopting ITO top contacts were further treated with a 110 °C and 30-min post-annealing to improve contact characteristics.

Thin films of high-conductivity PEDOT:PSS were prepared by spin-coating from a mixture solution of the aqueous PEDOT:PSS solution (Clevios, Heraeus Co.) and 7.5 vol% dimethyl sulfoxide (DMSO). Adding the polar co-solvent DMSO into the PEDOT:PSS had been reported to substantially increase the conductivity of PEDOT:PSS [18–21]. Spin-coated PEDOT:PSS films were subsequently annealed on a hot plate at 130 °C for 17 min under ambient conditions. A typical thickness of ~75 nm was used for the PEDOT:PSS films. With adding the 7.5 vol% DMSO co-solvent into the PEDOT:PSS aqueous solution, the spin-coated PEDOT:PSS film achieved a conductivity of 900–1000 S/cm (corresponding to a sheet resistance of ~140 Ω/□ for a 75-nm-thick film as determined by the van der Pauw measurement). More details of preparation and characterization of the high-conductivity transparent PEDOT:PSS films can be found in previous works [21].

a-IGZO thin films were deposited by radio frequency (RF) magnetron sputtering using the IGZO target (In_2O_3:Ga_2O_3:ZnO = 1:1:2 mol.%, LTS Chemical Inc.). The sputtering chamber had a base pressure of ~2×10^{-6} Torr. The deposition of a-IGZO thin films were conducted with a mixed Ar/O_2 sputtering gas (Ar/O_2 = 39/1 sccm), a working pressure of 2 mTorr, and a RF power of 150 W. In this work, different a-IGZO layer thicknesses (50–160 nm) of a-IGZO were used to study their influences on the characteristics of the Schottky diodes. The ITO top contact was also deposited by RF magnetron sputtering using the ITO target (Well-Being Enterprise Co.), with a working pressure of 1.3 mTorr, a pure Ar gas flow rate of 40 sccm, and a RF power of 60 W. All the a-IGZO and ITO films were deposited with no intentional substrate heating during growth.

The photographs in Fig. 2(*a*) and (b) show the patterns of layers for the fabricated PEDOT:PSS/a-IGZO diodes with different top electrodes (either Mo or ITO). Different combinations of (substrate, top contact) yielded different types of devices. The combination of (glass, Mo) gave the non-transparent and rigid Schottky diode as shown in Fig. 2(c); the combination of (plastics, Mo) gave the non-transparent and flexible Schottky diode (thereafter named as the flexible device) as shown in Fig. 2(d); the combination of (glass, ITO) gave the transparent and rigid Schottky diode (thereafter named as the transparent device) as shown in Fig. 2(e); the combination of (plastics, ITO) gave the transparent and flexible Schottky diode (thereafter named as the flexible transparent device) as shown in Fig. 2(f).

After the device fabrication, the current density–voltage (J–V) characteristics of the diodes were measured using an Agilent B1500A Semiconductor Parameter Analyzer. The capacitance–voltage (C–V) characteristics of diodes were measured with an impedance analyzer (Gamry Instruments Reference 600) at 100 kHz.

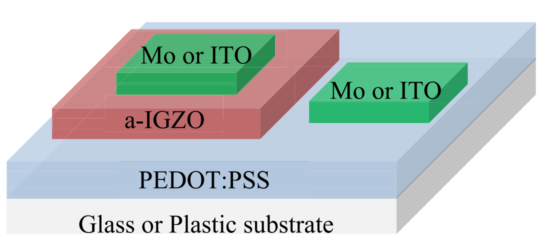

Fig. 1. Schematic device structure of the PEDOT:PSS/a-IGZO Schottky diodes on glass or plastic substrates.

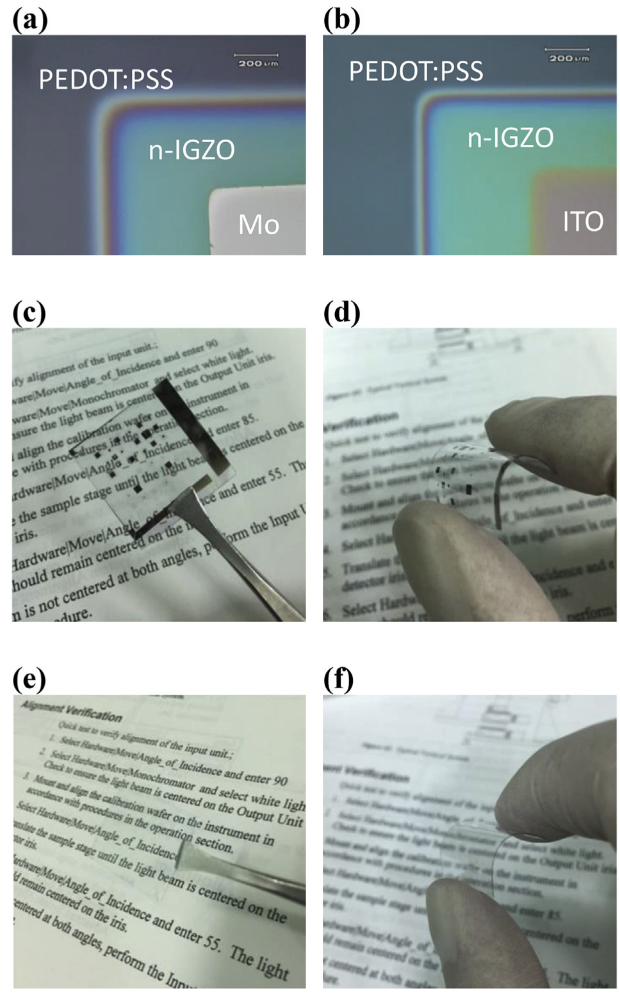

Fig. 2. (a), (b) The optical micrograph of the layer patterns of the fabricated PEDOT:PSS/a-IGZO diodes with Mo or ITO top electrodes. (c), (d) Diodes having Mo top electrodes and fabricated on the glass or plastic substrates. (e), (f) Diodes having ITO top electrodes and fabricated on the glass/plastic substrates.

3. Results and discussions

In the following, we first use the PEDOT:PSS/a-IGZO/Mo devices on glass substrates (i.e., glass/PEDOT:PSS/a-IGZO/Mo devices) to investigate and discuss the detailed junction/diode characteristics