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Studies on the photoconductivity of vacuum deposited ZnTe thin films

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ABSTRACT

The present paper reports the analysis of photoconductivity of vacuum deposited zinc telluride (ZnTe) thin films as a function of substrate temperature and post-deposition annealing. Detailed analyses were first carried out to understand the effect of substrate temperature and annealing on the structure, composition, optical and electrical properties of the films. The films deposited at elevated substrate temperatures showed faster and improved photoresponse. Post-deposition annealing was found to further enhance the photoresponse of the films. Attempts have been made to explain the improvement in the photoresponse on the basis of structural and compositional changes, taking place in the films, due to the substrate temperature and annealing.

1. Introduction

The II–VI compound semiconductors are known for their wide and direct bandgaps, because of which they have many potential applications in optoelectronics. ZnTe is one such II–VI semiconductor, having a direct bandgap of 2.26 eV at room temperature [1,2]. This bandgap energy corresponds to a wavelength of about 550 nm which falls in the green region of the electromagnetic spectra. Hence ZnTe is a potential candidate for the fabrication of green light emitting diodes [3–6]. Besides ZnTe is also a promising material for the fabrication of various devices such as THz emitters and detectors [3,7], and photodetectors.

One of the main potential applications of ZnTe is the photodetection in visible region. At present silicon is widely used for photodetectors in the visible region although its bandgap is not optimal and its quantum efficiency is very low. On the other hand, ZnTe has optimum bandgap energy and high quantum efficiency for photodetection in visible region. Studies on photodetection properties of ZnTe are therefore very useful for the fabrication of photodetectors. The properties of ZnTe in thin film form depend largely on various deposition parameters. The conditions maintained at the time of deposition greatly influence the crystal structure, composition and morphology of the films which in turn affect the electric and opto-electric properties of the films. In the present paper the effect of substrate temperature and post-deposition annealing on the photoconductivity of vacuum deposited ZnTe films has been investigated.

2. Experimental

ZnTe films were deposited on glass substrates by thermally evaporating 99.99% pure ZnTe ingots (from Aldrich) in a molybdenum boat inside a 12 in. vacuum chamber (HINDHIVAC 12A4D). A residual pressure of 10^{-5} Torr was maintained inside the vacuum chamber at the time of deposition. The films were deposited at various substrate temperatures, ranging from 300 K to 553 K. Annealing of the films was carried out inside a hot air oven at about 553 K for 2 h. Typical ZnTe films having thickness of about 900 nm were used for characterization. Structural and compositional studies of the films were done by X-ray diffraction analysis (Rigaku Miniflex, Cu Kα) and Energy dispersive analysis by X-rays (JEOL JSM 5800) respectively. Optical absorbance spectra of the films were obtained by a UV–Visible spectrophotometer (Ocean Optics). Electrical measurements were made by Keithley Sourcemeter (Model 2400) and Multimeter (Model 2002) using ohmic silver contacts deposited on the films. Electrical conductivity and carrier mobility of the films were measured by Hall effect experiment using Van der Paw setup [8]. Spectral response of the ZnTe films was studied using a photoconductivity measurement setup comprising of a 150 W Xenon arc lamp (New Port), a computer interfaced monochromator (PI-Acton) and a photomultiplier tube (PMT) detector. The films were kept within a dark chamber. The light from Xe arc lamp was allowed to pass through the monochromator to obtain monochromatic light of desired

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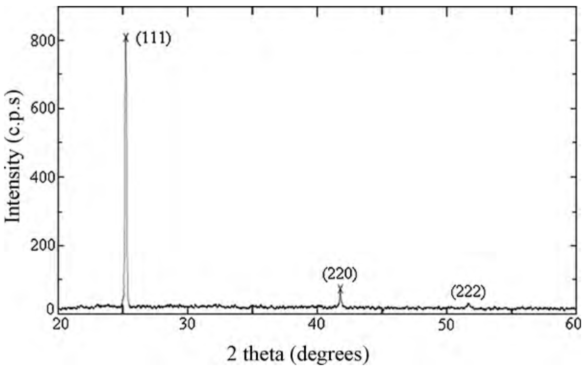

Fig. 1. A typical XRD pattern of vacuum deposited ZnTe thin film deposited at 553 K.

wavelength. This monochromatic light was then allowed to incident on the film. The resultant photocurrent was determined by measuring the difference between dark and illuminated currents. In order to determine the rise and decay times of photocurrent, pulsed light was made to incident on the film and the corresponding photoresponse of the film was analyzed. An optical chopper was used to obtain pulsed light from the Xe arc lamp. The power density of the pulsed light was about 0.35 mW cm^{-2}. A DC bias voltage of about 9 V was applied to the film in order to drive the photogenerated carriers through a circuit containing a standard resistance. The resultant electric field driving the photocurrent was 90 V/cm. Any rise or fall in the circuit current, due to the changes in photocurrent, resulted in the corresponding rise or fall of voltage across the resistor which was then analyzed by the help of a digital storage oscilloscope (HP 54603B).

3. Results and discussion

The X-ray diffraction analysis revealed that the films are polycrystalline in nature, having cubic structure with a strong (1 1 1) texture (Fig. 1). Considerable increase in grain size was observed both for the films deposited at elevated substrate temperatures and for the films annealed after deposition (Table 1). Since vapor pressures of zinc and tellurium are different, the films deposited at room temperature were rich in tellurium. Nearly stoichiometric films were obtained at elevated substrate temperatures (~553 K) due to the re-evaporation of excess tellurium (Table 2). Annealing also has similar effect on the films. The increased grain size and near stoichiometric composition of the films, deposited at higher substrate temperatures, together reduce the defects which act as carrier traps in the films. As a result, the films deposited at higher substrate temperatures show higher carrier mobility and electrical conductivity (Table 3). The detailed results of XRD, EDAX, optical and electrical characterization of the films have been published elsewhere [9]. A typical absorbance spectrum of the ZnTe film is shown in Fig. 2. The absorption coefficient α of the film was determined from this spectrum, for various frequencies ν. The absorption coefficient α is related to the optical bandgap E_g by the equation [10]

$$\alpha h\nu = B(h\nu - E_g)^n \tag{1}$$

where B is a constant which depends on the nature of transition and n is a number which can take the values 1/2, 3/2, 2 or more depending on whether the transition is direct-allowed, direct-forbidden, indirect-allowed or indirect-forbidden. In the present case of ZnTe thin films, the plot of $(\alpha h\nu)^2$ vs. $h\nu$ (inset of Fig. 2) shows a linear portion indicating that the relation in Eq. (1) holds good for ZnTe films if $n = 1/2$. This means that the optical transitions in the case of ZnTe films are direct transitions. The linear portion of the curve was extrapolated to get the optical bandgap (inset of Fig. 2) and the value of band gap thus obtained is equal to the bulk value of 2.26 eV.

The normalized spectral response curves of the films are shown in Fig. 3. The spectra show a peak at about 550 nm which corresponds to the bandgap (2.26 eV) of ZnTe. Photocurrent decreases on either side of this peak. The decrease in photocurrent in the shorter wavelength region can be attributed to the high rate of surface recombination [11]. A slightly broader peak was observed at longer wavelengths. This broader peak arises due to the multiple trap levels present within the bandgap [12]. The mechanism of photoconductivity in ZnTe films can be explained, to

Table 1
The grain size of ZnTe films deposited at various substrate temperatures.

Substrate temperature (K)	Grain size (Å)
300	379
300[a]	513
373	433
473	503
553	552

[a] Annealed at 523 K.

Table 2
The Zn:Te atomic ratio of ZnTe films deposited at various substrate temperatures.

Substrate temperature (K)	Zn:Te
300	0.84
300[a]	0.96
373	0.88
473	0.94
553	1.01

[a] Annealed at 523 K.

Table 3
The electrical parameters of ZnTe films deposited at various substrate temperatures.

Substrate temperature (K)	Mobility (cm^2/V s)	Resistivity (Ω cm)
300	12.8	1538
300[a]	32.4	367
373	21.2	709
473	36.9	310
553	37.6	287

[a] Annealed at 523 K.

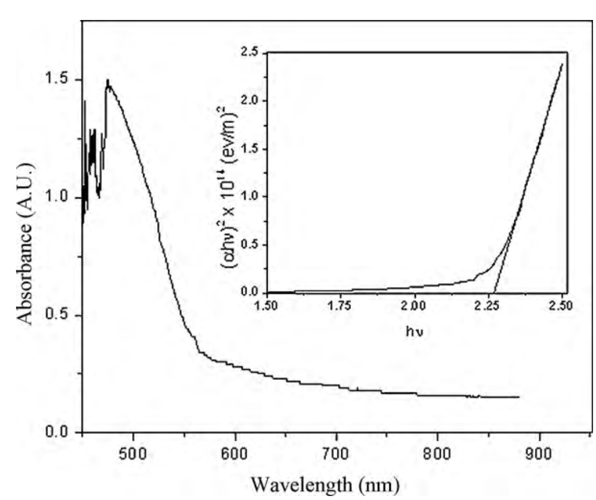

Fig. 2. A typical absorbance spectra of ZnTe film deposited at 553 K (Inset: The graph of $(\alpha h\nu)^2$ vs. $h\nu$).

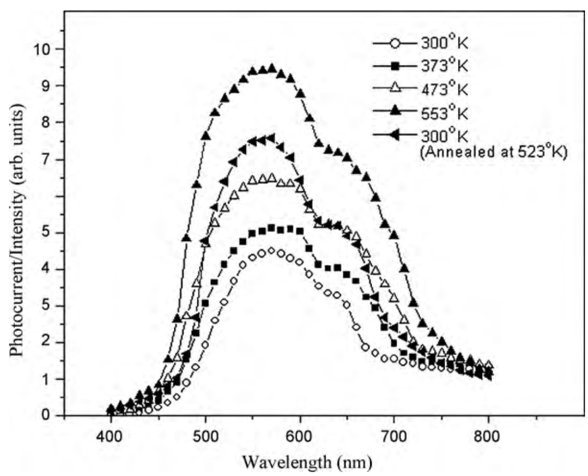

Fig. 3. The normalized spectral response curves of ZnTe thin films deposited at various substrate temperatures.

a good extent, by the models proposed by Slater [13] and Petritz [14]. According to these models, illumination of the films leads to the generation of free charge carriers and lowering of the inter-grain potential barriers in the films. The increase in photocurrent, with the increase in substrate temperature, is caused by the higher mobility of charge carriers. Annealing of the films also increased the photocurrent. The ratios of film resistance under dark (R_d) and illuminated (R_i) conditions, given in Table 4, further emphasize the improvement in photoresponse with substrate temperature and annealing. Since the films show maximum photosensitivity at 550 nm, all the reported studies were carried out at this wavelength.

Fig. 4 shows a typical response of the film for an incident light pulse. The rise in photovoltage is quick, followed by a relatively slow decay. The rise and decay times observed for the films are given in Table 5. The decay curve follows the equation [15],

Table 4
The ratios of film resistance under dark (R_d) and illuminated (R_i) conditions for films deposited at different substrate temperatures.

Substrate temperature (K)	R_d/R_i
300	3.73
300[a]	17.17
373	5.23
473	15.33
553	21.11

[a] Annealed at 523 K.

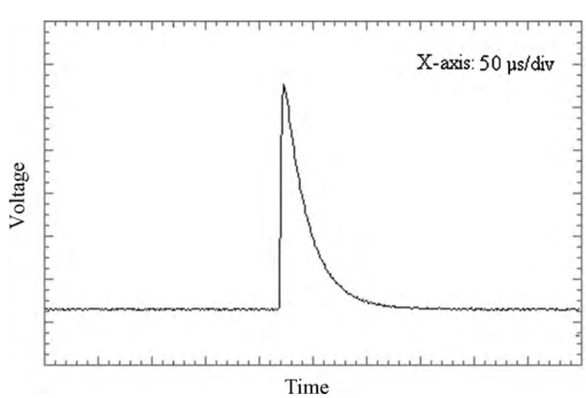

Fig. 4. Typical response of ZnTe thin film (deposited at 373 K) to an incident light pulse.

Table 5
The rise and decay times of photocurrent for films deposited at different substrate temperatures.

Substrate temperature (K)	Rise time (μs)	Decay time (μs)
300	17	89
300[a]	8	33
373	12	56
473	8	31
553	7	25

[a] Annealed at 523 K.

$$V_t = V_0 \exp(-pt) \quad (2)$$

where V_t is the voltage across a standard resistor connected in series with the film sample at any instant of time t and p is the probability of escape of an electron from the trap per second; which is given by,

$$p = S \exp(-E_t/kT) \quad (3)$$

where $S = 10^{10}\ s^{-1}$ is the frequency factor and E_t is the trap depth.

The values of trap depth E_t computed for the ZnTe films were in the range of 0.30–0.34 eV. Both the rise and the decay times reduce considerably with increase in the substrate temperature. This is attributed to the reduction in the trap density in the films at higher substrate temperatures. The carrier traps in the films hold the photoinduced carriers for longer duration. Hence when the trap density reduces, the photoresponse of the films becomes faster. Since annealing also reduces the trap density in the films, the same result can be seen in the films which were annealed after deposition.

The variation of photocurrent with power density of incident light is shown in Fig. 5. The photocurrent i_{ph} varies with the light power density P according to the power law [16],

$$i_{ph} \propto P^m \quad (4)$$

where m is a constant. In the present case the value of m was found to be in between 0.76 and 0.81, which means that the variation is sublinear (i.e. $m < 1$). This sublinear behaviour of the curves can be attributed to the exponential distribution of the traps in the bandgap [16]. As the intensity of the radiation increases, the quasi-Fermi level shift towards the conduction band edge and an increasing number of traps are converted into recombination centers.

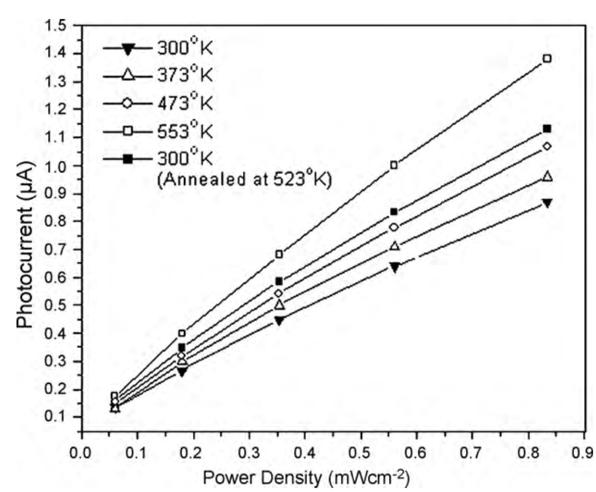

Fig. 5. The variation of photocurrent with power density of the light for films deposited at different substrate temperatures.

4. Conclusions

ZnTe thin films, vacuum deposited on glass substrates kept at different temperatures, have been characterized by various methods to understand the effect of substrate temperature on the structural optical and electrical properties of the films. The films deposited at a substrate temperature of 553 K showed better and faster photoresponse. Annealing of the films also produced similar results. The variation of photocurrent with intensity of incident light was found to be sublinear due to the exponential distribution of traps in the bandgap.

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