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PHOTOCAPACITY RELAXATION PECULIARITY OF NONIDEAL HETEROSTRUCTURE

For Schottky barrier structures it can be stated that the contribution of tunneling of non-equilibrium carriers, trapped near the interface, is significant in photocapacitance relaxation. For a depletion region width less than 0,3 μm, the application of theory, based on thermal release of centers, to determine the parameters of those centers gives an error close to the measured value. In case of thin barriers the parameters have to be obtained from the slow phase of photocapacitance relaxation.

INTRODUCTION

Investigation of the relaxation of a heterojunction photocapacitance from excited to equilibrium state allows to determine depth and capture cross section of traps, located in space charge region. However in structures with high density of states near the interface it is impossible to obtain realistic data of trapping states by the methods cited.

DISCUSSION

Relaxation of barrier capacitance from photoexcited to equilibrium condition has been carried out on thin-film CdS—Cu_2S heterostructures. The mechanism of current transfer in these structures is not obvious and demands special study. However, the effects of photocapacitance can be described by a simple theory. In all cases the capacitance measurements were made on short-circuited samples. Such heterostructures are the typical representatives of nonideal Schottky-barrier structures. Photocapacitance relaxation of heterostructures consists of two phases. During the initial period the capacitance falls steeply at a rate which is not dependent on temperature. For the second phase the time constant is considerably larger and temperature-dependent.

An analysis of experimental results by the method suggested in [1] does not yield characteristic curves, that can be used to evaluate hole trap parameters. This means that for nonideal heterostructures the well known model, based on thermal emission from traps, is invalid. The essence of the proposed model is that tunnel processes affect significantly the transition of exited heterostructure to equilibrium state.

MECHANISMS OF HOLE RELEASE

In the energy diagram (Fig. 1) all mechanisms of hole release from traps, located in space charge region of cadmium sulfide, are shown. For those non-equilibrium holes with density p_t the rate equation is given by:

$$\frac{dp_t}{dt} = -p_t \bar{v} S_p P_{v_1} e^{E_t/kT} - p_t \bar{v} S_p P_{v_2} D_1(x) - p_t \bar{v} S_n n_0 D_2(x), \quad (1)$$

where $\bar{v}$ is the average thermal velocity of carriers, S_p and S_n are capture cross sections for holes and electrons, P_{v_1} and P_{v_2} are densities of hole states in valence band of CdS and Cu_2S, respectively, and $D_1(x)$ and $D_2(x)$ are transparency coefficients of potential barrier, corresponding to the tunnel transitions 1 and 2 (Fig. 1).

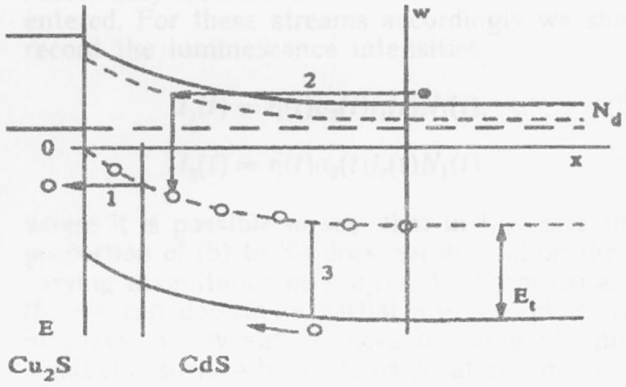

Fig. 1. Energy diagram of CdS—Cu_2S heterojunction

On the right hand side of the above equation the first term represents thermal emission of holes into the valence band of CdS (transition 3), the second term represents the tunneling into valence band of Cu_2S (transition 1) and the third term corresponds to two-stage recombination process with electrons being transmitted by tunneling (transition 2).

TRANSPARENCY COEFFICIENTS

The transparency coefficients $D_1(x)$ and $D_2(x)$ can be obtained from:

$$D_1(x) = \exp\left\{-\frac{2\sqrt{2m^*}}{\hbar}\int_0^x \sqrt{E(\xi) - E_t(x)}\,d\xi\right\}. \quad (2)$$

Here we choose the origin of energy axis at the energy of traps, located at the interface, x is spatial coordinate of a trap, from which the tunneling takes place, $E(x)$ is valence band edge energy and $E_t(x)$ is energy of the trapping states in depletion region of CdS.

If φ_0 is the barrier height, W is barrier width and the potential is assumed to be parabolic, then in case of zero bias:

$$E_t(x) = E(x) - E_t = \varphi_0 - \left(\frac{W-x}{W}\right)^2 \varphi_0. \quad (3)$$

The transparency coefficient for free electrons, tunneling from quasi-neutral region of CdS (transition 2 in Fig. 1), is:

$$D_2(x) = \exp\left\{-\frac{2\sqrt{2m^*}}{\hbar}\int_x^W \sqrt{E(\xi)}\,d\xi\right\}. \quad (4)$$

For the parabolic barrier potential we obtain:

$$D_2(x) = \exp\left[-\frac{2\sqrt{2m^*\varphi_0}}{\hbar W}(W-x)^2\right]. \quad (5)$$

RESULTS

To solve eqn (1) with expression $D_1(x)$ and $D_2(x)$, the initial conditions should be set at each point x. Since in depletion region the energy distance between Fermi level and trapping levels depends on the coordinate, then for tow occupancy of traps (the most interesting case) the distribution of charge Q is exponential [2—4]. Thus, for the initial period and for the parabolic approximation of the potential we have:

$$p_t(0, x) = p_t(0, 0)\exp\left(-\frac{\varphi(x)}{kT}\right) =$$

$$= p_t(0, 0)\exp\left[\frac{\varphi_0\left(\frac{W-x}{W}\right)^2 - \varphi_0}{kT}\right]. \quad (6)$$

To solve eqn (1) we use computer calculations. The independent variables are the parameters of investigated heterojunction, found from measurements of barrier capacitance in darkness and during illumination.

According to definition $C = dQ/d\varphi_0$, where Q is the total charge in space charge region. Since φ_0 is time-dependent (short-circuit regime), capacitance relaxation is controlled by the change in the total charge and this process does not depend on the region of SCR, where it takes place. The barrier capacitance is related to the width of space charge region by:

$$W = \varepsilon\varepsilon_0 S/C. \quad (7)$$

On the other hand:

$$W = \left[\frac{2\varepsilon\varepsilon_0\varphi_0}{e^2(N_d + \bar{p}_t)}\right]^{1/2}, \quad (8)$$

where $\bar{p}_t$ is the average density of non-equilibrium holes, trapped in depletion region in CdS, and N_d is donor concentration in CdS. Therefore measurements of barrier capacitance of heterostructures give the possibility to determine N_d and $\bar{p}_t$ from eqns (7) and (8).

Since the barrier for electrons is lower than for holes the calculations of $D_1(x)$ and $D_2(x)$ (Fig. 2) show that the probability of tunnel recombination by transition 2 is preferable rather than by transition 1.

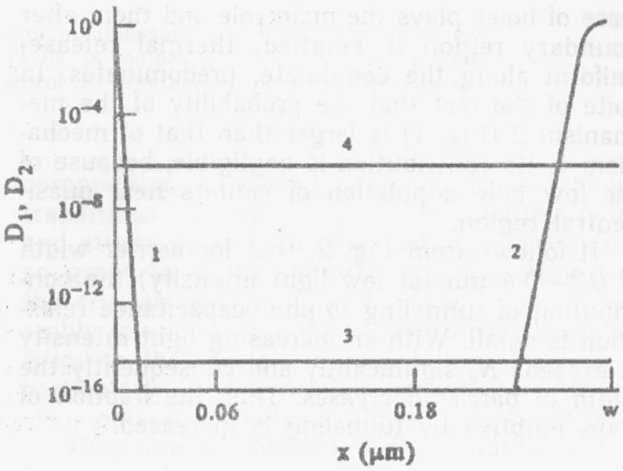

Fig. 2. Calculated value of D_1 (curve *1*) and (curve *2*) vs the coordinate x. Curve *3* and curve *4* represent the value $\exp(-E_2/kT)$ vs coordinate x for $T = 128$ K and $T = 310$ K, respectively. For all cases $E_t = 0.38$ eV

In case of uniform occupancy of hole centers the fraction of the carriers, recombining after tunneling in depletion region is too small to significantly affect the relaxation curve.

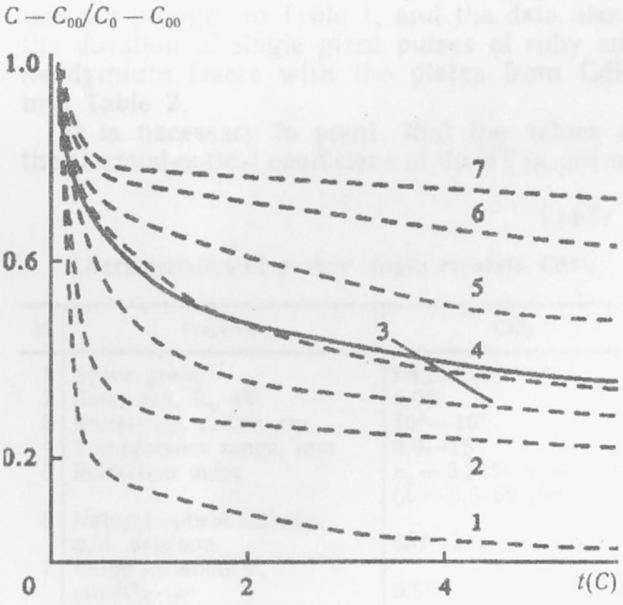

Fig. 3. Photocapacitance relaxation curves for the inhomogenous distribution of charge. (a) At different values of E_t: *1* — 0.18 eV; *2* — 0.29 eV; *3* — 0.34 eV; *4* — 0.38 eV; *5* — 0.42 eV; *6* — 0.50 eV; *7* — 0.65 eV. Continuous curves represent experimental data and dashed curves calculated value

For the exponential distribution of charge a large number of trapped non-equilibrium holes accumulates near the interface. In this realistic case, the contribution of tunneling processes to photocapacitance relaxation may be considerable, even if possible tunneling of holes is small.

Figure 3 represents the calculated values of $C(t)$, for an inhomogeneous distribution of the charge and different values of E_t. These curves exhibit a characteristic inflection and for reasonable values of E_t fit well the experimental data. For the initial relaxation phase the tunnel release of holes plays the main role and then, after boundary region is emptied, thermal release, uniform along the coordinate, predominates. In spite of the fact that the probability of the mechanism 2 (Fig. 1) is larger than that of mechanism 1, its contribution is negligible, because of the low hole population of centers near quasi-neutral region.

It follows from Fig. 2, that for barrier width of 0.3—0.4 μm (at low light intensity) the contribution of tunneling to photocapacitance relaxation is small. With an increasing light intensity p_t exceeds N_d significantly and consequently the width of barrier decreases. Thus the fraction of traps emptied by tunneling is increased.

CONCLUSIONS

For Schottky barrier structures it can be stated that the contribution of tunneling of non-equilibrium carriers, trapped near the interface, is significant in photocapacitance relaxation. For a depletion region width less than 0.3 μm, the application of theory, based on thermal release of centers, to determine the parameters of those centers gives an error close to the measured value. In case of thin barriers the parameters have to be obtained from the slow phase of photocapacitance relaxation.

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