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Mechanisms and modification of nonlinear shunt leakage in Sb_2Se_3 thin film solar cells

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ABSTRACT

Antimony selenide (Sb_2Se_3) based thin film solar cells have recently drawn a growing research interest due to their increasing power conversion efficiency, proper bandgap, high absorption coefficient, and earth abundant nature. Herein, the Sb_2Se_3 thin films were prepared by close spaced sublimation (CSS) for efficient Sb_2Se_3 solar cells. The origin and the mechanisms of shunt current were analyzed. Non-ohmic space-charge limited current (SCLC) was identified to be an important contribution to the nonlinear shunt current in Sb_2Se_3 thin film solar cells. To tackle this issue, a high-resistance SnO_2 buffer was introduced at the front contact. With the insertion of a SnO_2 buffer, the micro-shunt paths were modified and a significant efficiency improvement to 5.18% was obtained.

1. Introduction

Antimony selenide (Sb_2Se_3) is a promising photovoltaic material with a variety of attractive features, such as proper band gap (1–1.2 eV), high absorption coefficient, intrinsically benign grain boundaries, low toxicity, earth-abundant elements and high theoretical conversion efficiency up to 31% [1,2]. Sb_2Se_3 based thin-film solar cells have demonstrated increased power conversion efficiency (~ 6.5%) in recent years [2–4]. However, due to the relatively short history and rather small scientific community devoted to the Sb_2Se_3 solar cell research, many fundamental problems, both material and device, are remained to be investigated. From the point of view of material, Sb_2Se_3 has a one-dimensional (1D) crystal structure. The film growth and microstructure are very sensitive to preparation process and experimental conditions. To improve the solar cell performance further, the most challenging work is to obtain high quality Sb_2Se_3 film [4]. So far, various approaches including vacuum evaporation, sputtering, spin-coating, electrodeposition, spray pyrolysis, and chemical bath deposition have been explored to fabricate the Sb_2Se_3 thin films [4–10]. Tang et al. had developed a fast Sb_2Se_3 film deposition based on rapid thermal evaporation (RTE) technique, which demonstrated a simple and successful method to get high quality p-Sb_2Se_3 layer that can be finished in tens of seconds [2,4]. From the point of view of device, the CdS/Sb_2Se_3 thin film solar cell is typically made in the superstrate configuration with Glass/TCO/CdS/Sb_2Se_3/Metal structure [3,4]. Thickness of the Sb_2Se_3 layer influences the performance of the devices. Taking into account the factors such as the optical absorption coefficients, the junction depletion width and the minority carrier (electron) diffusion length, the optimal thickness of the Sb_2Se_3 absorber layer was found to be about 500 nm [11]. This is a rather small thickness and is one reason for the limited efficiency of the devices reported. In Sb_2Se_3 solar cells, the CdS layer works as a n-type window layer, which absorbs photons with energy greater than its bandgap of 2.42 eV [12]. In order to reduce the light absorption in the CdS window layer, the thickness of CdS layer should be decreased to as thin as several ten nanometers. However, when the CdS layer is too thin, the pinholes or discontinuity would inevitably happen so that Sb_2Se_3 directly contacts the front electrode, leading to electric micro-shunt paths and low quality p-n junction diode [12,13]. In addition, due to the fabrication procedure of superstrate structure, the interdiffusion/reaction occurred at the CdS/Sb_2Se_3 interface during the subsequent deposition of Sb_2Se_3 would lead to part of the CdS consumed up [14]. Actually, the discontinuity in CdS or the interdiffusion at junction interface induced shunt leakages have been reported in both superstrate CdTe thin film solar cells and substrate $CuIn_{1\text{-}x}Ga_xSe_2$ thin film solar cells [15,16]. Shunt leakage is a key issue affecting solar cell performance especially for large area thin film solar cells. Shunt currents are detrimental to the cell/module output parameters, especially fill factor (FF) and open-circuit voltage (V_{oc}) [13]. Understanding the origin of shunt current and minimizing shunt current loss are essential to enhance solar cell efficiency further.

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Herein, we employ close spaced sublimation (CSS) deposition to grow Sb_2Se_3 thin films. CSS is a rapid and industrially scalable deposition technique which was widely used in many kinds of inorganic film deposition for photovoltaic application, like binary compound CdTe [17]. This work demonstrated that CSS is highly suitable for fabrication of Sb_2Se_3 thin film solar cells. Focusing on the relatively large and nonlinear shunt current discovered in this study, we tried to make clear the physical origin of shunt leakage in Sb_2Se_3 solar cells and to find solutions to improve the device performance. On the basis of the experiments and theoretical models, the device characteristics were analyzed and the non-ohmic space-charge limited current (SCLC) was identified to be responsible for the nonlinear shunt current in Sb_2Se_3 solar cells. The shunt paths were found mainly caused by the local discontinuity or pinholes in the CdS window layer. With the insertion of a high-resistance tin oxide layer as front contact buffer, the micro-shunt paths were effectively modified. The presence of SnO_2 buffer significantly reduced the shunt current and improved the junction quality, resulting in the cell efficiency increasing from 3.73% to 5.18%.

2. Experimental

The Sb_2Se_3 solar cells fabricated in this study had superstrate structures of glass/FTO/CdS/Sb_2Se_3/Au or glass/FTO/SnO_2/CdS/Sb_2Se_3/Au. CdS window layers with a thickness of ~ 60 nm were prepared on glass/FTO or glass/FTO/SnO_2 substrates by chemical bath deposition (CBD) technique from a solution composed of de-ionized water, cadmium acetate, ammonium acetate, and thiourea. The Sb_2Se_3 absorber layers, which had a thickness of ~ 550 nm, were deposited by the CSS technique in a home-made film-deposition system, as sketched in Fig. 1(a). The source material is commercial Sb_2Se_3 powder with 99.999% purity. The source temperature was 520 °C and the substrate temperature was 320 °C. The detailed CdS and Sb_2Se_3 fabrication processes can be found in our previous work [10,15]. The highly resistive SnO_2 buffer layer between FTO and CdS was deposited by the RF magnetron sputtering technique at a substrate temperature of 200 °C. A 99.99% SnO_2 target (diameter 3 in.) was sputtered in a reactive gas mixture of O_2 and Ar with an O_2/Ar pressure ratio of 1/20. The working pressure was 0.5 Pa and the RF power was 60 W. The SnO_2 layer thickness was controlled by varying the sputtering time. The Au back contact was prepared by thermal evaporation in a vacuum chamber. The size of individual Sb_2Se_3 solar cell was $4 \times 4\,mm^2$ defined by Au contacts.

The film morphologies were characterized by using a field emission scanning electron microscope (SEM, FEI Apreo LoVac) and conductive atomic force microscopy (C-AFM, Veeco Multimode V). X-Ray Diffraction (XRD) measurements were performed by an X-ray diffractometer (Bruker D8 Advance). The solar cell current density–voltage (J–V) curves of Sb_2Se_3 solar cells were recorded using a Keithley 2400 source measurement unit and a Newport solar simulator (Oriel-SOI3A) with an AM1.5 G spectrum. The light intensity was adjusted to 100 mW/cm^2 using a standard Si solar cell (91150 V). The external quantum efficiency (EQE) spectra were measured with a spectral response system (Enlitech QE-R).

3. Results and discussion

3.1. Properties of Sb_2Se_3 thin film and solar cell performances

The quality of the Sb_2Se_3 absorber layer is crucial to the performance of Sb_2Se_3 solar cells. Fig. 1(b) shows the surface morphology of a

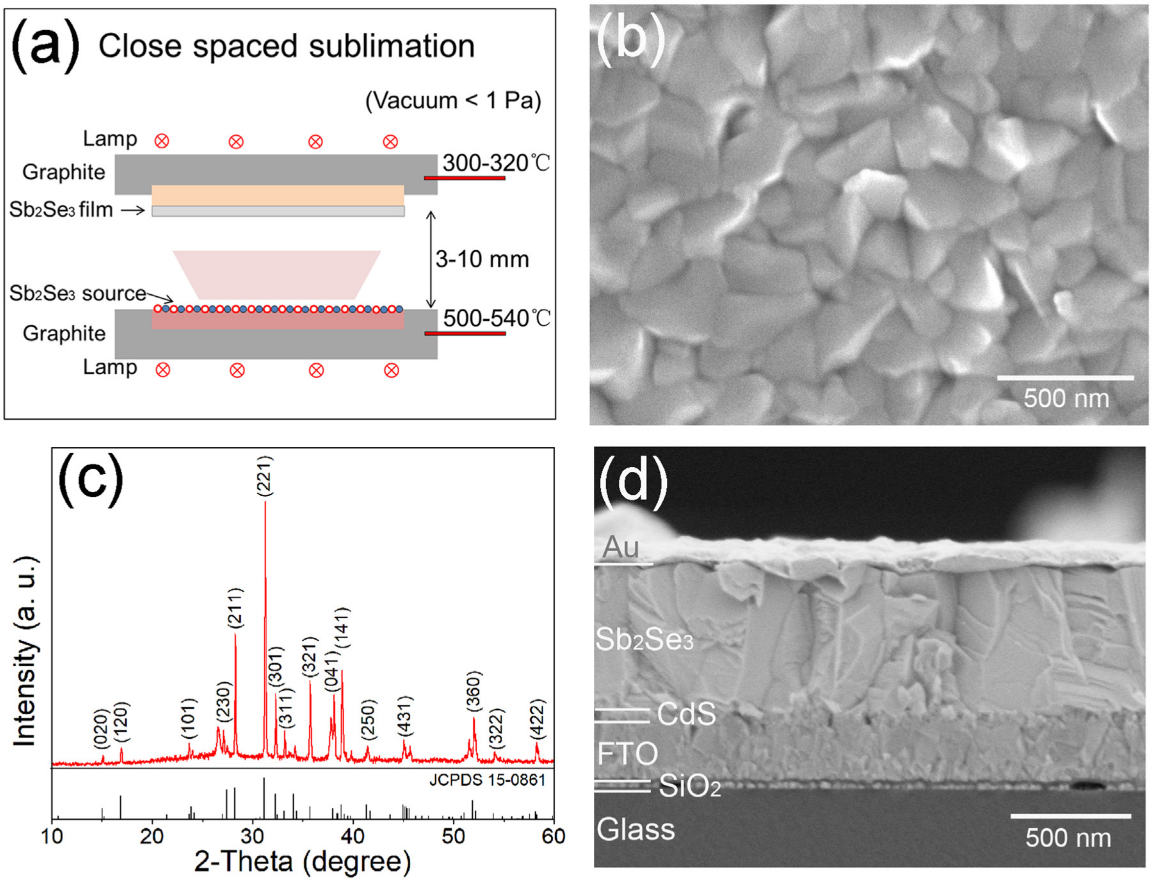

Fig. 1. (a) The schematic diagram of CSS equipment for Sb_2Se_3 film deposition; (b) SEM surface morphology and (c) XRD pattern of Sb_2Se_3 film with a thickness of ~ 550 nm; (d) cross-sectional SEM image of a Sb_2Se_3 thin film solar cell with a structure of glass/FTO/CdS/Sb_2Se_3/Au.