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A DIFFERENTIAL EVALUATION OF I-V CHARACTERISTICS OF ONE-CARRIER SEMICONDUCTING CRYSTALS. APPLICATION ON CdS SINGLE CRYSTALS

By

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1. INTRODUCTION

By plotting the experimental I-V characteristic for the most one carrier semiconductors one may observe four regions (Fig. 1). At very low voltages the I-V characteristic slope is ~ 1 (region 1), while at a little higher voltages its slope becomes ~ 2 (region 2). At a certain voltage just higher than those of region 2, i.e. in region 3, its slope rises sharply until region 4 is reached, where it obtaines again the value ~ 2 [1], [2].

At very low voltages (regions 1) the injected carrier density is less than the free carrier density and Ohm's law is obeyed. For an n-type semiconductor, one has,

$$I = ne\mu_n \frac{V}{l} \tag{1}$$

where n is the free electron density, e the electron charge, μ_n the electron mobility and V the applied Voltage between the two electrodes at a distance l.

When the injected electron density becomes greater than that of the free one the current is modified by the trap in the semiconductor, i.e. region 2. At a certain higher voltage V_L the trap is filled with electrons and the current rises in region 3 almost vertically, until it reaches its trap free space-charge limited region 4. The value V_L is given by

$$V_L = eXd^2/\varepsilon \tag{2}$$

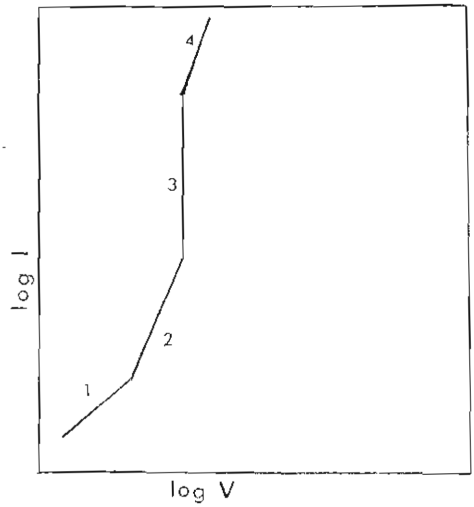

Fig. 1. I-V characteristic for a n-type semiconductor. 1) Ohm's law region. 2) Modified Mott and Gurney law region due to the traps. 3) Trap filled limit region, and 4) Trap free Mott and Gurney law region.

where X is the concentration of the considered trap, ε the dielectric constant and d the thickness of the considered crystal [1], [2].

Since the concentration of majority carriers in the regions 2 and 3 depends on traps the I-V characteristics of one-carrier semiconductors have been used widely to determine both the concentration and the energy level, of these traps within the forbidden gap. In a series of publications I-V characteristics of space charge limited current were applied in various modifications for these purposes.

2. CONVENTIONAL ANALYSIS OF I-V CHARACTERISTICS

The free electron concentration n for an n-type and not degenerated semiconductor is given by equation [3], [4].

$$n + \sum_i X_i f(E_i - E_F) = C$$

where X_i is the concentration for localized states with the energy level $E_c - E_i$ under the conduction band-minimum E_c, $f(E_i - E_F)$ is its occupation probability with electrons and E_F is the Fermi energy. So C is a constant used to express the total amount of electrons in the conduction band plus the electrons which are in localized states in the energy gap. If only one kind of levels X_1 is present, then eq. 3 becomes

$$n + X_1 \frac{n}{n + n_x} = X_1 \tag{4}$$

where n_x is the free electron density when $E_F = E_{x_1}$ [5].

In the case when injection of electrons in the semiconductor takes place, one must add in the right side of eq. (3) a term C_{inj} for the concentration of the injected carriers

$$n + \sum_i X_i \frac{n}{n + n_{x_i}} = C + C_{inj} \tag{5}$$

Let us examine the I-V characteristic of an n-type and not degenerated semiconductor including only one kind of electron traps at the energy level $E_c - E_1$ under E_c and with concentration X_1.

For low voltages, i.e. $E_F < E_1$ all the injected carriers are trapped in the level E_1; C_{inj} is much smaller than n and ep. (5) becomes:

$$n + X \frac{n}{n + n_x} \simeq n \frac{n + n_x}{n_x} = C \tag{6}$$

Since I is given from $I = nblV\mu_n e/d$ where d is the crystal thickness, it results that $I = \text{Const.} \times V$ (Ohm's law).

For higher voltages $C_{inj} \simeq n$. In this case E_1 is almost filled with electrons and $E_F \simeq E_1$. Eq. (5) becomes:

$$n + X \frac{n}{n + n_x} \simeq n + \frac{X}{2} = C + C_{inj} \tag{7}$$

Since C_{inj} is a linear function of V [1], [6] it results that $I \sim V^2$ (modified Mott and Gurney law).

For the critical voltage V_L, which corresponds to the situation when the level E_1 is just filled with electrons, can be proved [6] that

$$V_L = eX_1^2 d^2/\varepsilon \tag{2}$$

In this case I rises superlinear with increasing voltage, since the total amount of the injected carriers remains new in the conduction band.

For stronger voltages, E_F is shifted far away over E_1, so that $E_F > E_1$ and eq. (5) may be written as

$$n \simeq C_{inj} \tag{8}$$

The current becomes really space-charge limited. The I-V characteristic shows the slope ~ 2.

Fig. 2a shows the modification of the I-V characteristic by the concentration X_1; Fig. 2b shows the modification of the I-V characteristic by C.

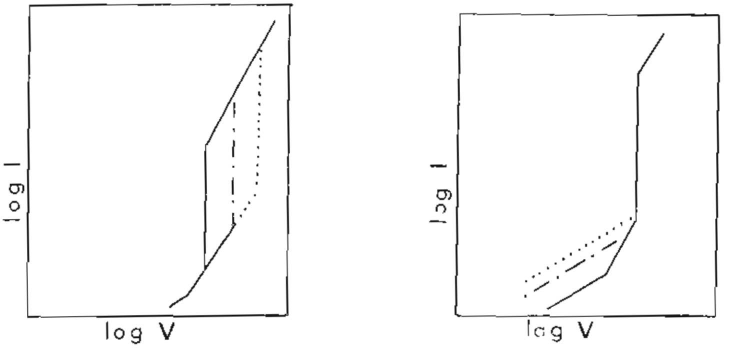

Fig. 2a and b: Modification of the I-V characteristic by the trap concentration X_1 *(Fig. 2a) and by the compensation C (Fig. 2b). The full curve of Fig. 2b is computed for* $X_1 = 4 \times 10^{15} cm^{-3}$, $E_1 = 0{,}25 eV$ *and* $C = 10^{-5} X_1$; *the dashed curve of Fig. 2b is computed for* $X_1 = 4 \times 10^{15} cm^{-3}$, $E_1 = 0{,}25 eV$ *and* $C = 10^{-3} X_1$; *the dot-dashed curve of Fig. 2b is computed for* $X_1 = 4 \times 10^{15} cm^{-3}$, $E_1 = 0.25 eV$ *and* $C = 10^{-1} X_1$. *The curves of Fig. 2a show how the initial I-V characteristic (dot-dashed/ curve) is modified if the concentration* X_1 *of the trap increases from* $4 \times 10^{9} cm^{-3}$ *to* $4 \times 10^{12} cm^{-3}$ *(full curve) and then to* $4 \times 10^{15} cm^{-3}$ *(dashed curve).*

The simple way for the determination of a trap as reported above is possible only if one discrete level is assumed and if C has a small value. When two traps are present the situation is much more complicated and one has to be very lucky to discriminate the two different levels [7], since not only the superlinear regions overlap, but also the transitions from linear regions to superlinear ones are not sharp enough. To avoid this difficulty we tried another way. Namely, we evaluated the I-V characteristics differentially, as follows.

3. DIFFERENTIAL EVALUATION OF THE I-V CHARACTERISTIC.

The relation between the amount of injected carriers C_{inj} and the voltage V, which is responsible for the injection, is given by the Poisson equation

$$\frac{d^2V(z)}{dz^2} = \frac{e}{\varepsilon\varepsilon_0} C_{inj}(z) \qquad (9)$$

where z is the distance of a point in the semiconductor interior from the injection electrode and $\varepsilon_0 = 8.85.10^{-12}$ A.s/V.m. Approximating this expression for the anode region one obtaines

$$\frac{d^2V(z)}{dz^2} = 2V/l^2 \simeq \frac{e}{\varepsilon\varepsilon_0} C_{inj} \qquad (10)$$

Using eq. (10), eq. (5) becomes

$$n + \sum_i X_i \frac{n}{n + n_{xi}} = C + \frac{2\varepsilon\varepsilon_0}{el^2} V \qquad (11)$$

In this case if V increases by ΔV, then the Fermi level is shifted towards E_c by ΔE_F. Differenting eq. (11) with respect to E_F one obtains:

$$\frac{2\varepsilon\varepsilon_0 kT}{el^2} \frac{\Delta V}{E_F} = \frac{2\varepsilon\varepsilon_0 kT}{el^2} \frac{dV}{dE_F} = \frac{d(n + \sum_i X_i \frac{n}{n + n_{xi}})}{dE_F} = n + kT \sum_i X_i \frac{n.n_{xi}}{(n+n_{xi})^2} \qquad (12)$$

In the right side of eq. (12) the terms $kTX_i(nn_{xi}) / (n + n_{xi})^2$ represent in a log $d(n + \sum_i X_i n(n + n_{xi})/dE_F$ versus $E_c - E_F$ plot, hyperbola-like curves having maxima at the points $(E_c - E_{xi};\ X_i/4)$. The quotient $\Delta V/\Delta E_F$ can be obtained from the measured I-V characteristic by numerical differentation; plotting then $\log(2\varepsilon\varepsilon_0 kT/el^2)\Delta V/\Delta E_F$ versus $E_c - E_{F_n}$ we can directly determine the energy levels and the concentrations of the traps from the hyperbola-like curves maxima due to them.

Ten discrete traps have been resolved at 0.055ev; 0.065eV; 0.145eV; 0.157eV; 0.255eV; 0.280eV; 0.420eV; 0.500eV; 0.580eV and 0.625eV under the conduction band minimum. Their corresponding concentrations are in the range $10^{14}cm^{-3} - 10^{15}cm^{-3}$.

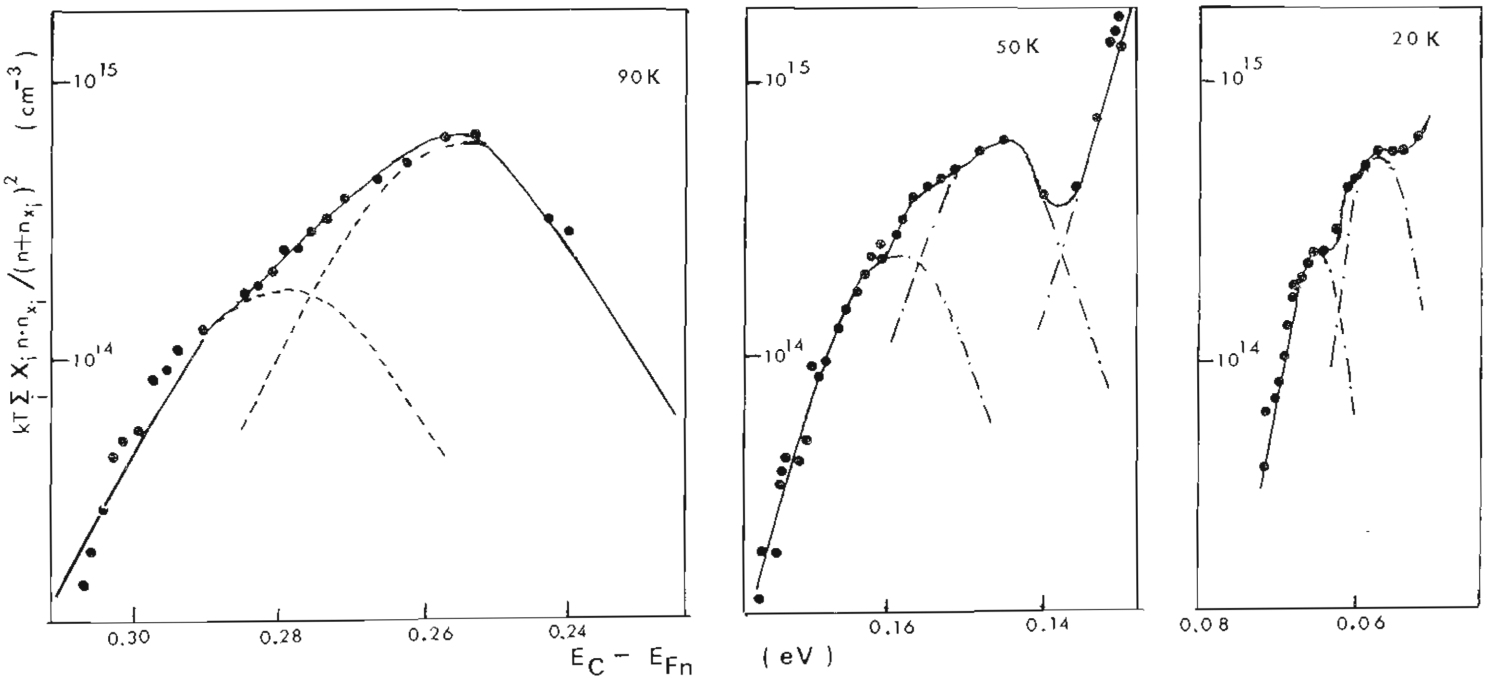

Fig. 3. $\log kT\sum_i nn_{x_i}X_i/(n \times n_{x_i})^2$ *versus* $E_c - E_{F_n}$ *for CdS single crystals (full curves). The points show the experimental data; the dashed curves shows the single terms of the sum* $kTnn_{x_i}X_i/(n \times n_{x_i})$ *in a log plot versus* $E_c - E_{F_n}$.

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ΠΕΡΙΛΗΨΗ

ΔΙΑΦΟΡΙΚΗ ΑΠΟΤΙΜΗΣΗ ΧΑΡΑΚΤΗΡΙΣΤΙΚΩΝ ΤΑΣΗΣ-ΕΝΤΑΣΗΣ ΣΕ ΗΜΙΑΓΩΓΟΥΣ ΕΝΟΣ ΕΙΔΟΥΣ ΦΟΡΕΩΝ. ΕΦΑΡΜΟΓΗ ΣΕ ΚΡΥΣΤΑΛΛΟΥΣ CdS

Ὑπὸ

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