Letter to the Editor

THE EFFECTS OF ACOUSTIC MODULATION OF ENERGY LEVELS IN A PIEZOSEMICONDUCTOR[1)]

ЭФФЕКТЫ АКУСТИЧЕСКОЙ МОДУЛЯЦИИ ЭНЕРГЕТИЧЕСКИХ УРОВНЕЙ В ПЬЕЗОПОЛУПРОВОДНИКАХ

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At the ultrasound wave (USW) propagation the modulation of the bandgap as well as of the conduction band bottom and the top of the conduction band bottom and the top of the valence band takes place in the crystal: the bandgap W_d being expressed by the sum of the balanced width W_{d_0} and the variable term ΔW, which is proportional to the strain:

$$W_d = W_{d_0} + \Delta W = W_{d_0} + (\xi_n - \xi_p)\, \mathrm{d}u/\mathrm{d}x\,,$$

where ξ_n, ξ_p are strain potential constants for electrons and holes, respectively. In a medium featuring piezoeffect the modulation of the band edges of the same phase takes place, the amplitude being defined by the displacement amplitude U_0 and the piezoconstant e_{ik}:

$$\Delta W = (q e_{ik}/\varepsilon_{ik}\, \varepsilon)\, U_0\,,$$

where ε_{ik} is the dielectric constant. A quantitative assessment shows that at the intensity of W/cm^2 the amplitude of the bandgap edges modulation in the piezoelectric may reach the electron-volt value. The potential relief wave inhomogeneity of such a kind leads to the widely known phenomenon of free charge carriers bunching with the screening of the intrinsic field with free carriers and the changing of their local concentration the modulation of the unbalanced Fermi level occurs, e.g. the double concentration results in the level displacement by kT and due to the non-linearity of the task it must be taken into account that in some points the concentration may drop to zero, while in the linear case the modulated Fermi quasi level is:

$$W_F' = W_F + \Delta W_F(x, t) = W_{F_0} \exp \mathrm{i}(kx - \omega t)\,,$$

where ΔW_{F_0} is the amplitude value defined by local concentration.

When local impurity levels exist within the bandgap, their interarrangement relative to the modulated Fermi level varies and since their occupancy depends upon the local concentration in the

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zone, it varies, in the case of rather "quick" traps their occupancy varies leading to the concentration change in the band when a definite intensity USW eixsts in the crystal. Thus, if we take into account that the grouped charge consists of the charge in the band and on the traps, i.e. $n_s = n_{s_0} + n_{st}$, current carriers concentration data become dependent on the modulation levels depth, i.e. on the USW intensity: $n_{s_0}, n_{st} = f(W)$. Variation of the sulphide cadmium crystal electroconductance at the USW propagation has already been noted by us [1] as well as by others [2]. The positive and negative acoustoresistive effect has been determined there.

The variation of the stationary electric conductance $\Delta\sigma_{st}$ following the irradiation of the semiconductor (exposure and USW) may be represented by:

$$\Delta\sigma_{st} = q\,[(\alpha_{h\nu} BJ \pm \alpha\beta W)\,\mu_n\tau_n],$$

here it is assumet that $\mu_n\tau_n \gg \mu_p\tau_p$, $\alpha_{h\nu}$, α — are the coefficients of light and USW absorption, respectively, β is the quantum efficiency, β_{ak} the quantity (magnitude, parameter) analogous to the quantum efficiency for USW, μ the mobility, τ — the lifetime. I and w the light and the ultrasound wave intensity, respectively. The plus or minus sign for the second term reflects the current carrier liberation from the traps or the accelerated capture (recombination). The current carrier forcing out the traps was described for the first time theoretically [3, 4, 5] and it was found [5] that the respective conductance variation is given by

$$\frac{\Delta\sigma}{\sigma} = \frac{n_{t0}}{n_0} - \frac{B}{U_0},$$

where B is a definite constant. Thus, it follows that $\Delta\sigma$ will be the biggest when all the traps are empty and the USW displacement amplitude will be so big that $B/U \to 0$.

The picture is much more complicted when there exist minority current carriers; then μ_n and τ_n values for the majority current carriers may undergo significant changes. The experimental data of relaxational curve ΔR have shown that the rise time τ' and the tail time τ'' differ with the USW cut off. This presumes the process of square recombination, i.e. $\partial n/\partial t = \alpha\beta W - \gamma(\Delta n)^2$, when $\Delta n \approx \Delta p$. In such a case the USW generates an additional amount of the majority Δn and the minority Δp current carriers; thiss becomes clear if the conclusion of paper [5] is applied to holes when $\Delta p \sim \sqrt{W}$. It may be explained by the mechanism of tunnelling from shallow levels at the barrier deflection as described in paper [6], where it is shown that tunnelling probability at the USW significantly increases.

In the present situation the lifetime τ_n consists of the current carrier staying time in the region τ_1 and on the traps τ_2; $\tau_n^{-1} = \tau_1^{-1} + \tau_2^{-1}$. Carriers capture by traps is defined by the capture factor $f = n_{s_0}/n_s$. A phase difference is produced between the waves of free $n'_{s_0} = n_{s_0} \exp[i(\omega t - kx)]$ and bound $n'_{st} = n_{st} \exp[i(\omega t - kx + \delta)]$ charges and in general f is a complex quantity [7]:

$$f = \frac{f_0 + \omega^2\tau^2}{1 + \omega^2\tau^2} - i\frac{\omega\tau(1 - f_0)}{1 + \omega^2\tau^2} = \frac{bf_0}{1 + ia},$$

where $a = \mathrm{Im}f/\mathrm{Re}f$. The greatest variation of bf_0 and a takes place near $\omega\tau \to 1$: when $\omega\tau > 1$, $bf_0 \to 1$ and $a \sim \omega^{-1}$ while at $\omega\tau < 1$, $bf_0 \to f_0$, and $a \sim \omega$. It has been repeatedly noted that the majority current carrier capture depends on wave intensity W, thus $f = f(W)$.

Following the above linear relations and employing the experimental data of the critical quantities of acoustoelectric interactions it is possible to evaluate the lifetime variation of the majority current carriers in the USW field. For this, the data of critical carrier velocity at different USW intensities for sulphide cadmium crystals with different photoelectric characteristics have been used. It has been determined that the real part f_r of the capture factor varies more intensively than the imaginary one f_i. For example, for photosensitive crystals with sensibilization centres when W increases on the radiator to 4 W/cm^2 a values are changed from 0.380 to 0.564, i.e. by 48 per cent.

Having multiplied the value f'_r by a we find that the imaginary part f'_i is equal to -0.26. According to the data, when the real f_r part f''_r at a high intensity is equal to $0.7 \times f'_r = 0.49$, we can see that $f''_r = -0.274$, i.e. its variation accounts only for ~ 5 per cent. According to the calculated data it is possible to evaluate the interaction frequency range in relation to $\omega\tau$, here $\omega = 9\pi \times 10^7\ \mathrm{s}^{-1}$. Assuming that $\mu_x = 250\ \mathrm{cm}^2/\mathrm{Vs}$ at a low intensity of USW $(bf_0)' = \mu'/\mu_x = 0.8$. The high value of a shows that $\omega\tau$ is close to unit. Assuming that $\omega\tau = 0.9$ we obtain $f_0 = 0.46$, while $bf'_0 = 0.804$ and then $\tau = 3.2 \times 10^{-9}$ s. For a high intensity $(bf_0)'' = 0.65$. By solving equation systems which consist of expression bf_0 and a we define f and $\omega\tau$. We obtain $f = 0.35$. Taking into account that $f^{-1} = (1 + \tau_2/\tau_1)$ we obtain for high intensity $(\tau_2/\tau_1)'' = 1.85$. This interrelation at low intensity is equal to 1.16. Time interrelation $(\tau_2/\tau_1)'/(\tau_2/\tau_1)'' = 0.62$. The lifetime when $\omega\tau = 0.55$ is equal to $\tau = 2 \times 10^{-9}$ s. The relative capture factor variation for the given intensity is equal to 28 per cent.

Positive acoustosensitivity is observed for sulphide cadmium semiconductor crystals. Similar assessment for them gives the following values: $(bf_0)' = 0.18$; $(bf_0)'' = 0.21$. The value a is low and it indicates that the investigations were carried out in the $\omega\tau \ll 1$ area. The increasing value of bf_0 with the growth of the USW intensity indicates the displacement as a result of the capture and the recombination wave presence in the direction of an τ increase. Numerical assessment gives the following values: $f_0 = 0.18$, $f = 0.25$, $(\omega\tau)' = 0.035$, $(\omega\tau)'' = 0.065$.

Thus, the modulation of energy levels by the USW in photosensitive crystals causes lifetime reduction accelerating the carriers exchange between bands and impurity local levels; the lifetime in semiconductor crystals is increased, as if the wave slightly reduces the trap influence forcing the carriers into the band.

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