THE ROLE OF BULK RECOMBINATION IN THE FIELD-EFFECT IN ILLUMINATED CdS SINGLE CRYSTALS

By J. Łagowski and J. Sochański

Institute of Physics, Polish Academy of Sciences, Warsaw*

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Field-effect mobility in illuminated CdS single crystals is by several orders of magnitude smaller than the carrier (electron) mobility and augments with increasing of light-induced conductivity. This can be explained on the basis of a model which takes into account relaxation effects in an *RC*-system together with recombination of light-excited holes with volume centres. Comparison between the simple theory and experiment permits to determine the majority carrier (elctron) lifetime in photoconducting CdS.

1. Introduction

The dependence of the field-effect mobility in CdS single crystals has been measured *versus* light-induced conductivity by several authors [1—3]. All experiments showed that the field-effect mobility rises with increasin conductivity, changing by several orders of magnitude. It is not clear as yet whether such behaviour can be explained by the bulk properties of CdS or whether it is influenced predominantly by the surface region, especially by surface states.

In our previous paper [4] an explanation is given of field effect pinch-off in CdS crystals, where an essential role is postulated for bulk recombination of light-excited holes. A similar argumentation is presented here in explaining the above mentioned effects.

2. Experimental

The experimental arrangement, sample material and preparation of samples were the same as described in our previous paper [4]. The majority carrier lifetimes measured by the stationary conductivity method in various samples ranged from 1 to 100 μsec.

Perpendicularly applied voltages were so low that the induced change of the conductance were much smaller than the initial values (without applied field). In such conditions the change in conductance varied linearly with the voltage. The ambient gas had little effect on the experimental results and the measurements were carried out at room atmoshpere.

Address: Instytut Fizyki PAN, Warszawa, Zielna 37, Polska.

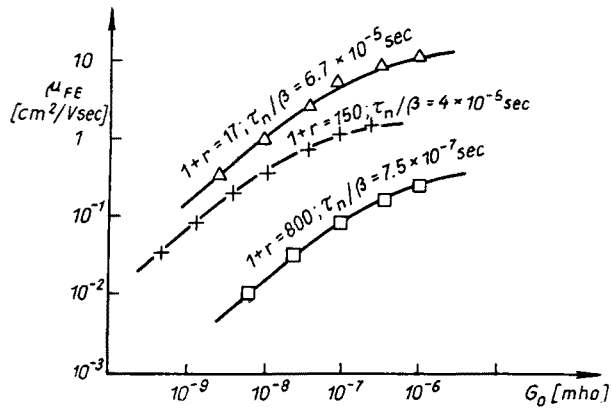

Fig. 1. Experimental dependence of the field-effect mobility μ_{FE} on the conductance G_0 (points). Theoretical curves correspond to chosen values of parameters $1+r$ and τ_n/β

Fig. 1 shows the results of measurements for three samples. Field-effect mobility is defined by the formula

$$\mu_{FE} = S \frac{d\Delta G}{dQ}, \tag{1}$$

where ΔG is the field-induced change in "surface conductivity" *i.e.* bulk conductivity times sample thickness, S — the area of the sample, and Q — the field-induced electric charge.

3. Discussion

We shall apply the same notation and, in principle, the same model as in our previous paper [4]. Let us assume that a small voltage U is applied perpendicularly to the sample surface at the moment $t = 0$. Beginning from this moment, an electric charge accumulates on the surface of the sample (and correspondingly, on the field electrode) according to the equation

$$\frac{dQ}{dt} = \frac{U}{R} - \frac{Q}{RC}, \tag{2}$$

where R is the sample resistance mearused between the current electrodes. Eq. (2) follows from the assumption that the system: field electrode-sample can be compared to a simple RC-system. This is obviously a simplification made in order to reveal the essental features of our model.

For the time-dependence of Q we obtain from Eq. (2)

$$Q = CU\,(1-e^{-\frac{t}{RC}}). \tag{3}$$

On the other hand, a similar argumentation as that leading to Eq. (18) in [4] gives for the case of exhausted surface layer (corresponding to negative voltage on the field electrode)

$$Q = S\varrho_0 x + S\beta\gamma n_0 xt, \tag{4}$$

where n_0 is the equilibrium concentration of light-excited electrons in the conduction band, $\gamma = q/\tau_n$ and the parameter β is a slowly varying function of t fulfilling the condition $\frac{1}{2} \leqslant \beta \leqslant 1$. The first term in Eq. (4) is equal with opposite sign, to the electron charge in the conduction band, and in donor levels, in a layer of thickness x. The existence of the second term in Eq. (4) is related with recombination of the light-excited holes and negatively charged acceptors in the same layer. The time-dependence of follows from time-dependent investment of the acceptor levels. Its exact form can be found but is not essential for the discussion.

The symbol x in Eq. (4) denotes the depth of field penetration or the thickness of an insulating layer.

Eqs (3) and (4) yield for the time-dependence of x

$$x = \frac{CU\left(1-e^{-\frac{t}{RC}}\right)}{S(\varrho_0+\beta\gamma n_0 t)}. \tag{5}$$

The quantity ΔG in Eq. (1) corresponds to the maximum value x_m of x. This may be obtained from the condition

$$\frac{dx}{dt} = 0. \tag{6}$$

Differentiation of (5), together with Eq. (6), yields

$$\varrho_0+\beta\gamma n_0 t_m = \beta\gamma n_0 RC\left(e^{\frac{tm}{RC}}-1\right), \tag{7}$$

where t_m is the value of t for $x = x_m$. Eq. (7) can be solved numerically, giving the dependence of t_m on R or on G_0. Putting $x = x_m$ and $t = t_m$, we get from Eqs (5) and (7)

$$x_m = \frac{Ue^{-\frac{tm}{RC}}}{S\beta\gamma n_0 R}. \tag{8}$$

On the other hand, Eq. (1) together with Eq. (19) of [4] yields

$$\mu_{FE} = \frac{S}{C}\frac{d\Delta G}{dU}. \tag{9}$$

The maximum change in surface conductivity ΔG amounts to

$$\Delta G = qn_0 x_m \mu_n. \tag{10}$$

Eqs (8)—(10) and the formula $\gamma = q/\tau_n$ yield

$$\mu_{FE} = \frac{\mu_n\tau_n}{\beta RC}e^{-\frac{tm}{RC}}. \tag{11}$$

It can be shown from Eq. (7) that for $n_0 \to 0$ we have $t_m/RC \to 0$. Thus, for small n_0, Eq. (11) acquires an approximate form

$$\mu_{FE} = \frac{\mu_n\tau_n}{\beta RC}. \tag{12}$$

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As $R \sim n_0^{-1}$, we get for $n_0 \to 0$

$$\mu_{FE} \sim n_0 \text{ or } \mu_{FE} \sim G_0. \tag{13}$$

In the extreme case of $n_0 \to \infty$, Eq. (7) gives

$$\varphi_0 = \beta \gamma n_0 RC \, e^{\frac{tm}{RC}}. \tag{14}$$

Eqs (11) and (14) together with Eq. (4) of [4] give for n_0

$$\mu_{FE} = \frac{\mu_n}{1+r}, \tag{15}$$

where r is the ratio of the number of electrons in donor states and in the conduction band.

In Fig. 1, theoretical curves corresponding to Eq. (11) and the experimental dependence of μ_{FF} on G_0 are compared. Relatively good fitting is obtained by choosing the proper values of the parameters $1+r$ and τ_n/β. The results for τ_n are of the same order of magnitude as those obtained by the stationary conductivity method.

It is worth reminding that in the case of pinch-off effect [4] we were unable to get the correct results for τ_n without making the assumption that the field-excited holes are extracted from the sample by the electric field. This assumption is unnecessary in the present case. the reason of this may be the following: In the case of low conductance, when $t_m/RC \ll 1$ (which represents the assumption leading to Eq. (12)) the electric field existing at the moment of maximum change in conductance can be too low for extracting the holes.

The field attains a sufficiently high value only after the time RC when relaxation of conductance sets in. Thus the essential feature of the experiments described in the present paper consits in the circumstance that the measured change in conductance corresponds to the moment in which only a small portion of the total charge $Q = CU$ is induced in the sample. It follows from Eq. (5) that after a sufficiently long time the change in conductance is inversely proportional to t. The experimental dependances are indeed of this type and comparizon with the theoretical formula permits to evaluate the parameters τ_n. These are found to be of the same order of magnitude as those obtained from the pinch-off effect, confirming the preceding reasoning. Thus we come to the conclusion that the results for τ_n which correspond to the curves in Fig. 1 are correct, not being influenced by the effect of field extraction of holes.

4. Conclusions

It was our aim to show that field-effect experiments on illuminated CdS crystals can be explained on the basis of a model which does not take into consideration the existence of surface states. This obviously not imply that they play no role at all; we can nevertheless state that the experimental method is inadequate for detecting and studying them.

On should note that the above-descibed model cannot be applied for positive voltages on the "field-electrode" electric field causing the increase in conductance. The examination

of this case would strongly complicate the discussion in view of our insufficient knowledge of the necessary parameters in the samples measured.

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REFERENCES

[1] Thielemann, W., *Z. Naturforsch.*, **4a**, 92 (1959).
[2] Eckart, F., Tesch, H., *Z. Naturforsch.*, **16a**, 717 (1961).
[3] Auth, J., Krenzke, G., Niekisch, E. A., *Z. Phys. Chem.*, **213**, 17 (1960).
[4] Łagowski, J., Sochański, J., *Acta Phys. Polon.*, **28**, 193 (1965).