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Thickness-dependent field emission from ZnTe films prepared by magnetron sputtering

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ABSTRACT

The thickness effect on the field emission properties of ZnTe films deposited on silicon substrates by magnetron sputtering is investigated. All the films exhibit amorphous structure with nanocrystalline embedded. As the thickness increases, the surface becomes much smoother, while the Zn/Te ratio, the turn-on field and the work function decrease. Their field-emission characteristics show a low turn-on field of 7.5 $V\mu m^{-1}$ and a high current density of 67 $\mu A cm^{-2}$ at an electric field of 8.9 $V\mu m^{-1}$. The thickness-dependent electron field emission phenomenon is explained by a space-charge-induced bandbending interlayer model.

1. Introduction

Developments of electron field emitters with high performance such as high-emission current operation at a low voltage are strongly desired for applications to vacuum microelectronics and flat panel field-emission displays (FED) [1,2]. Recently, many researches have been carried out on different field emitter materials, such as metals (Cs [3]), wide band-gap semiconductors (GaN [4], AlN [5], ZnO [6]), carbon nanotubes [1], graphene [7], diamond or diamond-like carbon [8,9]. However, no studies have been reported on the field emission (FE) properties of zinc telluride (ZnTe) up-to-date. The current researches on FE properties of ZnTe films pave the way for more detailed studies and will be impetus for novel and intriguing functional applications.

ZnTe, as a direct semiconductor with a band gap of 2.28 eV at room temperature and a work function of 5.43 eV [10,11], is an attractive II–VI group compound for various optoelectronic devices, such as green light emitting diodes (LEDs) [12], photodetectors [13], and photovoltaic solar cells [14,15]. Many methods have been used to grow ZnTe films, such as electrodeposition [16], metal organic vapor phase epitaxy [17], molecular beam epitaxy [18], vacuum evaporation [19], magnetron sputtering [20]. Among them, sputtering technique is an economical, widely used and low temperature synthesis route and would be potentially suitable for large area flat panel displays [21]. Generally, during sputtering process, the properties of ZnTe films depend largely on various deposition parameters. The deposition time, namely thickness, greatly influence the crystal structure, composition and morphology of the films which in turn affect the electric and opto-electric properties of films. Salem et al. reported that the particle size and the refractive index of the ZnTe films, deposited by electron beam gun evaporation technique, increased and the estimated optical gap energy value decreased with the increase of the film thickness [22]. In addition, Balu et al. found that the root mean square value of the roughness decreased and the conductivity increased with increased thickness of ZnTe films [23]. Farag et al. observed that due to increased crystallite size and reduced internal potential barrier, the mobility increased with increased thickness of ZnTe films, and the transition voltage between the Ohmic conduction and trap-charge limited conduction was proportional to the thickness of the films [24]. However, no report has been made on the thickness-dependent FE properties of ZnTe films.

In this paper, the thickness effect on the FE properties of ZnTe films is investigated. In order to understand thickness effect, the films were characterized by employing glancing incidence X-ray diffraction (GIXRD), high resolution transmission electron microscopy (HR-TEM), field-emission scanning electron microscopy (FE-SEM), and current–voltage (I–V) measurements.

2. Experimental

ZnTe films were grown on n-type Si(100) substrates ($1 \times 1 cm^2$, 0.8–1.2 Ω cm) by magnetron sputtering with a pulsed DC power supply. The pulse frequency and the duty factor of the supply were fixed to 40 kHz and 70%, respectively. An stoichiometric ZnTe metal plate (purity > 99.999%) with a diameter of 80 mm was used as target. Prior to deposition, the chamber was pumped down to 1.0×10^{-3} Pa by a turbo molecular pump. Then Ar gas (purity > 99.99%) with a flow rate of 30 SCCM (SCCM denotes standard cubic centimeter per minute at STP) was

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introduced to the sputtering system. The sputtering pressure and current of deposition were retained to 5.0 Pa and 0.1 A, respectively in this work. The growth time varied from 5 to 30 min. The as-prepared thin films adhered well to Si substrates and didn't undergo any thermal treatment.

The structure characteristic of the films was determined by GIXRD using a Philips X'Pert diffractometer with Cu Kα1 radiation (λ = 1.54056 Å). Further structural analysis of films was carried out by a HR-TEM (FEI Tecnai F30). Surface morphologies and composition were characterized by a FE-SEM (Hitachi S-4800) equipped with an energy-dispersion X-ray detector (EDX, INCA300). The field emission measurements were carried out in a parallel-plate-electrode configuration at a pressure of 6.0×10^{-5} Pa by our home-made automatic characterization system. During the measurements, the interelectrode distance remained 200 μm. The emission data were taken at room temperature after stabilized emission current was achieved. The emission *I–V* characteristics were measured by LabVIEW programming through a Keithley 248 power source with a computer-controlled data-acquisition card.

3. Results and discussion

The XRD patterns of ZnTe films with various growth time of 5, 15 and 30 min are shown in Fig. 1. It can be seen that no obvious peaks can be ascribed to ZnTe, Zn, or Te phases except the peaks originated from Si (200) plane, indicating all the films are of typical amorphous structure despite of the increased growth time. Given that XRD is nonsensitive to nanocrystalline phases, further HR-TEM characterization of the films has been conducted. Fig. 2(a) shows a typical plane-view TEM image of the 5 min grown film, indicating that the film contains very fine grains with an average size of about 3 nm embedded in the amorphous matrix and the grains have random orientations. The inset image shows a ring pattern from a selected area electron diffraction (SAED), illustrating the polycrystalline nature of the film.

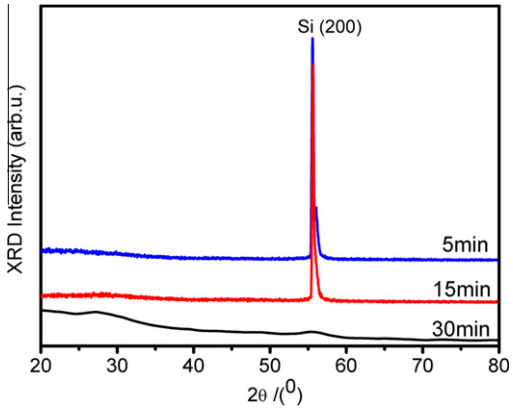

Fig. 1. XRD patterns of ZnTe films with various growth time of 5, 10, and 30 min.

Surface morphologies of synthesized ZnTe films were observed through SEM. It can be seen from the Fig. 2(b–d) that the films consist of many tiny particles. As the growth time increases from 5 to 30 min, the particle size decreases and the surface becomes much smoother. Additionally, the composition and thickness of the films were determined from EDX and cross-section SEM images, respectively. The ratio of Zn/Te and thickness of the films are listed in Table 1. As the thickness increases, the the Zn/Te ratio reduces from 1.07 to 0.48 Fig. 3 depicts the emission current density of ZnTe films versus the applied electric field curve (*J–E*). It is noted that the emission current density *J* exponentially increases with an increase of the applied field *E*. resulting in a decreased resistance (data not shown here), which is consistent with results obtained by Takahiro et al. [25]. This improved conductivity may advantage the current forming and following in the films.

Their field-emission characteristics show a low turn-on field (defined as the electric field at the emission current density of 10 μA/cm^2) of 7.5 Vμm^{-1} and a high current density of 67 μAcm^{-2} at an electric field of 8.9 Vμm^{-1}. The turn-on field of ZnTe films with different thickness is also listed in Table 1. It is obvious that with increasing film thickness the turn-on field decreases and the current density increases remarkably. Thus, it can be inferred that the thickness has evident effect on the field emission behavior of the films. In order to address this effect, different modes have been proposed to describe electron field emission from thin films.

The FE *J–E* characteristics are first analyzed by the Fowler–Nordheim (*F–N*) equation [26],

$$J = \left(\frac{A\beta E^2}{\phi}\right) \exp\left(\frac{-B\phi^{3/2}}{\beta E}\right) \quad (1)$$

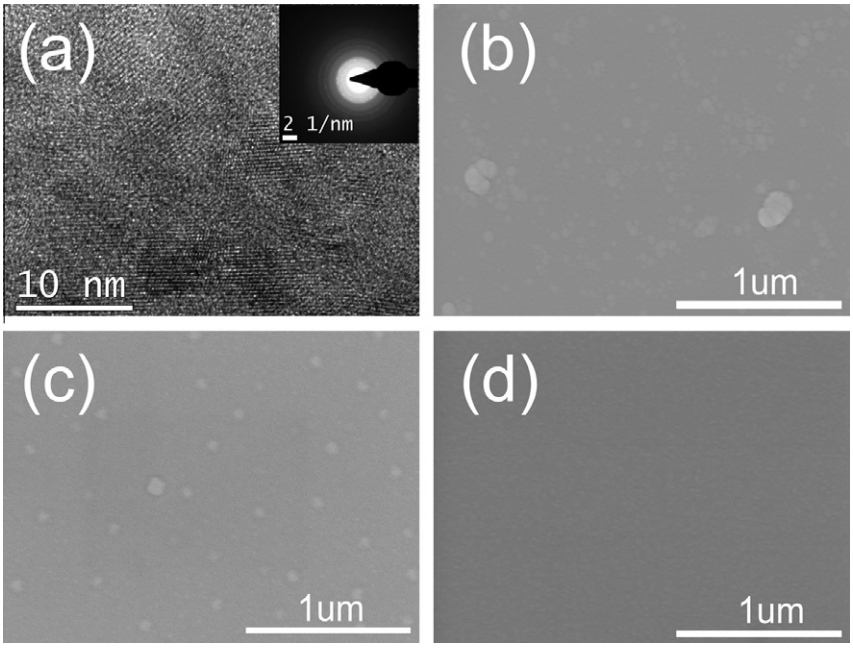

Fig. 2. (a) HR-TEM image of ZnTe film grown for 5 min. the inset is the pattern of SAED. Plane SEM images of ZnTe films with various growth time of 5 (b), 10 (c), and 30 min (d).