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CALCULATION FOR MIGRATION-DEPENDENT CHANGES IN NEAR-CONTACT SPACE-CHARGE REGIONS OF SENSITIZED CRYSTALS

Energy shape for contact barrier to crystal contained R-centers has been calculated. It was shown that migration of sensitizing centers can cause the longtime changes in shape of photocurrent relaxation curves.

Longtime relaxation of photocurrent up to 50—60 minutes was observed in sensitized CdS samples under illumination by intrinsic light 515 µm (Figure 1). It is characteristic that photocurrent became stable within the range of 10 minutes under low illumination. With increase of light flux, the raise of photocurrent is found to be non-proportional. The value of photocurrent increased only several times with raise of exposure level in one order. This situation certifies that several concurring processes take place in the crystal.

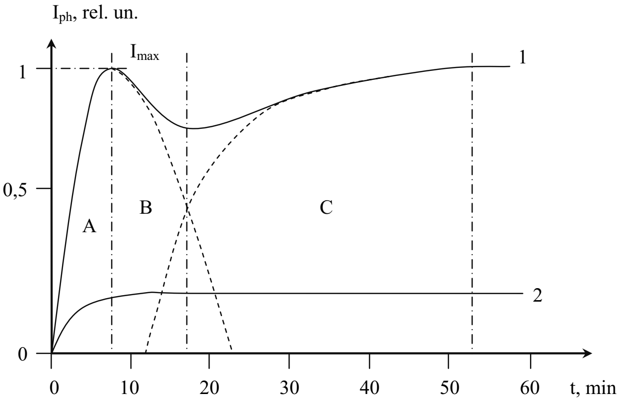

Fig. 1. Relaxation of intrinsic photocurrent at illumination level: (1) — 10—15 lx; (2) — 1—3 lx.

Besides, relaxation was accompanied firstly by decrease of photocurrent during 10—15 minutes in some crystals with rather large distance between contacts (not less than 1 mm). And then the restoration of photocurrent value took place during the period of 40—50 minutes.

The similar times for the flowing processes exclude the electronic explanation only and are the typical for migration-ionic phenomena [1,2]. The transition of impurity ions along crystal lattice is possible already at field intensities 10^4 — 10^5 V/cm that was shown previously [1,2]. At barrier height of order 1 eV and width ~1 µm it is possible to reach such level of fields in near-contact regions of crystals.

Volt-current characteristics for investigated samples was of symmetric sublinear shape that was typical for back branches of Schottky barriers [3]. It indicates that closing contacts exist in both sides of crystal (Figure 2).

Barrier fields in that time has the directions which promote withdrawal of negatively charged doping to the central part and extraction of positively charged impurity to space-charge regions (SCR) of contacts.

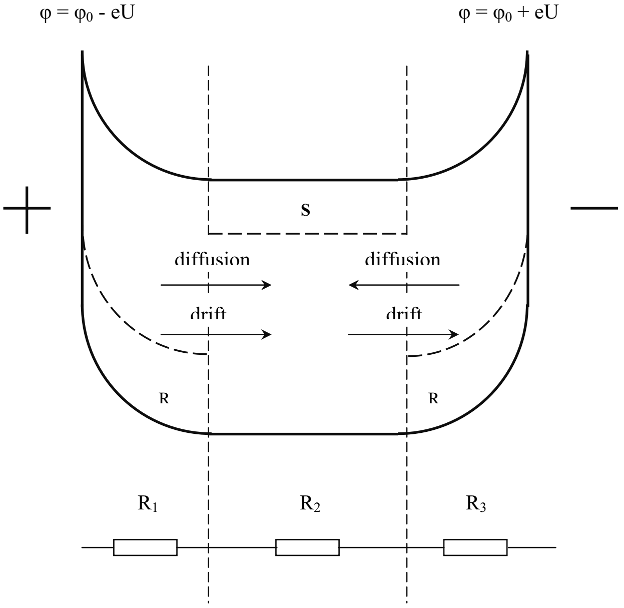

Fig. 2. Migration processes in crystal by electric light and field.

In studies of IR-quenching effect we showed that the samples had rather high concentration of S- and R-centers. But the behavior of these impurities in electric fields is different. Naturally S-center is the complex of sulphur vacancy and interstitial cadmium [4]. It can not have the observable conductivity to move along crystal lattice. As a first approximation for this study we consider that distribution of S-centers remain uniform with electric field strength applied.

On the contrary, R-center is cooper in cadmium sublattice [4] that can move rather easily along the crystal.

According to paper [5], R-centers create the levels in the forbidden band with depth of occurrence 0.9—1,1 eV. It is obvious that these centers can capture the intrinsic holes and contain them for a long time. In paper [6] it was shown that R-centers charge positively. In the described conditions their extraction out of the crystal regions with width of diffusion length from barrier internal boundary and accumulation of this impurity in SCR of contacts take place under effect of Schottky barrier fields.

In whole, the distribution of R-center concentration comes to the shape shown in Fig. 2. The part of these centers losses its charge as result of slack recombination processes. So, concentration of charged N_2^+ -centers in near-contact regions under equilibrium conditions is considerably lower than their general concentration N_2.

When the crystal is simultaneously affected by intrinsic light and external voltage (Fig. 1), its internal situation changes. Let's firstly observe the initial state of contacts. In darkness and under condition $N_2^+ < N_{dn}$, the charge in SCR is concentrated in ionized donors. As far as the barrier is closing we neglect the influence of free electric charge. Then $\rho = eN_{dn}^+$.

Distribution of potential in SCR can be found from Poisson equation

$$\frac{d^2\varphi}{dx^2} = \frac{4\pi e^2}{\varepsilon} N_{dn} \ , \tag{1}$$

which standard solution is

$$\varphi(x) = \frac{2\pi e^2}{\varepsilon} N_{dn} (L-x)^2 . \tag{2}$$

Value L in (2) specifies width of SCR at equilibrium height of barrier ϕ_0:

$$L_d = \sqrt{\frac{\varepsilon}{2\pi e^2}\frac{1}{N_{dn}}\varphi_0} \tag{3}$$

At exposure with higher light intensity the condition $N_2^+ < N_{dn}$ is broken. R-centers, already located in SCR and distributed there uniformly, capture the great amount of non-equilibrium holes and completely ionized $N_2^+ = N_2$. We used high-ohmic crystals, therefore, concentration of donors there is not large. Simultaneously the striking effect of IR-quenching indicates the great concentration of R-centers. As result, $N_2^+ = N_2 >> N_{dn}$.

The positive charge in SCR is observed now in R-centers and equations (2)-(3) are modified :

$$\varphi_b^1(x) = \frac{2\pi e^2}{\varepsilon} N_2 (L-x)^2 ; \tag{4}$$

$$L_b^1 = \sqrt{\frac{\varepsilon}{2\pi e^2}\frac{1}{N_2}(\varphi_0 - eU)} . \tag{5}$$

where ϕ and L were calculated for the case of light values at high intensities. Here we take into account that barrier height decreased up to value $\varphi(0) = \varphi_0 - eU$ under influence of internal voltage. It will be shown below that the changes in second barrier that increased in the same field affected insignificantly.

Equations (3)-(5) make possible to explain the increase of photocurrent within the region "A" in Fig. 1. It is seen that width of barrier (5) in light and because of condition $N_2 >> N_{dn}$ decreased comparatively to dark value (3). Simultaneously the barrier became lower. Resistance R_1 (Fig. 2) in this part of crystal decreases and the current raises. Because the processes are limited only by the time of capture to holes, the changes take place quickly.

However, the processes that occur in the barrier (in Fig. 2 it is the left one) are more complicated. If the number of light quanta is small the concentration of non-equilibrium holes is created insignificant. In SCR of the contact they distributed according to the law

$$\Delta p(x) = \Delta p \exp\left[\frac{\varphi(x)}{kT}\right], \tag{6}$$

where Δp - concentration of holes near barrier origin; $\varphi(x)$ - potential distribution. As the criterion of low illumination we choose

$$\Delta p \exp\left[\frac{\varphi(x)}{kT}\right] < N_2 . \tag{7}$$

This means that the number of holes is insufficient in any barrier point to occupy all R-centers. In such conditions the positive charge registered is the holes captured at R-centers correspondingly to formula (7):

$$\rho = eN_2^+(x) = e\Delta p \exp\left[\frac{\varphi(x)}{kT}\right]. \tag{8}$$

Then Poisson equation has the form:

$$\frac{d^2\varphi}{dx^2} = \frac{4\pi e^2}{\varepsilon}\Delta p \exp\left[\frac{\varphi(x)}{kT}\right]. \tag{9}$$

or

$$\frac{d^2 z}{dx^2} = A\exp(z) \tag{10}$$

where

$$z = a\varphi \ ; \ A = \left(\frac{4\pi e^2}{\varepsilon}\Delta p\right)\frac{1}{kT} \ ; \ a = \frac{1}{kT} . \tag{11}$$

Integration of formula (10) gives

$$\left(\frac{dz}{dx}\right)^2 = 2A\left[\exp(z) - 1\right]. \tag{12}$$

Equation (12) requires the numerical integration of formula (7). But it can be simplified. The condition (7) supposes the small number of hole near barrier bottom and, correspondingly, the small charge in sensitizing centers. Otherwise, the remote boundary of the barrier is dependent on ionized donors:

$$\Delta p(L)\exp\left[\frac{\varphi(L)}{kT}\right] < N_{dn}^+ . \tag{13}$$

Here we take into account the low levels of exposure $\Delta p(L) < n_0$ and small potential of barrier $\varphi(L) \to 0$. Thus, the barrier now consists of two parts, the greater one submitted to equation (12), and the boundary is defined by analogy to (2). In order to value the width of SCR for such barrier it is enough to apply (12) in condition $e^z >> 1$.

Then

$$\frac{dz}{dx} = \pm\sqrt{2A}\exp\left(\frac{z}{2}\right). \tag{14}$$

In whole SCR with increase of x the value φ, and then z too, decays (see Fig. 2, the left barrier). In such situation the sign "+" in equation (14) should be rejected as the symbol without any physical meaning. Then, taking into account (11) we obtain

$$\exp\left(-\frac{\varphi}{2kT}\right)=\sqrt{\frac{2\pi e^2\Delta p}{\varepsilon kT}}\left(x-L_1\right)+1\,. \tag{15}$$

Theoretically, there is no difficulty to obtain the explicit shape of potential distribution

$$\varphi = 2kT\ln\left[\frac{1}{1-\sqrt{\dfrac{2\pi e^2\Delta p}{\varepsilon kT}}\left(L_1-x\right)}\right], \tag{16}$$

and, owing to condition (7), equation (16) should join to equation (2). But formula (15) is sufficient to value the width of SCR. In the left boundary, when $x=0$

$$\exp\left(\frac{\varphi_0-eU}{2kT}\right)=1-\sqrt{\frac{2\pi e^2\Delta p}{\varepsilon kT}}L_1\,. \tag{17}$$

Here we took into account that voltage decreased barrier height was applied together with light (as shown in Fig. 2). But L_1 is only the part of barrier, although the greater one, that is defined by the charge captured in R-centers

$$L_1=\frac{1-\exp\left(-\dfrac{\varphi_0-eU}{2kT}\right)}{\sqrt{\dfrac{2\pi e^2}{\varepsilon}\Delta p\dfrac{1}{kT}}}\,. \tag{18}$$

Taking into account equation (5) for greater levels of exposure let's calculate

$$\frac{L_1}{L_{\mathrm{b}}^{\mathrm{l}}}=\frac{1-\exp\left(-\dfrac{\varphi_0-eU}{2kT}\right)}{\sqrt{\dfrac{\varphi_0-eU}{kT}}}\cdot\sqrt{\frac{N_2}{\Delta p}}\cdot\exp\left(\frac{\varphi_0-eU}{2kT}\right) \tag{19}$$

In other case, applying formula (13) we obtain

$$\frac{L_1}{L_{\mathrm{b}}^{\mathrm{l}}}>\frac{\exp\left(\dfrac{\varphi_0-eU}{2kT}\right)-1}{\sqrt{\dfrac{\varphi_0-eU}{kT}}}\,. \tag{20}$$

And expression for L_1 being solved for the large barriers, owing to condition $\exp\left[\dfrac{\varphi(x)}{kT}\right]\gg 1$. So, unit in numerator (20) can be removed. It is evident, that any exponent with index exceeding unit is greater than its degree. So, finally we obtain

$$\frac{L_1}{L_{\mathrm{b}}^{\mathrm{l}}}>\sqrt{\frac{\exp\left(\dfrac{\varphi_0-eU}{kT}\right)}{\dfrac{\varphi_0-eU}{kT}}}>>1\,.$$

Here L_1 — only the part of barrier under the condition of low illumination level. Finally,

$\mathrm{L}^{\mathrm{l}}_{\mathrm{b}}$, $\mathrm{L}^{\mathrm{l}}_{\mathrm{s}}$, L^{d} , with :l — light, b — big, d — dark

$$\frac{L_{\mathrm{s}}^{\mathrm{l}}}{L_{\mathrm{b}}^{\mathrm{l}}}>>1\,. \tag{21}$$

It means that at low illuminations the barrier having the same height considerably broadens. This is the second cause for the current to be lower in curve 2 within region "A" of Fig. 1.

We also note that owing to $N_2^+=N_2>>N_{dn}$ the comparison of equations (3) and (5) gives $L^d>L_b^l$. At the same time, any occurrence of the positive charge within SCR in light must decrease its width [3]. So, the logical order of equations (3), (5) и (21) is aligned as follows $L^d>L_s^l>L_b^l$. With illumination the width of SCR decays, the higher light intensity the greater decrease. This is in accordance with equation (18) (Δp in denominator) and with formula (5).

Now let's observe the influence of light on formation of ionic-coordination mechanisms.

The travel of charged R^+-impurity can occur in applied electric field within the times of tens minutes (region "B" of Fig. 2). And the behavior of SCR in both ends of crystals is observed different.

Let the polarity of applied field is such as shown in Fig. 2. Then it must cause the withdrawal of N_2^+-centers from the left barrier and the increase of their concentration owing to drift component in the right barrier. Simultaneously, diffusive withdrawal of N_2^+-centers from both contacts is forming because N_2^+-centers charge in light everywhere. It is seen from Figure 2 that both causes for the left barrier add together but for the right barrier they concur. And application of field and light results in the greater extraction of R-centers from the left contact to the central part, but the height of this contact diminishes by external field. In the right contact the external field would increase the height, but the greater concentration of residual N_2^+-charge decrease it. So, the parameters of the right SCR are controlled by the complex of causes that concur each other. As a first approximation the right SCR should be considered as stable region and changes of Fig. 1 connected only with the left contact. The dominating mechanism for it is expansion that was shown above. The height of this barrier can be also considered stable because the external field decreases it and the departure of R^+-charge — increases.

Thus, the region "B" of Fig. 1 is controlled only by one process — the left SCR expands and its resistance increases but current decays. This process will be the stronger the higher intensity of light. Firstly, concentration of charged centers in this case is greater. Secondly, the barrier is wide for twilight illumination as shown in (21). This just the case when we did not observe the longterm decrease of current in curve 2 of Fig. 1.

We note that the change in polarity of applied voltage does not vary the view. The barriers simply switch places and roles.

The sensitizing centers that extract out of near-contact SCR actuate two more mechanisms outside. Depending on light intensity, large or small concentration of positive charge captured to centers is found in subsurface layer that was shown above. Respectively, these centers by the action of diffusion or drift leave this region that accompany by its expansion. The change in length for the central part of crystal take place at the same time.

As far as the total length of crystal — central part plus two contact regions — remain invariable, the expansion in of the contact should inevitably result in narrowing of central part. And its electrical resistance (R_2 in Fig. 2) decreases because of the simple reduction in length. But resistance of the whole tandem raises because the part of inter-electrode space replaced by the higher ohmic region of barrier.

This would result in the further stimulation of photocurrent decrease, but this process is put over by the other one. R-centers coming to central part sensitized it. In accordance to paper [8] lifetime of majority carriers can increase up to five orders. We showed [6] that such situation will take place when concentrations of S- and R-centers become approximately equal: $N_2 \sim N_1$.

The increase of lifetime in its turn causes the increase of conductivity

$$\sigma = en\mu = e(f\tau)\mu . \qquad (22)$$

As far as decrease of conductivity with barrier expansion carries out approximately linear and even sublinear, the process (22) is accompanied by avalanche increase of conductivity. And the current in region "C" of Fig. 1 must raise as shown by dotted line. But the term of this process is longer. Firstly, it initiates by several concurring mechanisms in contrast to the region "B" and all the more to region "A" in Fig. 1. Secondly, the simple increase in concentration of sensitizing centers at the bottom of SCR $N_2 >> N_1$ does not initiate the additional changes. The definite time to distribute groups of R-centers along a crystal is required. Namely this is the cause for asymmetry in well sides at relaxation in Fig. 1.

The abovementioned processes are obviously absent for twilight illumination (curve 2 in Fig. 1). The number of R^+-centers is considerably lower and their doping in central part of crystal is insignificant. Besides, the barrier was considerably wider primarily (see (21)). For comparatively short samples SCR of contacts can join upon the whole. The sensitizing centers have no space to extract. We connect the absence of current decrease in region "C" of curve 1 (Fig. 1) observed experimentally with the described situation.

In conclusion we note — after finishing all the processes of redistribution for curve 1 in Fig. 1, current becomes stable at the same level in region "C" (I_{max}) as in maximum after termination of capture processes in region "A" that was expected earlier. This can be explained taking into account the following: as many sensitizing centers has left SCR as the equal number of them has finally caused the changes in the central part of crystal

References

1. Виктор П. А. "Некоторые особенности фотопроводимости неоднородных монокристаллов сульфида кадмия". Диссертация на соискание ученой степени кандидата физико-математических наук. Одесса.1999 г. с.140
2. Игнатов А. В. "Исследование влияния ионных процессов на электрические и фотоэлектрические свойства кристаллов сульфида кадмия". Диссертация на соискание ученой степени кандидата физико-математических наук. Одесса. 1999 г. — с.114 .
3. Стриха В. И. "Контактные явления в полупроводниках" — Киев, "Вища школа", 2002 г., с.223
4. Лошкарев В. Е., Любченко А. В., Шейкман М. К. Неравновесные процессы в фотопроводниках — Киев: "Наукова думка", 1999. — с.264.
5. Р. Бьюб "Фотопроводимость твёрдых тел" — Из-во Ин. лит. М., 2002г. с.558.
6. Ye.V.Britavsky, Y. N. Karakis, M. I. Kutalova, G. G. Chemeresyuk "On the charge state of rapid and slow recombination centers in semiconductors"//Photoelectronics, n. 17. 2008. P. 65 — 69.
7. Марсет Санчо Педро. "Исследование переходных процессов в области пространственного заряда гетеропереходов на основе сульфида кадмия". Диссертация на соискание ученой степени кандидата физико-математических наук. Одесса. 1999г. с.138 .
8. А. Роуз. "Основы теории фотопроводимости" — М.: Мир, 1999 — с.192 .

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Abstract

Energy shape for contact barrier to crystal contained R-centers has been calculated. It was shown that migration of sensitizing centers can cause the longtime changes in shape of photocurrent relaxation curves.

Key words: cristals, R-centers, photocurrent, relaxation curve.

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РАССЧЁТ МИГРАЦИОННО — ЗАВИСИМОГО ИЗМЕНЕНИЯ ПРИКОНТАКТНЫХ ОПЗ ОЧУВСТВЛЁННЫХ КРИСТАЛЛОВ

Резюме

Рассчитан энергетический профиль контактных барьеров к кристаллу, содержащего R-центры. Показано, что миграция центров очувствления способна вызвать долговременные изменения вида релаксационных кривых фототока.

Ключевые слова: кристалл, R-центры, фототок, релаксационная кривая.

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РОЗРАХУНОК МІГРАЦІЙНО — ЗАЛЕЖНОЇ ЗМІНИ ПРИКОНТАКТНИХ ОПЗ З ПІДВИЩЕНОЮ ЧУТЛИВІСТЮ КРИСТАЛІВ.

Резюме

Розраховано енергетичний обрис контактних бар·єрів до кристалів, в яких знаходяться R — центри. Доведено, що міграція центрів підвищення чутливості спроможна викликати багатотермінові зміни вигляду релаксаційних кривих фотоструму.

Ключові слова: кристал, R- центри, фотострум, релаксаційна крива.