ELECTRICAL CONDUCTIVITY OF ZINC OXIDE AT HIGH FIELDS

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The current-voltage behaviour of Al-ZnO-Al sandwich structure (0.8 mm thick sample) have been investigated at different temperatures. At low voltage, the conduction is ohmic while at high voltage, the current has a quadratic dependence on the voltage. The voltage at which the transition from ohmic to non-ohmic conduction takes place, decreases as temperature increases. The results are interpreted in terms of theory of space-charge-limited currents in defect insulators containing shallow traps. From the temperature behaviour of *I–V* characteristics, the sample was found to have electron trapping levels at energy 0.58 eV below the conduction band with a density of the order of 10^{11} cm^{-3}.

INTRODUCTION

EARLIER investigations into the electrical properties of zinc oxide have been undertaken by a number of workers (Hutson, 1959; Kroger, 1965; Chandra *et al.*, 1967; Jain & Garg, 1979; Kiess, 1973; Utsch & Hausman, 1975). The material, when pure, acts as an insulator (Brown, 1957) and the energy band gap of this compound is 3.2 eV at room temperature. The chemical reduction of crystal yields oxygen vacancies which act as donors. Current-voltage characteristics of ZnO single crystals at 77 °K was measured by Meyer and Jorgensen (1966) while Kiess (1970) investigated the high field behaviour of the single crystals in contact with electrolytes. Mead (1966) measured *I–V* characteristics of Zn-ZnO-Au sandwiched system and pointed out that the conduction mechanism obeys Rechardson-Schottky law. A current limited by the space charge but depending on the polarity of bias voltage, was observed in single crystal of ZnO doped with lithium between asymmetric contacts (Meaudre & Guy, 1969). In the present work, the present authors have investigated the electrical properties of zinc oxide sandwiched system between aluminium (symmetric) electrodes as a function of electric field at different temperatures and have discussed the possible conduction mechanism in the sample.

MATERIALS AND METHODS

Zinc oxide specimen in pellet form have been obtained from puratronic (J. M.) grade powder by the same method as described earlier (Jain & Garg, 1979). Current and voltage measurements were carried out by a vernier potentiometer. The details of measuring instruments and experimental procedure are described elsewhere (Jain & Garg, 1978).

RESULTS AND DISCUSSION

A typical current-voltage characteristic on log-log scale in air at different temperatures

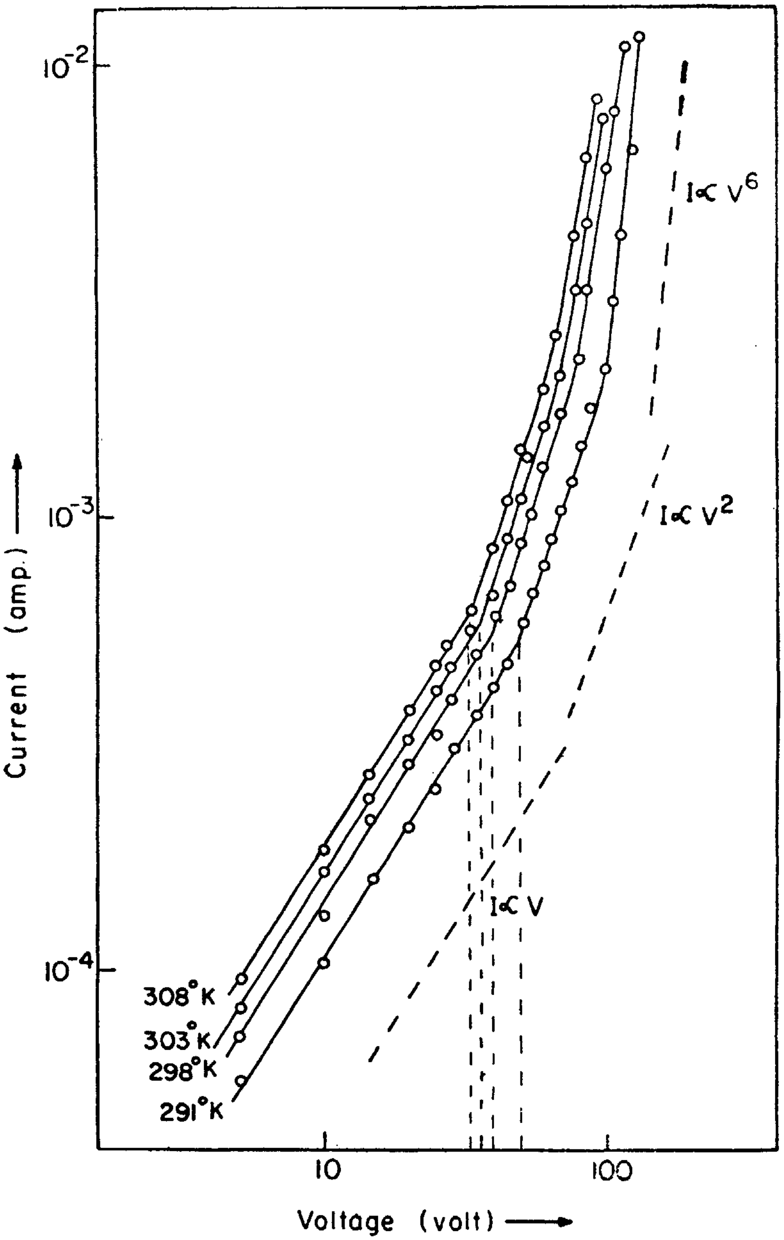

FIG. 1. Variation of current (I) with voltage (V) at different temperatures in ZnO.

ranging from 291 °K to 308 °K is shown in Fig. 1. The plot is characterized by a linear region at low fields, quadratic dependence at intermediate fields, followed by a region in which the current rises as the sixth power of the applied voltage at high fields. The ohmic dependence was observed up to about 50 volts at room temperature. The transition voltage V_T at which ohmic conduction changes to non-ohmic conduction are being estimated from Fig. 1 and the values are given in Table I. It is

TABLE I

The transition voltage values

T (°K)	V_T (Volt)	θ	n_0 ($\times 10^{11}$ cm^{-3})
291	50	0.17	1.75
298	47	0.31	1.40
303	45	0.48	1.26
308	43	0.64	1.16

seen that as the temperature increases, the transition voltage V_T decreases. The ohmic behaviour can be explained by the fact that at low voltages there is negligible injection of carriers from the electrode in the bulk of zinc oxide pellet and the initial current is governed by the intrinsic free carriers in the material. The ohmic region of the current-voltage characteristics followed by a square-law dependence of the current on voltage at higher fields is characteristic of space-charge-limited currents (SCLC) in solids. The theory of SCLC has been examined in detail for various trap distributions in insulators by Rose (1955) and Lampert (1956). The magnitude of the current I_0 passing through a perfect insulator, limited by space charge, is governed by the relation.

$$I_0 = \frac{10^{-13}\epsilon\mu A V^2}{d^3}, \qquad ...(1)$$

where ϵ is the relative static dielectric constant of the solid, μ is the mobility of carriers in cm^2/V-sec., V is the applied voltage in volts, d is the separation between electrodes in cm and A is the area of the sample in cm^2.

When the insulator contains shallow traps, the magnitude of the current I_t is governed by the relation

$$I_t = \frac{10^{-13}\epsilon\mu A\theta V^2}{d^3}, \qquad ...(2)$$

where θ is the the ratio of free electrons n_f to trapped electrons n_t and is given by

$$\theta = \frac{n_f}{n_t} = \frac{N_c}{N_t}\exp\left(\frac{-E_t}{k_B T}\right)_0 \qquad ...(3)$$

N_c is the effective density of states in the conduction band, N_t is the trap density and E_t is the trapping level below the conduction band.

In deriving eqn. 2, it was assumed that the free space charge density is negligible in comparison to the trapped space charge density that is θ is much less than one. When θ is comparable to one eqn. (2) assumes the form

$$I_{t,\theta} = \frac{10^{-13}\epsilon\mu A V^2}{d^3(1+\theta^{-1})} \qquad ...(4)$$

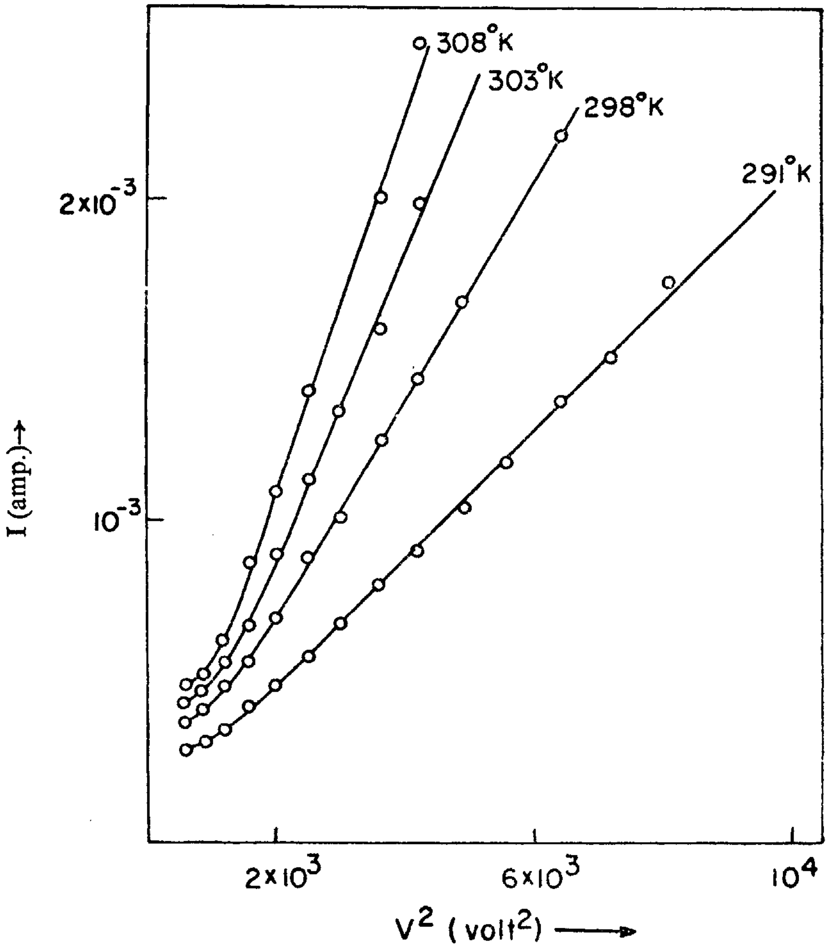

FIG. 2. Variation of current (I) with voltage² (V^2) in square-law region at different temperatures in ZnO.

Fig. 2 depicts I_{vs} V^2 curves in the square-law region which are straight lines at working temperatures. Using $\mu = 200$ cm²/ V sec (Hutson, 1957), $\epsilon = 36$ (Heiland *et al.*, 1959), $d = 0.08$ cm and $A = 1$ cm² the slopes of the straight lines are found to be less than the calculated values of the coefficient of eqn. (1) and thus indicates the presence of shallow traps in the sample. The ratio of trapped to free space charge density θ is calculated using eqn. (4) at different temperatures and are inserted in the table.

Fig. 3 shows a plot of log θ against $10^3/T$. Assuming that N_c and N_t are not strong functions of temperature, the intercept at $10^3/T$ being equal to zero yields a ratio of $N_c/N_t = 1.1 \times 10^{10}$. If we assume that the effective density of states N_c in the conduction band is of the order of 10^{21} cm^{-3}, the trap density N_t is found to be equal to 9×10^{10} cm^{-3}. The trap depth E_t is found from the slope of the straight line plot (Fig. 3) and is equal to 0.58 eV below the bottom of the conduction band.

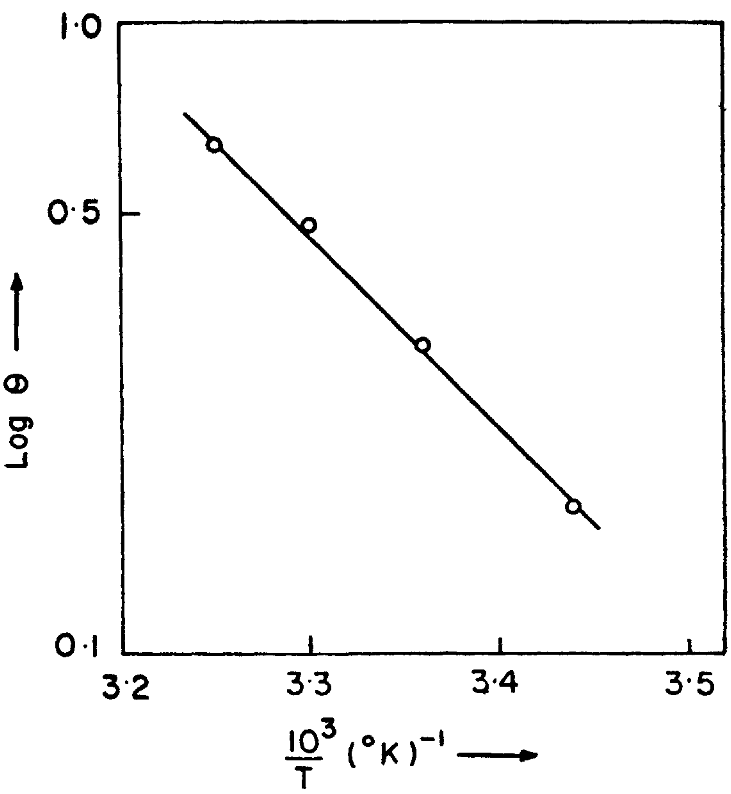

FIG. 3. Variation of log θ with temperature.

The voltage V_T, at which transition from ohmic to non-ohmic conduction takes place, is a measure of concentration of volume generated carriers n_0 and relation between them is given by

$$V_T = \frac{10^{13}\, n_0\, e d^2}{\epsilon}. \qquad \ldots(5)$$

The values of n_0 calculated using eqn. (5) are given in the table and are about 10^{11} cm^{-3}.

It has been mentioned earlier that in the high field region, the square law dependence terminates to a steeply rising current versus voltage relationship which may possibly be approximated by $I \propto V^6$ dependence. An attempt to explain the observed dependence on the basis of trap filled limit theory (Lampert, 1956) was unsuccessful. As the observation of such $I \propto V^n$ characteristics ($n > 5$) is common in semi-conductors, the observed steep rise in currents may possibly be attributed either to the heating effects or to impact ionization of trapped or valence electrons, the latter being temperature dependent.

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