

# Influence of temperature, thickness and intensity of illumination on the capacitance-voltage and current-voltage characteristics of coplanar ZnTe thin films

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This paper examines the influence of temperature, thickness and illumination of different intensities on the capacitance-voltage ( $C-V$ ) and current-voltage ( $I-V$ ) characteristics of coplanar ZnTe thin films of thickness range (300-700 nm). Capacitance-voltage ( $C-V$ ) measurements of ZnTe thin films were performed by a sweep of voltages from -10 to +10 V at different elevated temperatures in the range 298-398 K. The temperature dependence of the measured capacitance for the different applied voltage was studied. The dependence of capacitance on the reciprocal of film thickness, yields a permittivity value of ZnTe, assuming that the capacitance follows a simple parallel plate relationship. The current-voltage ( $I-V$ ) characteristics of ZnTe films at room temperature (RT) for different thicknesses showed the Ohmic conduction mechanism at low voltages, while at higher voltages, the trap-charge-limited conduction (TCLC) was dominant. The temperature dependence of current allows the determination of some essential parameters of ZnTe. Discussion of the obtained results and their comparison with the previously published data are also given.

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## 1. Introduction

Research and development on thin films has led to the conclusion that different classes of materials are of particular interest for different applications. Semiconductor compounds of the  $A^{II}B^{VI}$  group have attracted considerable interest of the international physical community due to their potential for solving a number of problems in semiconductor electronics and optoelectronics and thus remain in the focus of considerable intellectual and funding effort in the world's leading industrial countries [1].

In recent years, zinc telluride (ZnTe), has been the focus of great interest due to its low cost and high absorption coefficients for applications in photovoltaic, photo-electrochemical cells [2-4], optoelectronic devices such as pure-green light-emitting devices, terahertz detectors, solar cells, waveguides and modulators. ZnTe has a direct band gap of 2.2–2.3 eV at room temperature and it is usually a p-type semiconductor. These have generated a great deal of effort toward the growth and characterization of this material. To the present, ZnTe films were prepared by different techniques such as thermal evaporation [5], hot-wall evaporation [6], radio-frequency sputtering [7], molecular beam epitaxy [8], solvothermal process [9-10] and electro-deposition [11].

Most of the reports address themselves to the structural aspects of ZnTe films [12] emphasizing the

inter-relation between the substrate materials, film structure [13] and their optical applications in industry as well as in their practical use [14]. Although there have been a number of investigations on the electrical, optical and structural properties of the films, limited systematic study appears to have been done on the current-voltage and capacitance-voltage characteristics for the coplanar geometry of ZnTe film which has been proposed to eliminate the effect of electrode on the electrical characteristics of the film. Moreover, there is a considerable lack of understanding the effect of different temperatures and illumination on the properties of this structure.

In the present work, we have reported the investigation of the high frequency capacitance-voltage ( $C-V$ ) and current-voltage ( $I-V$ ) characteristics of ZnTe films. Such studies of Ohmic and space charge limited conduction in ZnTe are capable of providing considerable insight into charge transport mechanisms and carrier trapping in this material. Such information is of particular importance in the development of viable ZnTe thin film applications. Measurements were performed in the temperature range 298-393 K under dark and illumination at different intensities in the range 500-2000 lx.

## 2. Experimental

Thin films of ZnTe were prepared using thermal evaporation technique with thickness ranging from 300 to 700 nm, deposited onto a pre-cleaned glass substrates separated 21 cm from the source of evaporation, which keeps substrate at room temperature during the deposition. A high vacuum coating unit (Edwards, E-306A) was used. Thin films were deposited by using a molybdenum boat under vacuum of  $2 \times 10^{-5}$  Torr. The rate of deposition was  $10 \text{ nm.s}^{-1}$  and the film thickness were controlled using a quartz crystal thickness monitor (FTM4, Edwards). X-ray diffraction pattern of ZnTe thin film contain only one single crystalline peak of {111} plane of a cubic phase. This crystalline peak represents the preferred orientation (permanent plane) in this films.

Two Aluminum electrodes were evaporated firstly on the pre-cleaned glass substrates to be used for the electrical contacts as described before [15]. This coplanar configuration was used to eliminate the effect of electrodes on the electrical properties of ZnTe films as shown in Fig. 1 [16]. Capacitance-voltage measurements were performed on ZnTe film samples using a computer controlled 410 C-V meter with an operating frequency at 1 MHz. The measurements were performed under a sweep of voltage from -10 to +10 V in the temperature range 298-398 K. The temperature of the device was recorded using chromel–alumel thermocouple (Type-K) connected to temperature controller. The measurements of the current-voltage ( $I-V$ ) characteristics in dark were taken using high internal impedance electrometer (Keithely 617A).

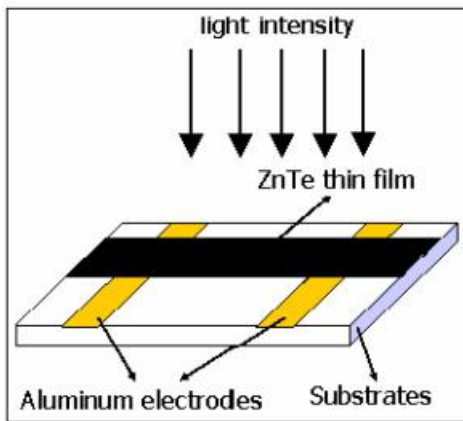


Fig.1. ZnTe thin film and aluminum electrodes pattern as-deposited on a glass substrate. This design is chosen in order to minimize the effect of the electrical contacts on the measured signal.

The source of light was a 500 W halogen lamp containing iodine vapor and tungsten filament. A water filter was used to eliminate the far infrared component from the light source. The intensity of light was measured with a digital lux meter (LX-101, Taiwan). The intensity of light was varied by changing the voltage across the lamp. During the effect illumination on the investigated

samples, the silver electrodes were well-covered with aluminum foil to avoid photo diffusion.

## 3. Results and discussion

### 3.1. Capacitance-voltage characteristics under dark conditions

It is known that when a blocking (or Schottky barrier) contact is provided to a semiconductor surface, a depletion region is established at the interface. Associated with the depletion region, there is a depletion region capacitance  $C_d$ , which varies with the voltage drop  $V_d$  across the junction. In Fig.2a, the dependence of the capacitance  $C$  on the applied dc voltage  $V$  at room temperature (298 K) is shown for both forward and reverse bias for a series of samples with thicknesses in the range of 300-700 nm. It is clear from this figure that the capacitance  $C$  is essentially independent of  $V$  and the depletion regions are not therefore evident. This type of behavior is a typical situation when an injecting or Ohmic contact is provided and offers confirmation that Al electrodes do indeed establish Ohmic contacts to ZnTe.

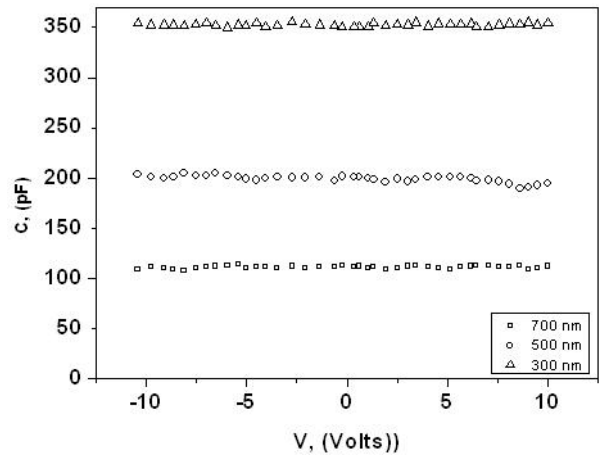


Fig.2a. Dependence of the capacitance  $C$  on the applied dc voltage  $V$  at room temperature (298 K) of different thicknesses.

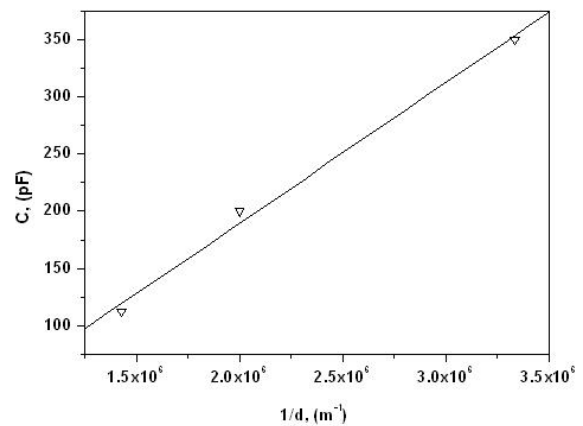


Fig.2b. Capacitance  $C$  as a function of reciprocal thickness.

In the case of application of an alternating voltage across a certain semiconducting material, the equivalent capacitance measured by a  $C$ - $V$  meter is given by [17]:

$$C_c = \left( \frac{A\sigma_{dc}}{d} \right) \left[ \tau_m - \frac{\tau_m}{1 + \omega^2\tau^2} \right], \quad (1)$$

where  $A$  is the area of the plate capacitor,  $d$  is the dielectric thickness,  $\tau_m = \frac{\epsilon}{4\pi\sigma_{dc}}$  is the Maxwellian

dielectric relaxation time,  $\epsilon$  is the dielectric constant and  $\tau$  is the dielectric relaxation time. After substituting  $\tau_m$ , Eq.(1) can be written as:

$$C_c = \left( \frac{A\epsilon}{4\pi d} \right) \left[ 1 - \frac{4\pi\tau\sigma_{dc}}{\epsilon(1 + \omega^2\tau^2)} \right], \quad (2)$$

At high frequency (1MHz), the second term of Eq.(2) can be ignored and the first term is dominant for the whole range of temperature and the applied voltage. Therefore, the capacitance is given by:

$$C_c = \frac{A\epsilon}{4\pi d}, \quad (3)$$

In Fig.2b, a plot of capacitance  $C$  as a function of reciprocal thickness  $1/d$  is presented. It is clear that the relationship between these two quantities is linear with the slope equal  $\epsilon A/4\pi$ , and confirm that Eq.(1) is obeyed; a permittivity value of  $7.7 \times 10^{-11} \text{ F.m}^{-1}$  ( $\epsilon_r = 8.7$ ) was derived from these data and this value is thus used in the analysis of the remaining measurements reported in this work. This value of  $\epsilon_r$  is in good agreement with the value quoted by Salem et al. [18].

### 3.1.1. Temperature dependence of the $C$ - $V$ characteristics.

Fig. 3 shows the temperature dependence of the capacitance  $C$  of ZnTe films of thickness 700 nm, as a representative example, at different applied bias voltages. It is observed that the capacitance increases with increasing temperature and this variation is less from 298 to 373 K, whereas above 373 K the rate of increase in capacitance with the temperature is more pronounced. The increase in the capacitance above room temperature may be partly due to the expansion of the lattice and partly due to the excitation of the charge carriers, which are likely to be present inside the specimen at defect sites. Hence, the decrease in capacitance with temperature in these thin films is due to the expansion of the lattice and also due to the excitation of charge carriers at the sites of imperfection [19-20].

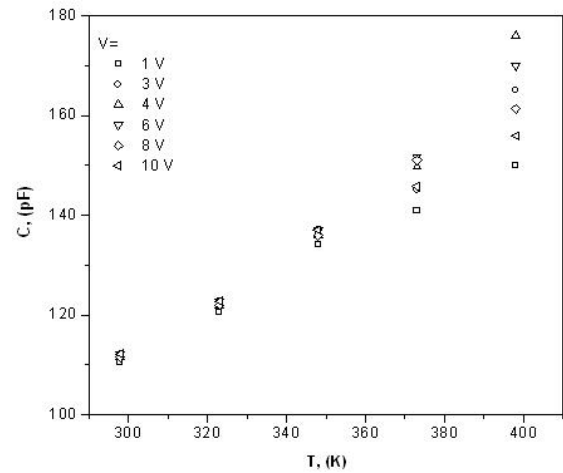


Fig.3. Temperature dependence of the capacitance  $C$  of ZnTe films of thickness 700 nm at different applied dc bias voltages.

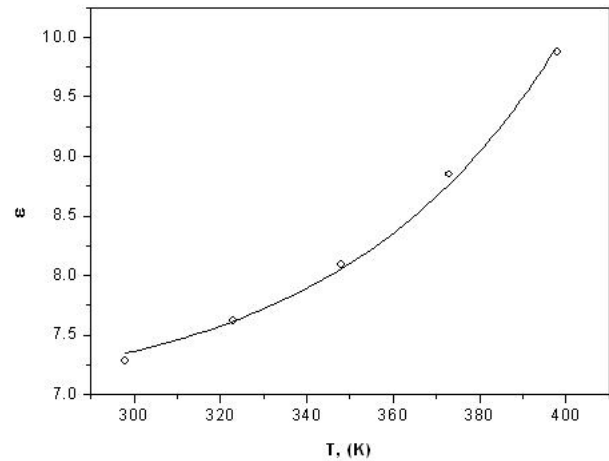


Fig.4. Temperature dependence of the dielectric constant  $\epsilon$  of ZnTe films with thickness 700 nm at high frequency (1 MHz).

Fig. 4 shows the temperature dependence of the dielectric constant  $\epsilon$  of ZnTe films at higher frequency (1MHz). This figure indicates that the increase in the dielectric constant  $\epsilon$  with temperature is clear, and a strong dielectric dispersion occurs at temperatures greater than 370 K. The increase in the dielectric of the sample is due to the electric field which is accompanied by the applied frequency. Such field will cause some ordering inside the sample as well as the formation of an electric moment in the entire volume of the dielectric and also in each separate polarizing molecule. The molecular dipoles in polar material cannot orient themselves at lower temperatures. When the temperature rises, the dipoles orientation is facilitated, and this led to the increase of the dielectric constant  $\epsilon$  [21-22].

### 3.1.2. Capacitance-voltage characteristics under illumination

The capacitance-voltage characteristics of ZnTe films of thickness 700 nm (as a representative example), under a sweep of dc biasing voltage from -10 to +10 V were measured before and after the effect of different intensities of illumination in the range 500-2000 lx as shown in Fig.5. This figure illustrates the voltage independence and illumination dependence of the measured capacitance  $C$  in this range of the intensity of illumination. This means that the capacitance is not voltage activated in this range of voltage. The variation of capacitance with increasing illumination is shown in Fig. 6.

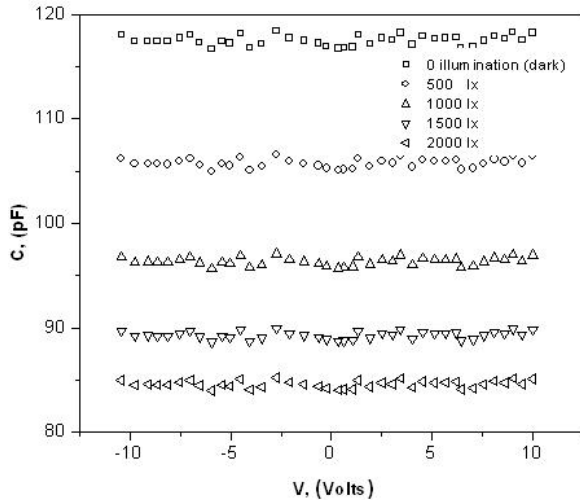


Fig.5. Capacitance-voltage characteristics under different intensity of illumination for ZnTe thin film of thickness 700 nm.

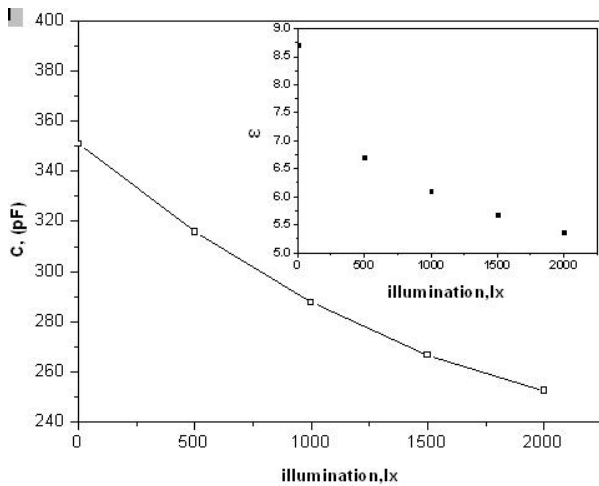


Fig. 6. Capacitance versus illumination and the inset shows the illumination dependence of the dielectric constant of ZnTe films of thickness 700 nm.

It is shown that the capacitance decreases with the increasing of the intensity of illumination and this indicates that the ionization is taking place on illumination exposure that in further leads to changes in the permittivity of the ZnTe films as shown in the inset of Fig. 6.

### 3.2. Current-voltage characteristics under dark conditions.

Fig.7 shows the  $I$ - $V$  characteristics in a logarithmic scale of the ZnTe films of different thicknesses (300-700 nm) at room temperature (298 K). As observed, there are two distinct regions in these characteristics. Firstly, At lower voltage, the slopes of the  $\ln I$  -  $\ln V$  plots are approximately equal to unity. Secondly, at higher voltages above a well-defined transition voltage  $V_t$ , the slopes are approximately  $\approx 2.7$  i.e. slopes are more than 2. These plots are typical for Ohmic conduction of voltage below  $V_t$  and trap-charge-limited conductivity (TCLC) at voltage above  $V_t$  [23].

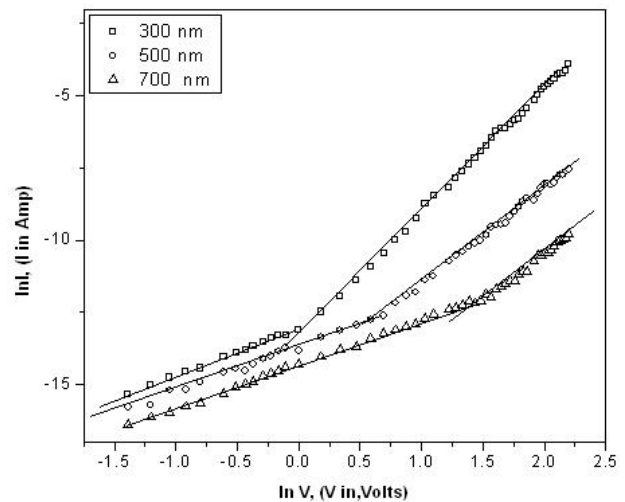


Fig.7.  $I$ - $V$  characteristics in a logarithmic scale of ZnTe films of different thicknesses at RT.

The origin of these traps may be attributed to the presence of inherent defects in the as-deposited ZnTe films. Such defect structures are also observed in high resistivity semiconducting films such as CdS, CdTe,...etc. [24]. The space charge limited hole currents were reported for semi-insulating ZnTe layers [25]. The Ohmic behavior observed at lower voltages may be due to the filling of a discrete set of traps lying below the Fermi level  $E_F$ . Since most of the traps are filled at lower voltages, further increase in the voltage causes a rapid increase in the current and the trap density  $N_t$  can be estimated [26].

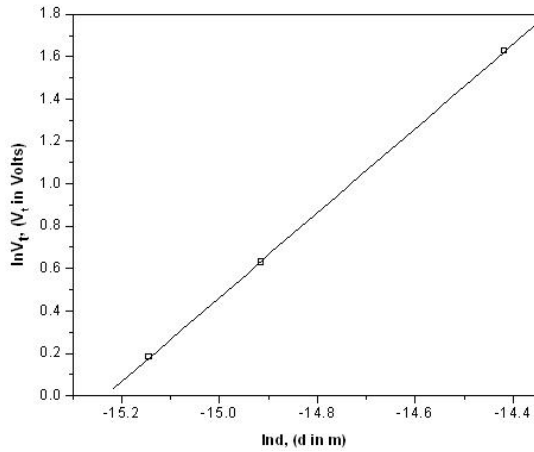


Fig. 8. Dependence of transition voltage on the film thickness  $d$ .

Since the ZnTe film behaves as p-type semiconductor, the Ohmic conductivity is assumed to be due to entirely holes and is described by Ohm's law at lower voltages region by the following equation [27]:

$$I = qp_0\mu_p AV / d, \quad (4)$$

where  $p_0$  is the concentration of thermally activated holes in valence band,  $\mu_p$  is the hole mobility and  $d$  is the thickness of ZnTe layer in the range 300-700 nm. The concentration of the hole at the thermal equilibrium is given by [28]:

$$p_0 = N_v \exp(-E_F / kT), \quad (5)$$

where  $N_v$  is the density of states in the valence band, and  $E_F$  is the separation of equilibrium Fermi level from the valence band edge (the equilibrium Fermi level value). Using Eqs.(4) and (5), the current in Ohmic region becomes:

$$I = q\mu_p N_v A(V/d) \exp(-E_F / kT), \quad (6)$$

the applied voltage above  $V_t$  (see Fig.6), the slopes of the relation between  $\ln I$  versus  $\ln V$  are about  $\sim 3.7$ . This means that the forward biased current is dominated by TCLC mechanism. According to TCLC mechanism, the current flow in ZnTe is restricted by the density of free injected carriers and trap concentrations and the relationship between current intensity and the applied voltage is given by the following equation [29]:

$$I = e\mu N_v A \left( \frac{\epsilon\epsilon_0}{eN_0 k_B T_t} \right)^r \frac{V^{r+1}}{d^{2r+1}}, \quad (7)$$

where  $N_v$  is the effective density of states in the valence band edge. The exponent  $r = (T_t / T)$ , where  $T_t$  is the temperature parameter characterizing trap distribution. For the cases where the exponent  $m = (r + 1) > 2$ , the power law ( $J \propto V^m$ ) representing TCLC region appears to be dominated by an exponential distribution of trap levels in energy above the valence band edge according to the equation [27-28]:

$$P(E) = P_0 \exp\left(\frac{-E}{kT_t}\right), \quad (8)$$

where  $P(E)$  is the trap density per unit energy range at an energy  $E$  above the valence band edge. From Fig.6, the slope of the straight line equal  $\sim 3.7$  implies that  $r=2.7$ , and thus the temperature parameter which characterizes the trap distribution  $T_t = 804.6$  K for the measurement temperature of 298 K.

A fairly well defined transition voltage  $V_t$  may be derived from each characteristic by obtaining the intersection point of the two linear sections of the logarithmic characteristics as shown in Fig.8. The transition voltage  $V_t$  separating Ohmic conduction and TCLC mechanism is given by [30]:

$$V_t = \left( \frac{P_0}{N_v} \right)^{1/r} \frac{d^2 e N_t}{\epsilon}, \quad (9)$$

The dependence of transition voltage on the film thickness  $d$  for ZnTe films is shown in Fig.8. A linear relationship is obtained with a slope equal to  $\sim 2$ , verifying Eq.(9) and also supporting the interpretation of the analysis of TCLC in ZnTe films.

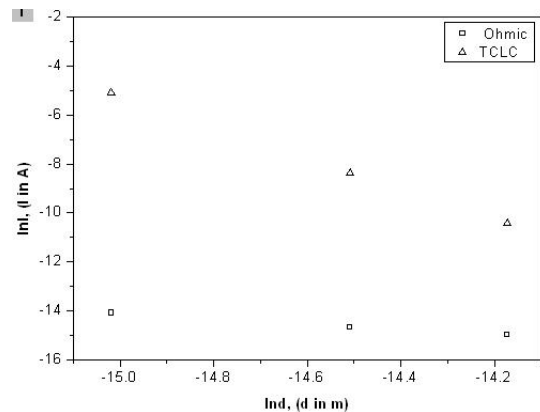


Fig. 9. Thickness dependence of  $\ln I$  for both Ohmic current and TCLC regions at certain fixed values of voltages 0.5 V and 6 V, respectively at 298 K.

Fig. 9 shows the thickness dependence of the current as  $\ln I$  for both Ohmic current and TCLC regions at a certain fixed values of voltages at room temperature. The Ohmic dependence (slope of  $\sim 1$ ) indicates that good Ohmic contacts exist and also verifying Eq.(4). The slope equals  $\sim 6.71$  in the SCLC region verifies the TCLC conduction is the dominant mechanism. From Eq.(7), the slope in this region should be  $(2r + 1)$  implying that  $r \sim 2.85$ , which is in excellent agreement with the values deduced from the  $I-V$  characteristics of Fig.6. More information about the material can be obtained from the variation of current with temperature in TCLC region.

### 3.2.1. Temperature dependence of the $I-V$ characteristics.

The dc current of ZnTe thin films was measured as a function of temperature from 298 to 398 K. The applied voltage was held constant in both Ohmic at  $V=0.5$  V and TCLC region at  $V=6$  V. Fig.10 shows the dependence of current on reciprocal of absolute temperature  $1000/T$  for a sample of thickness 700 nm.

In the Ohmic region (0.5 V), a straight line for the temperature dependence of the current was obtained, and then the Fermi level value as well as the hole mobility can be obtained from the slope and by extrapolating of these straight lines to  $1000/T = 0$ , respectively. The value of the Fermi level and the hole mobility of ZnTe films were obtained and listed in Table.1.

Table.1.  $I-V$  characteristic Parameters of ZnTe thin films in the Ohmic and TCLC regions.

|  | Ohmic region |  | TCLC region  |                             |   |
|--|--------------|--|--|-----------------------------|---|
|  | $E_f$ , (eV) | $\mu_p$ , ( $\text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ ) | $\mu_p$ , ( $\text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ ) | $N_t$ , ( $\text{m}^{-3}$ ) | $P_o$ , ( $\text{J}^{-1} \cdot \text{m}^{-3}$ ) |
| ZnTe (300 nm)                            | 0.33         | $2 \times 10^{-9}$   | $3.4 \times 10^{-9}$   | $2 \times 10^{23}$          | $1.8 \times 10^{43}$                            |
| ZnTe (500 nm)                            | 0.34         | $4 \times 10^{-9}$   | $5.2 \times 10^{-9}$   | $4 \times 10^{23}$          | $3.6 \times 10^{43}$                            |
| ZnTe (700 nm)                            | 0.36         | $6.2 \times 10^{-9}$   | $8.4 \times 10^{-9}$   | $5.2 \times 10^{24}$        | $4.6 \times 10^{43}$                            |
| Illuminated ZnTe of 700 nm under 500 lx  | -            | -  | $4 \times 10^{-9}$   | $6 \times 10^{24}$          | $5.4 \times 10^{44}$                            |
| Illuminated ZnTe of 700 nm under 1000 lx | -            | -  | $5.4 \times 10^{-9}$   | $7.5 \times 10^{24}$        | $6.2 \times 10^{44}$                            |
| Illuminated ZnTe of 700 nm under 1500 lx | -            | -  | $6 \times 10^{-9}$   | $8.3 \times 10^{24}$        | $7.5 \times 10^{44}$                            |
| Illuminated ZnTe of 700 nm under 2000 lx | -            | -  | $6.8 \times 10^{-9}$   | $9.1 \times 10^{24}$        | $8.2 \times 10^{44}$                            |

More information about the material can be obtained from the dependence of current in the space charge region. Fig. 10 shows the variation of  $\ln I$  against  $1000/T$  for the different thicknesses in the space charge region at a constant applied voltage equal 6V. For this temperature range, the characteristics show a linear segments and the slopes of these lines are given by [31]:

$$\text{Slope} = \frac{d(\ln I)}{d(1/T)} = T_i \ln\left(\frac{\varepsilon V}{ed^2 N_t}\right), \quad (10)$$

and the intercept on the  $\ln I$  axis is given by:

$$\ln I_0 = \ln\left(\frac{e\mu N_v V}{d}\right), \quad (11)$$

where  $I_0$  represents the current at infinite temperature ( $1/T = 0$ ). The value of the total trap concentration has been obtained using equation (10) at  $T_i = 804.6$  K at room temperature (298 K). Assuming that  $N_v = 2 \times 10^{24} \text{ m}^{-3}$  [32], the average calculated values of the mobilities for the investigated thicknesses and the trap density are calculated and given in Table.1. These values of drift mobilities and the trap density can be compared with the values obtained by other authors [33-34]. The mobility was observed to increase with increasing the film thickness. This behavior may be explained by an argument proposed by Berger et al. [35], in which increasing film thickness is accompanied by an increase in mean crystallite size and thus reducing the number of internal potential barrier.

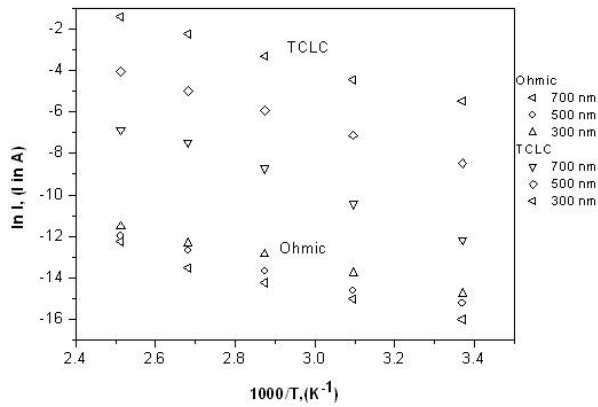


Fig.10. Temperature dependence of  $\ln I$  at different constant voltages ,0.5 for Ohmic region and 6 V for TCLC for a sample of thickness 700 nm in the temperature range 298–398 K.

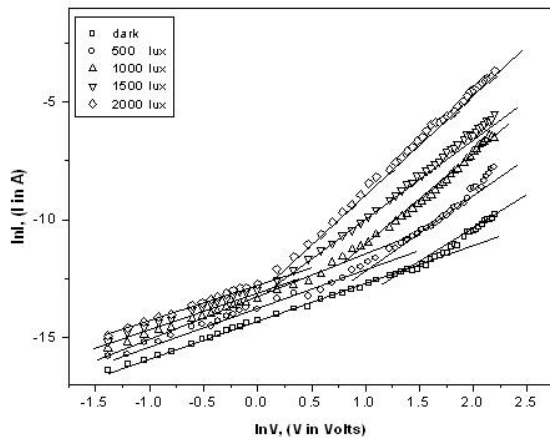


Fig.11.  $I$ - $V$  characteristics under different intensity of illumination for ZnTe of thickness 700 nm.

The characteristic energy of the trap distribution  $E_t = (r + 1)kT_t$ , calculated from the measured values of  $m = r + 1$  is shown in Fig.6. At higher temperature ( $T \approx 398$  K),  $E_t = 0.1$  eV, but as the devices are cooled down, it continuously decreases to a value of about 0.07 eV at 298 K. According to SCLC theory, at lower temperature, to thermally generate enough free carriers will sweep across regions of the trap distribution. Therefore, the part of the trap distribution dominating the  $I$ - $V$  characteristics and responsible for the power-law behaviour according to Eq.(9) will vary with temperature.

### 3.2.2. Current-voltage characteristics under illumination

In order to record the photo-induced current, the sample was exposed to the light radiation from a 500 W halogen lamp containing iodine vapor and tungsten

filament. The emission spectrum of the halogen lamp was observed to be a continuous one with wavelengths ranging from 300 to 1000 nm. The photo-induced current was recorded in the same range of the applied voltage. This study was done with a change of the incident light intensity from 500-2000 lx. An upward shift towards higher values of the photo-induced current with the increasing of the applied bias voltage was observed.

The voltage dependence of the dark and the photo-induced currents in ZnTe films are presented in Fig.11. It is observed that the photo-induced currents of ZnTe films increases with increasing the applied electric field. The photo-induced current is found to be larger than the dark current at the same applied voltage which is termed as positive photo-induced current. This may be attributed to the generation of mobile charge carriers caused by absorption of photons [36].

The variation in the current under different intensity of illumination (500-2000 lx) is shown in Fig.12. It has been observed that this variation obeys the power law [37]:

$$I_{ph} = F^\gamma, \quad (12)$$

where  $I_{ph}$  is the photocurrent (total current minus the dark current),  $F$  is the intensity of the light and  $\gamma$  is the exponent, which depends on the recombination mechanism. The photocurrent was found to be square-root-dependent on the illuminated light intensity, i.e.  $\gamma \approx 0.5$  for all the samples. The  $\gamma$  value was determined from the slope of  $I_{ph}$  versus light intensity and was found to be 0.67. The  $\gamma$  values for 0.5 and 1.0 correspond to bimolecular recombination and mono-molecular recombination mechanism, respectively [38]. Whereas, the value of the exponent lies between 0.5 and 1.0 for continuous distribution of trapping centers [39]. The obtained value of  $\gamma$  for the ZnTe films can not be understood by assuming a set of discrete trap levels but demands the existence of continuous distribution of traps in the band gap. This value suggests that the life times of the photo-carriers are determined by the trapping centers.

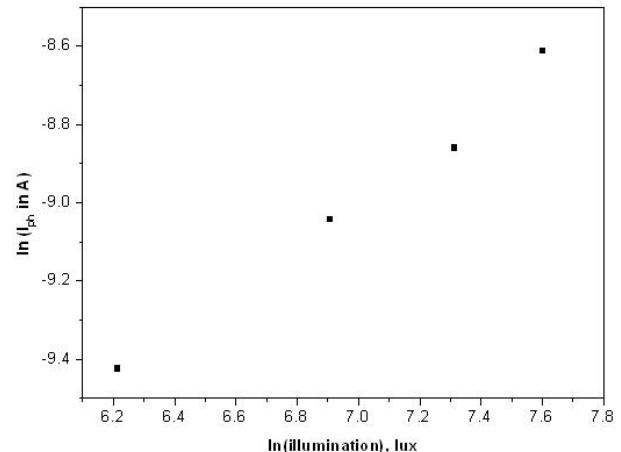


Fig.12. Photo-induced current  $I_{ph}$  versus light intensity ( $\ln$ - $\ln$  scale).

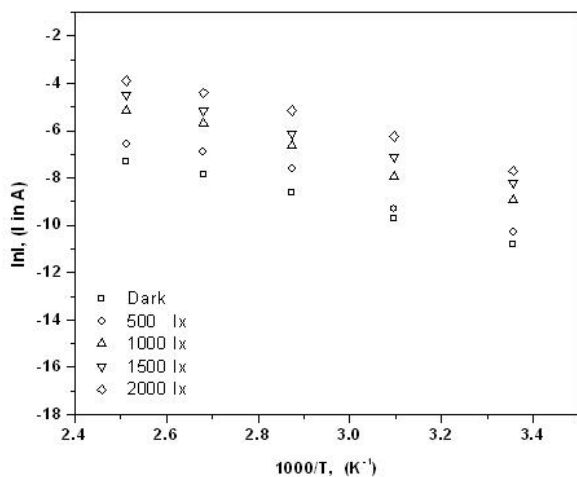


Fig.13. Temperature dependence of dark and illuminated current at different intensity of illumination of ZnTe thin film of thickness 700 nm.

Temperature dependence of the photo-induced current of ZnTe films (700nm) at different intensity of illumination is given in Fig.13. It is clear from this figure that the photo-induced current is a thermally activated process as  $\ln I$  versus  $1000/T$  in which show a straight line in the space charge region. Table.1 contains the parameters deduced under the effect of dark in the space charge region as well as under the effect of illumination.

#### 4. Conclusion

The main conclusion of the present work can be summarized as follows:

1- The capacitance voltage characteristics of ZnTe were measured at 1 MHz. This frequency is high enough to be able to neglect a dielectric relaxation in ZnTe. These characteristics showed a constant value independent of applied voltage. This indicated that the capacitance of ZnTe films equals to its geometric capacitance due to its longer dielectric relaxation time. The temperature dependence of ZnTe films showed an increasing in the capacitance with temperature which may be attributed to the expansion of the lattice and also due to the excitation of charge carriers at the sites of imperfection.

2- The current transport mechanisms of ZnTe are Ohmic conduction followed by trap-charge limited conduction (TCLC) at low and high voltages, respectively. The transition voltage between the Ohmic and the TCLC was proportional to the thickness, supporting the interpretation of the analysis of TCLC in ZnTe films.

3- Temperature measurements enabled the mobility to be derived and other important parameters are also obtained. The temperature dependence of photo-induced current at different intensities indicates that photo-induced current is thermally activated in all samples.

4- The typical photo-enhanced current-voltage relationship for ZnTe films is of the type  $I\alpha V^m$  with  $m > 2$  which results from the trap charge limited current.

5- The intensity dependence of photo-induced current shows bi-molecular recombination in the experimental range of temperatures.

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