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PARTICULARITIES OF CURRENT TRANSFER IN THE CRYSTALS WIHT TWO TYPES OF RECOMBINATION CENTRES

The lower limit for concentrations of recombination centers was calculated by change current transfer mechanism on lux-amper characteristics at higher and lower intensity of light. Analytical expression is obtained for dependency of quenching factor (Q) on intensities intrinsic and quenching light. It was stated that intensity of the applied field limited the repeated capture of holes on the centers of slow recombination. On the grounds of studies in temperature changes of $Q(T)$ value (outside the area of temperature quenching) is stated that liberation of the holes occurs in two stages with absorption of phonon, but then — of photon.

The effect of infrared quenching continues to attract the attention by the peculiarities of running processes. We researched filamentary crystals of cadmium sulfide with n-type conductivity with cross-section of the order 1 mm^2 and distance 1—1, 5 mm between In-Ga contacts. The applied voltage was varied within the range up to 50 V. Excitation was carried out from self-absorption band of CdS (510—530 nm). Monochromatic radiation was used for quenching within the range 800—1600 nm. The sample had strong infrared quenching of photocurrent. At low values for ratio of quenching light intensities to intensities of excited one, value of the factor of infrared quenching Q reached easily 100%. The curve of the spectral distribution $Q(\lambda)$ had the typical type with two maximums in the range of 1130—1380 nm, respectively. The second maximum in the range 1400 nm corresponds to excited R′ state of slow recombination center. The presence in forbidden band S- and R-centers, corresponded to model of A. Rose, correlates also with temperature quenching of photocurrent studied on these samples. The obtained depths for R and R′ level, equal to ~1,1 eV and ~0,9 eV and ratio for capture cross-sections for the second-class centers $S_{p2}/S_{n2} \sim 10^5$ correspond to the traditional parameters. The presence of both quenching type indicates the comparable concentrations of S- and R-centers. Herewith, absolute value of center concentration of each class must be significant.

When crystals are illuminated only by intrinsic light with intensities, I_e concentration of free electrons $n(e)$ (at factor of the absorption of the own light α and quantum output β) is defined by expression

$$n(e) = \alpha \cdot \beta \cdot L_e \cdot \tau_{n_1} \quad (1)$$

Expression (1) is taken into account that recombination is realized mainly through S-centers and, accordingly, life-times τ_{n_1} is defined by this channel. Under rather high intensities of excited light, τ_{n_1} does not depend on its intensity, since the difference in concentration of free carriers $n—p$, equal to the change in the filling recombination centers, turns out to be far less than concentrations these centers. So on graph of lux-amper characteristics two areas exists with different slopes by higher and lower intensities of the light. Change in the mechanism of photocurrent forming and, accordingly, slopes of LAC graphics occurs, when the number of incident photons becomes comparable to concentration of recombination centers. So, the experimental value of illuminance $L_{0e} = 69{,}7$ lx in this point allows to evaluate this concentration. Under mechanical equivalent of light A = 0,0016 and energy of photons, equal to width of the forbidden band CdS $E_g = 2{,}42$ eV, we get the number of photons $N_{ph} = L_{0e}/E_g = 2{,}88 \cdot 10^{17}$ s^{-1} m^{-2} in used light flux. At size sample $1 \cdot 1 \cdot 1{,}2$ mm from this flux on its frontal surface happens up to $N'_{ph} = 2{,}88 \cdot 10^{17} \times 1{,}2 \cdot 10^{-6} = 3{,}46 \cdot 10^{11}$ s^{-1} photons. All of them are absorbed in volume of the crystal $1{,}2 \cdot 10^{-3}$ sm^3. So volumetric concentration of recombination centre N_r, equal to the number of photons, uniformly distributed in this volume, will be equal to $N_r = 3{,}46 \cdot 10^{11}/1{,}2 \cdot 10^{-3} = 2{,}88 \cdot 10^{14}$ cm^{-3}. Obtained value $3 \cdot 10^{14}$ sm^{-3} we consider as lower limit for doping by recombination impurity. At simultaneous influence of intrinsic and infrared light, the analysis in dependencies of free electron concentrations, and, consequently, the flowing current, on their intensities in general case is presented in [1]. Owing to its common character, the obtained expression is difficult to be analyzed in application to particular experimental conditions. Besides, concentration of free carriers in [1] is expressed through the population of recombination centers of the 1-st and the 2-nd classes, which change themselves under different levels of excitation and quenching light. The expression for explicit type $Q(L_e; L_q)$ we didn't find in literature. When the infrared light of respective energy was applied, the redistribution of holes between recombination centers

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occurs. Condition of charge non-accumulation for this case at photo excitation rate f will be in the form

$$f_n = g'_{p1} = \frac{(p + \partial p)}{\tau_{p1}} \quad (2)$$

Here it is taken into account that the rates of the recombination for electrons and holes for one and the same level are equal to $g'_{n1} = g'_{p1}$. Besides, the infrared light, dislodging holes from R-centers, additionally reduces recombination there $g'_{n2} < g'_{p1}$. Under action of infrared light, the concentration of holes on the second-class centers decreases on p and the concentration of free charge increases on as much in valence band. If in the unit of time I_q quantums of quenching light is incident on crystal, then in the unit of volume $\alpha' \cdot I_q$ quantums will be absorb, where α' — value of absorption factor in IK-area. Then

$$\partial p = \alpha' \cdot I_q \cdot \beta' \cdot \tau_{p1}, \quad (3)$$

where β' — quantum output for long-wave excitation. If the level of intrinsic excitation is high enough, then concentrations of free electrons and holes are comparable. Then (2) with account (3) gains the type

$$\alpha \cdot \beta \cdot I_e = \frac{n(e;q)}{\tau_{p1}} + \alpha' \cdot I_q \cdot \beta',$$

where

$$n(e;q) = (\alpha \cdot \beta \cdot I_e - \alpha' \cdot \beta' \cdot I_q) \cdot \tau_{p1}. \quad (5)$$

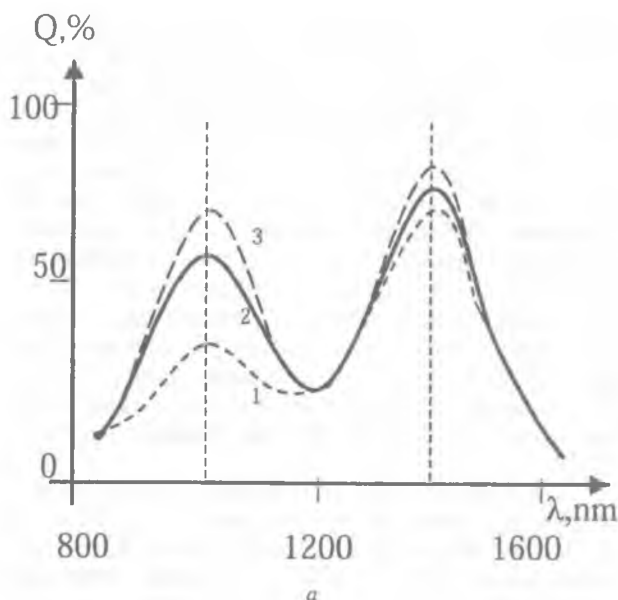
The formula (5) describes the dependency of free electron concentrations on intensity of simultaneously acting excited and quenching light. The expressions (1) and (5) allow to get the dependency of IR -quenching factor on intensity of used light flux:

$$Q = \frac{I_f(e) - I_f(e,q)}{I_f(e)} = \frac{n(e) - n(e,q)}{n(e)} =$$

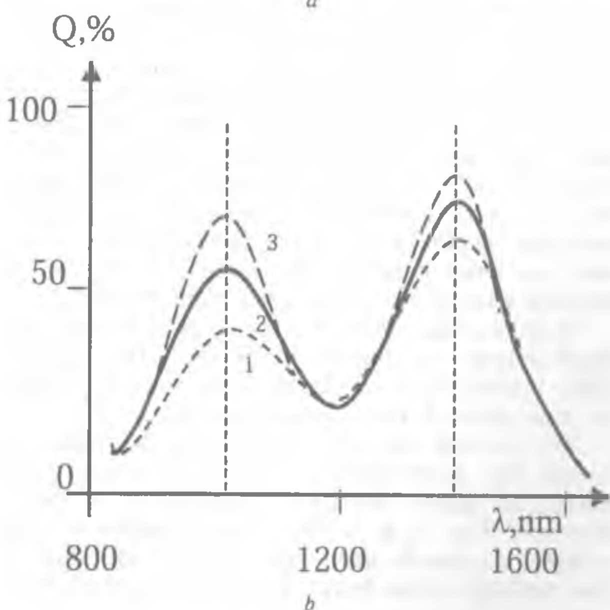
$$= \frac{\alpha \cdot L_e \cdot \tau_{n1} - (\alpha \cdot L_e - \alpha' \cdot L_q) \cdot \tau_{p1}}{\alpha \cdot L_e \cdot \tau_{n1}} =$$

$$= \left[\left(1 - \frac{\tau_{p1}}{\tau_{n1}}\right) + \frac{L_q}{L_e} \cdot \left(\frac{\alpha}{\alpha'} \cdot \frac{\tau_{p1}}{\tau_{n2}}\right)\right] \cdot 100\%. \quad (6)$$

As can be seen from (6) under fixed level of excitation, as the increase in intensities of infrared light value Q raises; under unchangeable value of IR -flux, with raising of illumination by intrinsic light, the quenching turns out to be lower. It should be noted that the obtained correlation is valid only for low intensities of quenching light and high levels of photo excitation, the change in population of recombination centers can not take into account. The total experimental results for the behavior of quenching factor Q with change in the values light flux were presented on the Figure 1. Curve *2* was taken as basic for them, measured under one



a



b

Figure 1. Dependency of quenching value on intensities of applied light:

a — I_q = const; $I_{e1} > I_{e2} > I_{e3}$; b — I_e = const; $I_{q1} < I_{q2} < I_{q3}$

and same intensity of intrinsic and quenching light both in the case of 1a, and in the case of 1b. The left part (Fig. 1, *a*) shows how changes the value Q at variation excited light under unchangeable quenching one. On the Fig. 1, *b*, on the contrary — how the intensity of quenching light under fixed excited one changed the basic curve.

All graphs Fig. 1 were obtained in stationary conditions. In each point rather long (before 20 minutes) relaxation to avoid the processes, described in [2] was kept. We shall note that under any combinations of the intensities I_q and I_e short-wave maximum of Fig. 1 was lower than long-wave one. We link this with thermal transfer of trapped carriers. At the expense of phonons absorption, the part of holes from the basic R-level moves to excited R′-level. But population

of these levels define the corresponding maximums. Because of thermal redistribution (Figure 1, *a*, *b*) short-wave maximum turns out to be also more sensitive to the change in the intensities of each light. As can be seen from Fig. 1, *b*, the lesser the intensity of quenching light, under I_e = const, the lower the value Q. Moreover, for lower intensities of intrinsic excitation this revealed strongly. Experimentally, we managed to create the situations, when short-wave maximum disappeared completely. In that time, under unchangeable intensity of quenching light (Fig. 1, *a*) as the decrease of excitation I_e the value quenching factor increases. This raise was observed higher if applied intensities I_q were slight.

The enumerated experimental particularities of $Q(I_e; I_q)$ behavior confirm validity of the formula (6). There was amongst restrictions, imposed under its derivation, all holes, dislodged by light from the levels R—R′ remain in valence band and enlarge the capture on S-centers. Speaking in generally, this is not true. The cross-sections for the capture of holes by S- and R- centers are equal. However, the hole, photo excitated just before, exists spatially near R-centre and more probably will be trapped by it for the second time [3]. The similar, probably multiple, oscillations do not reveal itself in any way on fixed external parameter and bring to useless absorption of infrared light photons.

It is obvious that this process conceals the dependency on intensity of IR-light. The applied field, making hole displaced from source R-center, can prevent the repeated capture.

We carried out the experiment, allowing to reveal this particularity. On Fig. 2 curve *a* is measured under the same conditions, as base curves *2* Fig. 1, *a*, *b*. 50 V was applied to the sample. As can be seen from Fig. 2, reduction of this voltage make lower both maximums $Q(\lambda)$.

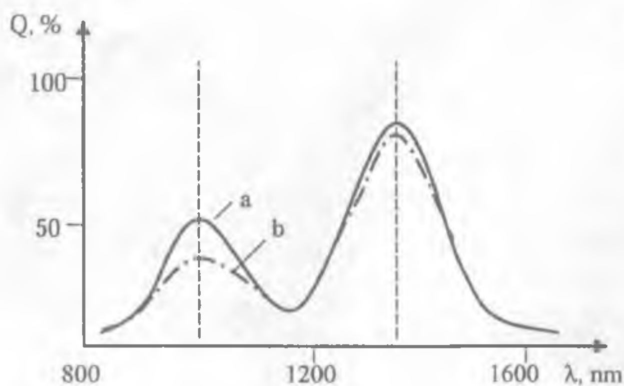


Figure 2. Dependency of quenching value from applied electric field:

a — 50 V is applied to sample; *b* — 30 V is applied to sample

Moreover, such behavior was typical for all combinations I_q and I_e. As in Fig. 1, the first maximum is found below the second and it was more sensitive to changes in electric field. This is connected with the described above thermal transfer between the main and excited condition of R-center. Under decrease of applied voltage we observed the increase in change of the first maximum, both in relation to long-wave maximum, and to initial condition short-wave one (look at the Figure). The presence of two maximums on curve of spectral distribution $Q(\lambda)$ is indicative about the presence excited R′-state with energy 0,9 eV aside the main R-conditions (1,1 eV). However, these data are not enough for determination of energy localization for such centers on band diagram.

Two variants are possible. In both cases, a hole is excited in two stages. Let R′-level are found closer to the main R-state, than to the top of valence band. Then transition of the hole into free state is realized first from R to R′-centers at the expense of thermal excitation (0,2 eV). And from R′-center in v-band at the expense of IR-light with energy 0,9 eV. But if 0,9 eV — is a distance between R and R′-centers then for the transition photon is first absorbed, but then phonon.

To reveal these circumstances we have conducted the special study, measuring the dependence of factor Q on temperature. Moreover, temperature range was chosen for the given intensity of excited light to exclude the influence of current thermal quenching. Intensity of excited light itself, and the quenching corresponding to it, was chosen so that both maximums were been visible clearly.

With temperature increase the second maximum in Fig. 3 is displaced to the right and downwards. Herewith it is characteristic the increase of its asymmetry — a steepness of the short-wave dip decreases then long-wave remains the same gentle. Simultaneously, the first maximum of the graphic practically does not change. We interpret the observed changes as follows.

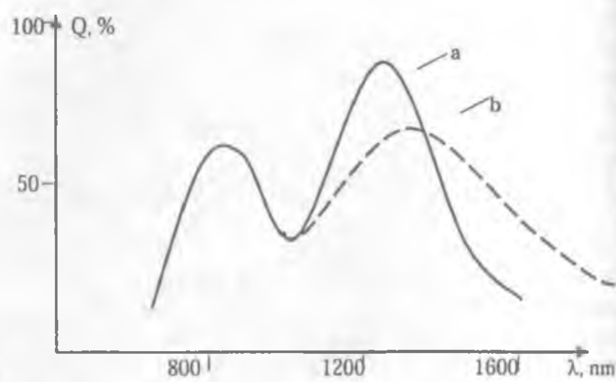


Figure 3. Spectral distribution for the factor of the infrared quenching at temperature:

a — 17 °C; *b* — 43 °C

It is obvious, that under zero temperature, the excited condition R-centers are absent, R and R'- levels coincide. As the heating R'- levels must gradually leave deeper from R- levels of energy. At the same time, for any temperature,

the sum of energy from R up to R′ and from R′ up to the top of valence band E_v it remains identical and Equals to the depth of the main state of R-center — 1,1 eV.

If the case, when photon is first absorbed, and then phonon, was realized, we must have observed the increase in contribution h\upsilon and, accordingly, wavelength reduction of the second maximum. We shall note that such situation is recommended by Richard Buba.

Our data witness for the situation with greater depth of R′-level.

The additional confirmation of this is a reduction in long-wave maximum of Fig. 3, *b* in the contrast with curve *a*. As the increase of necessary energy for thermal transition amount such phonon decreases in Maxwell distribution. Accordingly, the mechanism of thermal transfer for population of R′-centers, considered above, weakens.

It is clear that for dislodging holes from R′-levels not only light quantums with energy, equal to depth of such levels, work. Photons with greater energy work too. The lower the level, the contribution of such photons is essential. But long-wave edge of curve *b* is controlled as before only by dispersion of applied infrared flux. Because these mechanisms are different, the asymmetry of the second maximum in Fig. 3 increases.

References

1. *Serdyuk V. V., Chemeresyuk G. G.* Photoelectric processes in semiconductors. — Kiyv: Libid, 1993.

2. *Karakis Yu. N., Borschak V. A., Kutalova M. I., Zotov V. V., Zatavskaya N. P., Balaban A. P.* Study of relaxation of the photocurrent in semiconductor device // Fotoelektronika. — 2003. — No. 12. — P. 132—135.

3. *Karakis Yu. N., Borschak V. A., Kutalova M. I., Zatovskaya N. P., Zotov V. V.* Particularities in interaction of traps and carriers with real velocities // Fotoelektronika. — 2000. — No. 9. — P. 94—98.