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INVESTIGATION THE INFLUENCE OF ELECTRON BEAM PARAMETERS ON THE CATHODOLUMINESCENCE OF CADMIUM TELLURIDE.

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Abstract

The cathodoluminescence signal (Cl) has been investigated theoretically for p-type CdTe, in order to understand the effect of incident electron beam parameters (energy Eo, intensity Ip), at low injection level, on the excess carriers, the cathodoluminescence intensity (ICl) and the depletion region (Zd). To do this a self-consistent calculation method of (ICl) has been used.

The obtained results show that the excess concentrations of carriers have a maximum value near the surface and decrease when E0 increases. Regarding the depletion region we observe a decrease of the depth as a function of Ip for the relatively great values and an increase with increasing Eo. The curves ICl = f(E0) show a maximum in the energy interval of [30-40 keV] and a rapid decrease for high values of Ip. Additionally, we observe, in general, an increase of ICl with increasing Ip. Finally, we record a linear variation of the intensity Cl as a function of Ip, according to different energies E0.

Keywords: *cathodoluminescence, CdTe, self-consistent method, depletion region, excess carriers, low injection level.*

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I. INTRODUCTION

The cathodoluminescence phenomenon is a very effective means to study the surface and volume parameters of semiconductor materials [1-5].

Most theoretical studies of cathodoluminescence were performed on the III-V compounds, particularly GaAs [6-8]. In general, the method used is a self-consistent analysis, which gives a good agreement between calculations and experiment [8].

Although, several works have been done on the III-V materials, there are few investigations that have been carried out on the II-VI materials, despite their very interesting luminescence properties, particularly CdTe because of its direct gap and luminescence efficiency. That is why we are interested in the study of this material.

To do this we have used a generation function proposed by Wu and Wittry [9] using CdTe parameters [10]. In the previous work of the theoretical calculation of cathodoluminescence of CdTe ,we have reported the influence of surface and bulk parameters on the depletion region[11]

In this paper we investigated the influence of E_0 (energy of the incident beam) and I_p (intensity of primary electrons) on the excess carriers concentration, the depletion region developed at the surface of the semiconductor and the cathodoluminescence signal obtained after the interaction between electrons and material.

The calculation is based on the resolution of the continuity equation of both of the two type carriers in the neutral and depletion region.

2. BASES OF THE MODEL

∗ The studied material is: p type CdTe.

∗ The analytical shape of the dissipation function is that proposed by Wu and Wittry [9]; it is a modified Gaussian approximation.

∗ The study was performed using one dimension, the depth Z.

* The incident electron beam is perpendicular to the surface, which leads to a symmetrical resolution around incident beam axis.

∗ The penetration depth R_e of electrons is given by Kanaya and Okayama model [12].

∗ The surface carriers recombination is non-radiative.

* The occupation probability of any level is governed by Shockley-Read-Hall mechanism for the non-equilibrium conditions.

∗ The capture sections of electrons and holes are equal.

∗ The pseudo Fermi level is considered constant.

∗ The material is considered semi-infinite.

* In the depleted region, we assume that the recombination of excess carriers is negligible, while in the neutral region, the excess carriers have a stationary diffusion regime. The direct recombination of these carriers is at the origin of the cathodoluminescence phenomenon.

3. THEORETICAL CALCULATION OF Z_d AND I_{Cl}

3.1 Calculation of z_d

The absolute charge (Q) at the surface is given by [8]:

$$Q = e.Na.Z_d = e.N_t.(1-f) \quad (1)$$

Where e is the electron charge, Na the acceptor concentration, Nt the concentration of surface defects and f the occupation probability of the energy level of donors.
The depletion region width Zd is then deduced, it is given by:

$$Z_d = \frac{N_t(1-f)}{N_a} \quad (2)$$

The occupation probability f is given by the following expression:

$$f = \frac{\Delta n(0) + n_0 + n_i.\exp\left(\frac{E_i - E_t}{KT}\right)}{\Delta n(0) + n_0 + \Delta p(0) + p_0 + 2n_i.\cosh\left(\frac{E_t - E_i}{KT}\right)} \quad (3)$$

Where Δn(0) and Δp(0) are respectively the concentration excess of electrons and holes at the surface, n_i the intrinsic carrier concentration, n_o and p_o the electrons and holes concentrations at the surface respectively, E_i the intrinsic Fermi level and E_t the energy level in the band gap of surface defects.
In order to have Δn(0) and Δp(0) as a function of Z_d the continuity equation has been used. It is given by the following expression:

$$div.\vec{J} = G(z) - R(z) \quad (4)$$

Where $\vec{J}$ is the carrier flux, G(z) and R(z) are, respectively, the generation and recombination rates.
G(z) is expressed as a function of ϕ(u) by:

$$G(z) = \frac{\rho}{R_e}\phi(u) \quad (5)$$

Where ρ is the density of the semiconductor (in g/cm^3), R_e the penetration depth of electron (in g/cm^2) and ϕ(u) the dissipation function, expressed, according to Wu and Wittry [9] by:

$$\phi(u) = A.\exp\left[-\left(\frac{u - u_0}{\Delta u}\right)^2\right] - B\exp\left(-\frac{bu}{u_0}\right) \quad (6)$$

u is the normalized penetration ($u=\rho.Z/R_e$), Z being the depth.
u_0, Δu, A, B, b have been calculated by the authors, in a previous work, for CdTe [10], there are equal to:
Δu=0.17, u_0=0.057, b=3 and B/A=0.5
Δn(0) and Δp(0) are finally deduced and given by:

$$\Delta n(0) = \exp(\alpha.Z_d^2)[\theta_n - \xi_n erf(\sqrt{\alpha}.Z_d)] \quad (7)$$

$$\Delta p(0) = \exp(-\alpha.Z_d{}^2)[\theta_p - \xi_p F(\sqrt{\alpha}.Z_d)] \quad (8)$$

Where α is given by: $\alpha = \frac{e^2.N_a}{2.\varepsilon.KT}$ and θ_n,θ_p ,ξ_n,ξ_p are constants, obtained using the following boundary conditions:

$$\Delta n(Z_d^-) = \Delta n(Z_d^+)$$

$$\Delta p(Z_d^-) = \Delta p(Z_d^+)$$

$$\Delta n(Z_d^+) = \Delta p(Z_d^+)$$

$$J_n(Z_d^-) = J_n(Z_d^+)$$

$$\left.\frac{d\Delta n}{dz}\right|_{z=Z_d^-} = \left.\frac{d\Delta n}{dz}\right|_{z=Z_d^+}$$

To calculate Z_d we first introduce an initial value of Z_d in the transport equations for a given energy E_0 and intensity I_p. The resolution of these equations allows us to determine Δn(0) and Δp(0) and then to deduce a new value of Z_d. If the difference between the initial value of Z_d and the new one is weak, we take this latter as the value of Z_d. If, however, the difference is great we inject the new value in the program and run it again. We let's stop this process when the obtained Z_d is equal to the initial one.

3.2 Calculation of I_{Cl}

Only radiative processes in the neutral region are considered in the calculation of the cathodoluminescence intensity, which means that there are no recombinations in the depletion region, which allows the use of the low injection model. For a p type semiconductor, the I_{Cl} intensity is given by the formula:

$$I_{Cl} \approx \int_{Z_d}^{+\infty} \frac{\Delta n(z)}{\tau_r}\exp(-\alpha.z)dz \quad (9)$$

Where α is the absorption coefficient, and τ_r the radiative lifetime.
To obtain different values of I_{Cl} we calculate Δn(z) and Δp(z) related to final value of Z_d, calculated previously, and then I_{Cl} linked to (E_0, I_p) is calculated.

4. RESULTS AND DISCUSSION

4.1 Distribution of the excess carriers concentration:

The variation of the excess minority (electrons) and majority (holes) carriers concentration with the electron beam current are shown in Fig.1a and Fig.1b respectively. It is observed that these concentrations increase with the increase in the beam current near the free surface, where the curves $\Delta n(0) = f(E_0)$ and $\Delta p(0) = f(E_0)$ show a maximum around E_0 = 15 keV. This is due to the strong generation carriers at low energies, on one hand, and on the recombination at high beam energies, on the other hand. Furthermore, it is observed that the excess concentration varies significantly with I_p, especially in the energy interval [10-20 keV] and there is no significant change for the high energy beam. This can be explained by the increase of the size of the generation volume, due to the electron penetration depths, which is deeper for the high energy beam.

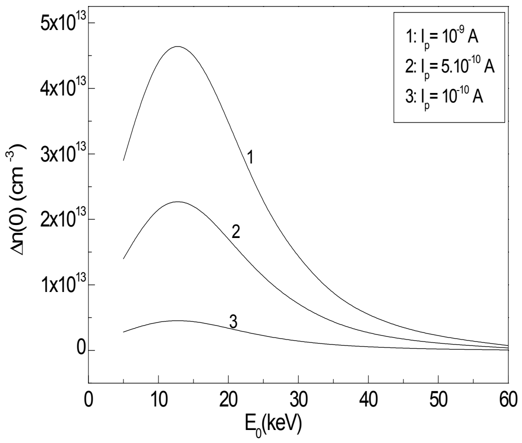

Figure 1a. Effect of the beam current on the minority carriers concentration - (E_t=1.4eV, L_n=1µm, $N_t=10^8cm^{-2}$, $N_a=10^{15}cm^{-3}$)

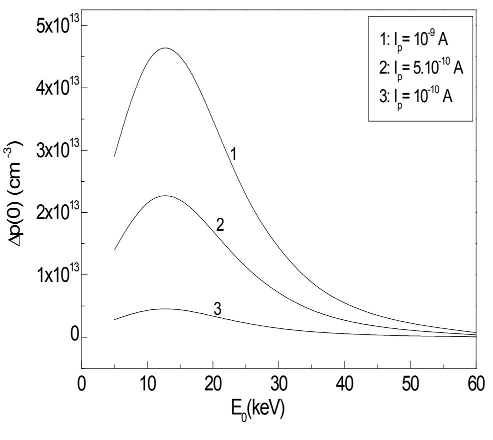

Figure 1b. Effect of the beam current on the majority carriers concentration - (E_t=1.4eV, L_n=1µm, $N_t=10^8cm^{-2}$, $N_a=10^{15}cm^{-3}$)

4.2 The depletion region

To study the behavior of the depletion region width as a function of the beam excitation conditions (E_0, I_p), the surface and volume parameters are fixed; they are for CdTe: E_t = 1.4 eV, L_n = 1µm, $N_t = 10^9cm^{-2}$, $N_a = 10^{15}cm^{-3}$.

Figure 2 shows the variation of Z_d as a function of I_p for different values of E_0.

It is observed that Z_d remains constant for low values of I_p ($I_p < 10^{-7}$A) and starts to decrease after that. This is explained in terms of the concentration of excess carriers created by the excitation, which is low for low values of I_p. That's why we do not record any effect on Z_d. For higher intensities, the excess carrier concentration becomes high, which leads to an increase of the probability of occupancy of the surface states and hence a decrease of Z_d.

On the other hand, it is known that: when E_0 increases the depth of the electrons penetration increases at the same time, and leads therefore, to have a larger volume of generation, and thus a reduction of excess carriers at the surface. This leads to a decrease of Z_d.

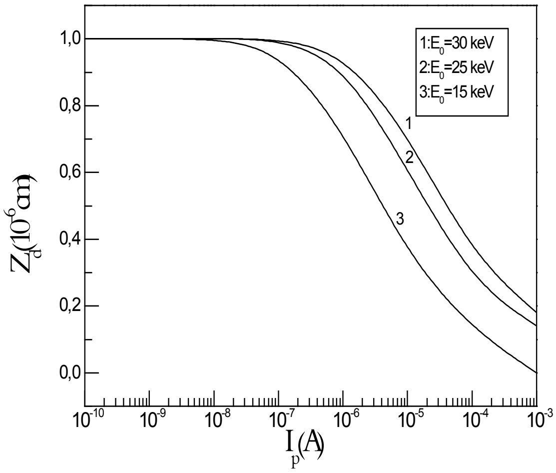

Figure 2. Influence of incident energy on the depletion region width
(E_t=1.4eV, L_n=1µm, $N_t=10^9cm^{-2}$, $N_a=10^{15}cm^{-3}$)

4.3 The Cl intensity

The theoretical curves ($I_{Cl} = f(E_0)$) have been used to determine, quantitatively, the surface and volume parameters. The effect of I_p on the curves ($I_{Cl} = f(E_0)$) is shown on Fig. 3, where it is observed, for each value of I_p, that the curves have a maximum between 30 and 40 keV. After that, the intensity starts to decrease.

The theoretical curves $I_{Cl} = f(E_0)$ have been used to determine the quantitative physical values of the volume and surface. Figure 3 shows the influence of the current intensity of the incident beam (I_P) on the $I_{Cl} = f(E_0)$ curves, which exhibit, for all I_P values, that the I_{Cl} intensity has a maximum in the range [30 - 40 keV] of the incident beam energy.

The low accelerating voltages are related, generally, to phenomena surface, which allows us to say that the increase of I_{Cl} as a function of E_0 up to the maximum is logical. In this section of the curve, it is estimated that the cathodoluminescence signal is exclusively related to surface recombinations.

Once the maximum is reached, it is the influence of the volume, through the optical absorption phenomenon, which occurs to drop I_{Cl}, we record a rapid decrease of I_{Cl} for relatively high values of I_p.

Figure 4 shows the influence of the energy of the incident beam on the curves $I_{Cl}= f (I_p)$. It is observed that I_{Cl} varies linearly as a function of I_p. This is in good agreement with previous works; which give the expression $I_{Cl} \sim I_p^m$, with $1< m < 2$, m depending on I_p and E_o. It indicates the low injection regime.

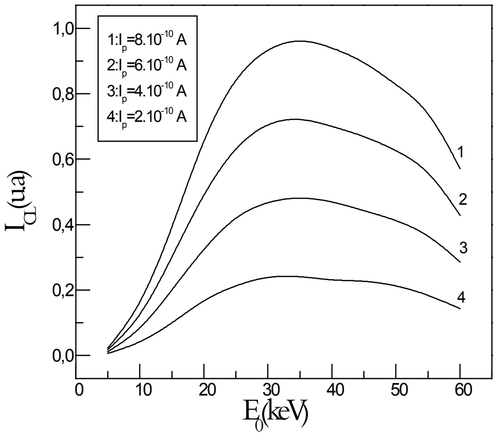

Figure 3. Variation of I_{Cl} intensity as a function of incident energy, for different current intensities (L_n=1μm, E_t=1.3eV, $N_t=10^8 cm^{-2}$, $N_a=10^{15} cm^{-3}$, $\alpha=10^4 cm^{-1}$)

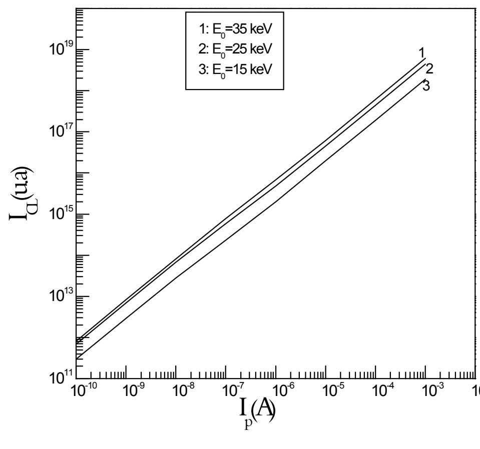

Figure 4. Variation of I_{Cl} intensity as a function of current intensity, for different energies (Ln=1μm, E_t=1.3eV, $N_t=10^8 cm^{-2}$, $N_a=10^{15} cm^{-3}$, $\alpha=10^4 cm^{-1}$)

5. CONCLUSION

In this study a theoretical investigation has been done to understand the effect of incident electron beam parameters (energy E_0, intensity I_p) on the excess carriers, the cathodoluminescence intensity (I_{Cl}) and the depletion region width (Z_d).

The influence of I_p on $\Delta n(0)$ and $\Delta p(0)$ is much greater for low values of the energy of the incident beam for large values.

On the other hand the calculation of the depletion region width (Z_d) and the cathodoluminescence intensity (I_{Cl}) as a function of electron beam parameters (E_0, I_p) indicates that Z_d remains constant for low values of I_p and decreases after that, and increases when E_0 takes great values. This analysis indicates also that the $I_{Cl} = f(E_0)$ curves have a maximum in the range [30 – 40 keV] for different values of I_p. However we record a rapid decrease of I_{Cl} for large values of I_p. Finally, the calculation results in a linear variation of I_{Cl} with E_0 if the energy is below 35 keV.

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