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Electrical and photovoltaic properties of SnSe/Si heterojunction

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ABSTRACT

Thin film of SnSe is deposited on n-Si single crystal to fabricate a p-SnSe/n-Si heterojunction photovoltaic cell. Electrical and photoelectrical properties have been studied by the current density–voltage (*J–V*) and capacitance–voltage (*C–V*) measurements at different temperatures. The fabricated cell exhibited rectifying characteristics with a rectification ratio of 131 at ± 1 V. At low voltages ($V < 0.55$ V), the dark forward current density is controlled by the multi-step tunneling mechanism. While at a relatively high voltage ($V > 0.55$ V), a space charge-limited-conduction mechanism is observed with trap concentration of 2.3×10^{21} cm^{-3}. The *C–V* measurements showed that the junction is of abrupt nature with built-in voltage of 0.62 V which decreases with temperature by a gradient of 2.83×10^{-3} V/K. The cell also exhibited strong photovoltaic characteristics with an open-circuit voltage of 425 mV, a short-circuit current density of 17.23 mA cm^{-2} and a power conversion efficiency of 6.44%. These parameters have been estimated at room temperature and under light illumination provided by a halogen lamp with an input power density of 50 mW cm^{-2}.

1. Introduction

In search of new semiconducting compounds for efficient solar energy conversion through solar cells, metal chalcogenides with layered structure are increasingly studied. The physical properties of layered compounds have been a field of intensive study for many years. The binary IV–VI layered semiconducting compounds generated a great deal of interest, during the last two decades, due to their interesting electrical and optical properties [1–8]. The optoelectronic properties of these compounds make them potential candidates in many applications, especially solar cells. These properties include the following: (1) the band gap is between 1.0 and 2.0 eV, making them capable of absorbing a major portion of solar energy; (2) they are chemically and electrochemically stable in either acid or alkaline condition; and (3) the constituent elements are abundantly available and cheap. Among these compounds, tin monoselenide (SnSe) meets these conditions closely, and is a promising material for energy conversion.

Considerable attention has been paid by various researchers in studying the properties of SnSe. It has been also mentioned that it can be applied in memory switching devices [9], holographic recording systems [10,11], and infrared electronic devices [12]. SnSe has been studied in the form of both single crystal and thin films. Considerable efforts have been made by the researchers to characterize the transport properties for electronic devices [2–6,13].

The fabrication and electrical properties of heterojunction diodes based on n-SnS and p-Si were reported by Huang et al. [14]. The effect of sulfide treatment of p-Si on the power conversion efficiency (PCE) of the n-SnS/p-Si solar cell was investigated. The n-SnS/p-Si device without sulfide treatment showed a rectifying behavior with an ideality factor of 1.6 and high series resistance. However,

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the n-SnS/p-Si diode with sulfide treatment for 40 s showed a good rectifying behavior with an ideality factor of 1.4 and series resistance [14]. The synthesis and heterojunction solar cell properties of ZnS microdisks prepared by the chemical bath deposition method were investigated [15]. The ZnS deposited on the p-Si blanket substrate exhibits good coverage. Lower reflectance spectra were found as the thickness of the ZnS film increased. The power conversion efficiency (PCE) η% of the AZO/ZnS/p-Si heterojunction solar cell with a 300 nm thick ZnS film was 2.72% [15]. The optical performance of organic photovoltaic (OPV) cells incorporating graphene as a transparent anode is investigated [16], and is also compared with those of ITO based devices. It turns out that graphene based OPVs can realize 7–10% higher J_{sc} values in planar heterojunction OPVs and ~5% higher total number of absorbed photons in bulk heterojunction OPVs than those in the ITO based OPVs, depending on the absorption wavelength of the OPVs [16]. Fe/Al-doped Si multilayer was prepared by magnetron sputtering [17]. After post-annealing, the Fe/Al-doped Si multilayer was converted to Al-doped β-$FeSi_2$ thin film. The conversion efficiency of a-Si/β-$FeSi_2$/c-Si double heterojunction reached 1.45%. The improved photovoltaic property is due to the reduced defect states of β-$FeSi_2$ thin film by Al-doping [17]. The p-ZnTe/n-Si heterojunction diodes were prepared by vacuum deposition of p-ZnTe films on n-Si substrates [18]. The electrical conduction in the diodes was found to take place by thermionic emission at low voltages and by space charge limited conduction at high voltages [18].

Zang et al. [19] report the enhanced photovoltaic properties in polycrystalline $BiFeO_3$ (BFO) thin films with graphene as top electrodes. The short circuit current density (J_{sc}) and open circuit voltage of the heterojunction are measured to be 25 $\mu A/cm^2$ and 0.44 V, respectively, much higher than the reported values for polycrystalline BFO with indium tin oxide (ITO) as top electrodes [19]. Yang et al. [20] investigated graphene quantum dots (GQDs) as a cathode buffer additive in inverted polymer solar cells (PSCs), showing that GQDs can act as an excellent cathode buffer additive in inverted PSCs to increase the power conversion efficiency from 2.57% to 3.17% due to enhanced exciton dissociation and suppressed free charge recombination at the cathode/polymer active layer interface with the introduced GQDs in the buffer layer [20]. Graphene–zinc oxide nanocomposites were prepared through a hydrothermal approach and used as electron acceptors in poly-(3-hexylthiophene) (P3HT)-based bulk-heterojunction organic solar cells (OSCs) [21]. The blended film, which was a mixture of different weight ratios of P3HT and G–ZnO, was applied as the active layer in the OSC device. The power conversion efficiency (PCE) increases first and then decreases with the increase in G–ZnO content in the blended films. The device containing 15 wt% (ratio to P3HT) of G–ZnO shows the best performance with a PCE of 0.98%, an open-circuit voltage of 0.81 V and a short-circuit current density of 4.92 mA cm^{-2} [21].

In our previous research, it was found that SnSe is a p-type semiconductor and has an orthorhombic crystal structure with lattice constants a=0.419 nm, b=0.446 nm and c=1.157 nm [1]. The analysis of spectral behavior of the absorption coefficient revealed indirect and direct allowed transitions with energy gaps of 0.895 eV and 1.27 eV, respectively [1]. Bicer and Sisman obtained SnSe films by the electrodeposition method and their optical absorption study showed that the film has direct transition with band gap energy of 1.3 eV [22]. Recently, Ma et al. fabricated SnSe/Ag nanoparticles on TiO_2 nanotubes [23]. The results showed that the deposition of SnSe and Ag nanoparticles increased light absorption intensity in the wavelength range of visible light, which implied that the SnSe/Ag–TiO_2 NT is a promising ternary hybrid material in photocatalysis [23].

In this work, our purpose is to fabricate a heterojunction by depositing SnSe thin film on the top surface of Si substrate and to investigate its electrical properties using current density–voltage (J–V) and capacitance–voltage (C–V) measurements. In addition, the photovoltaic properties necessary for solar cell parameters optimization and fabrication have been reported.

2. Experimental details

A heterojunction cell of p-SnSe/n-Si (as presented in Fig. 1) was fabricated by thermal evaporation of SnSe onto n-type CZ (1 0 0) silicon single-crystal substrate doped with about 2×10^{15} cm^{-3} phosphorus. The surface of silicon substrate was first treated with a buffer etchant of CP4 solution ($HF:HNO_3:CH_3COOH$ in the ratio 1:6:1) composition for 8 s, which removed effectively the surface film of silicon dioxide (SiO_2). After etching, the silicon wafer was washed for 2 min in pure alcohol and distilled water. After the substrate cleaning, 300 nm film of SnSe was deposited on the front side of the substrate by a conventional thermal evaporation technique in a vacuum of 10^{-4} Pa using a high vacuum coating unit (Edwards, E306A).

The powder of SnSe was supplied by Morton Mhioko Inc. Alfa, England, with a purity of 99.999%. The powder was located in a quartz crucible surrounded by a tungsten filament to supply the heat energy needed for evaporation. Ohmic contact was obtained by deposition of indium fingers (as a semitransparent mesh) onto the SnSe film; however the other Ohmic contact was made by evaporation of aluminum on the back side of the silicon substrate. During evaporation, the vacuum was better than 2×10^{-4} Pa and the film thickness was monitored by a quartz crystal thickness monitor (Edwards, FTM4).

The current density–voltage (J–V) measurements of the fabricated cell were performed by measuring the current corresponding to a certain potential difference across the junction, using a conventional circuit. The voltage across the junction and current passing through it were measured simultaneously using high impedance electrometers (Keithley 610 and 617 as the voltage source and current meter, respectively). The dark capacitance–voltage (C–V)

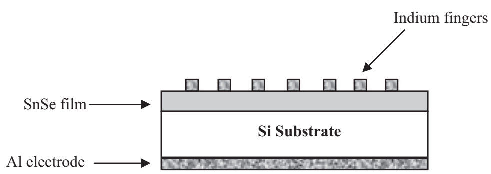

Fig. 1. Schematic diagram of In/SnSe/Si/Al heterojunction.