UDC 621.315.592

A. A. DRAGOEV, YU. N. KARAKIS, M. I. KUTALOVA

Odessa I. I. Mechnikov National University, 42 Pastera str, Odessa 65026, Tel. +38 048 7266356, E-mail: wadz@mail.ru

STUDIES OF PROCESSES WITHIN SHORT-WAVE THRESHOLD OF PHOTOCURRENT INFRARED QUENCHING

It is shown that spectral position for short-wave threshold of photocurrent infrared quenching can be the indicator for flowing processes of occupation-depletion in recombination traps. It is determined that the competition between photo-excitation and quenching of photocurrent is the characteristic for this spectral region. Thereby, the wavelength of shortwave edge for IR-quenching becomes sensitive to internal exposures. The model explaining the observed changes is developed.

In semiconductor crystal at illumination which wavelength within intrinsic excitation band does not change the photocurrent I_1 is formed. If simultaneously the monochromatic light of controlled length, being called later as the basic one, is directed to sample, so under certain conditions the flowing photocurrent I_2 becomes lower than the initial one: $I_1 > I_2$. At that time the wavelength of basic light usually locates in IR-part of spectrum. So, the effect is called "infrared quenching of photocurrent". Its mechanism is firstly suggested by A. Rose.

When wavelength of basic light decreases, it also turns out to be intrinsic. Then, under the conditions of additional excitation, $I_2 > I_1$. Since, $I_1 > I_2$ in longwave part of spectrum, and $I_2 > I_1$ in shortwave part, in accordance to Boltzano-Kochi theorem, the point when $I_2 = I_1$ must exist. Let's call this wavelength as shortwave threshold for the effect of IR-quenching of photocurrent or the point of bifurcation. The switching-on of basic light in this point of spectrum does not change photocurrent I_1 being already formed (see Figure 1 *b*).

The process taking place in this crystal had not been studied earlier and investigated firstly by us. Two variants are possible. Either the influence by basic light does not produce any changes. Its wavelength is too far from intrinsic excitation band and does not lead to increase in concentration of majority carriers. Simultaneously, it is too small to change concentration of minority carriers and does not produce IR-quenching process. Either both processes, even to a lesser degree, are activated but equal to each other. In the latter case, as it is usual under influence of the competitive mechanisms, the flowing current must be very sensitive to changes of external conditions — temperature, applied voltage, changes in intensity of basic light and illumination.

The goal of this paper is to study effects, which originate at that time in the region of IR-quenching threshold, and also to develop the corresponding models.

Figure 1 *b* shows the change in photocurrent I_2 under action of basic light with different wavelengths. Here, the photocurrent I_1 under influence of illumination is shown for convenience. As it is seen in Figure 1, the highest photoresponse in the sample appeared under illumination by green light (500 nm). Namely, this value of wavelength was used later as the exciting light for sample.

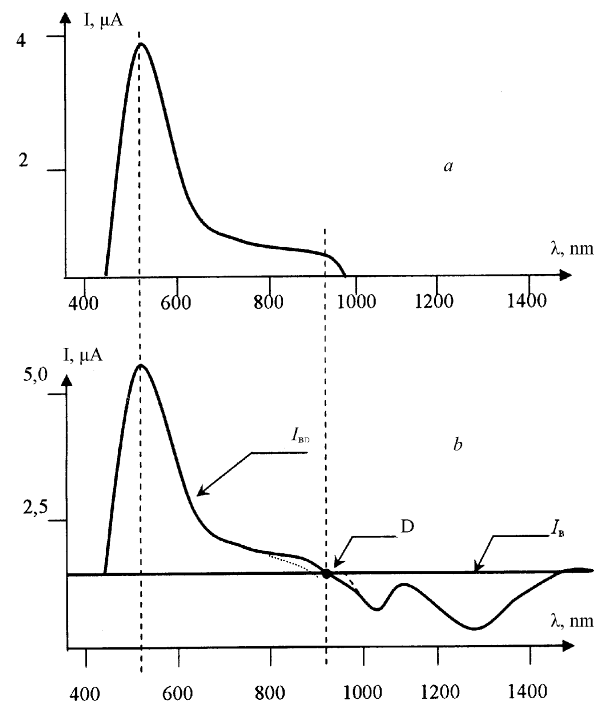

Fig. 1. Spectral distribution of photocurrent under influence of basic light only (*a*) and basic and additional lights in common (*b*)

Towards the longer wavelength, photosensitivity develops up to the limit of IR-part (~1000—1020 nm). Within wavelengths 600—850 nm we observed practically tabletop part of curve. Obviously, this region forms at the expense of deep traps depletion. These traps are responsible for relatively long photocurrent relaxation (up to 20 minutes in each point), described earlier [1]. All the results described below were obtained in the steady-state conditions.

The small absolute value of current at that time allows to suppose that the considerable part of impurity centres are recombination ones.

The samples showed the strong effect of photocurrent IR-quenching. Even at not very high correlations of quenching light intensity to exciting light one, the value of IR-quenching coefficient Q easily reached 100%. The curve of spectral distribution Q(λ) looks the typical shape with two maxima in the region 1000 and 1300 nm, respectively. The kinetics for magnitude establishment corresponded to [1].

It is characteristic that the first maximum Q(λ) is always found lower and narrower than the second one. We connect this with additional thermal transitions of holes from basic state to excited state of R-centers [3]. The tailing of the second maximum reflects Maxwell energy distribution of photons.

The intensity of basic and additional lights for curves in Figure 1 was chose as coordination on to study the influence of light fluxes on spectral position of bifurcation point (see below).

The values for depths of 2[nd] class centers - 1.1 eV and 0.9 eV obtained by spectral position of maxima for curve Q(λ) coincide with the indicated in [3].

In addition to infrared quenching of photocurrent we observed the effect of temperature quenching for our samples. The effect of temperature quenching corresponds to infrared quenching, only holes from centers of slow recombination are not knocked by photons but at the expense of temperature increase.

This effect under the applied light intensities was observed in samples investigated beginning from temperatures 50–60°C. Changes in photocurrent with temperature increase at several registered intensities of intrinsic light were processed by the procedure advised in [4]. This allowed to determine activation energy of R-centers. In our case it was 1.09 eV. The obtained energy values correspond to the parameters of slow recombination centers.

The presence of both quenching modes shows the availability if S- and R-centers of commensurable concentrations in investigated crystals, moreover, the absolute value for center number of each class should be considerable.

At selected light intensities, bifurcation point in Figure 1 accounted for wavelength 930 nm.

1. If photoexcitation processes might have finished at wavelength before bifurcation point, and the effect of R-quenching might have begun after it, so the diagram for $I_2(\lambda)$ should have the shape shown approximately by dotted line in Figure 1b. In this case about *D we would observe more or less distinct plateau coincided with value I_1. Namely, the absence of such plateau denotes that the other opportunity realises. In bifurcation area, excitation of sample by basic light and IR-quenching takes place simultaneously. Right in the point D these two processes are precisely compensated.
2. Figure 1 *a* shows spectral distribution of photocurrent when illumination is switched-off, on the same scale that in Figure 1 *b*. As it is seen from the curve, at that time the sample showed photosensitivity, though it was inconsiderable, up to wavelengths 1000 nm. The occurrence of longer-wave sensitivity with respect to *D we explain in the following way. Wavelength of exciting light here is too high. It absorbs slightly and the number of excited carriers is small. Obviously, in such conditions, occupation of R-centers by holes is inconsiderable. The process of R-quenching is difficult. We observed longwave edge of photoexcitation in the absence of quenching. But in this case, photoexcitation is present especially in the point of bifurcation.
3. Curve $I_2(\lambda)$ changes its smoothness to the left of point D (Figure 2). Beginning from wavelengths of order 880 nm, the curve $I(\lambda)$ decays more sharply to bifurcation point. This can take place if the process of IR-quenching has already interfered in photocurrent distribution.

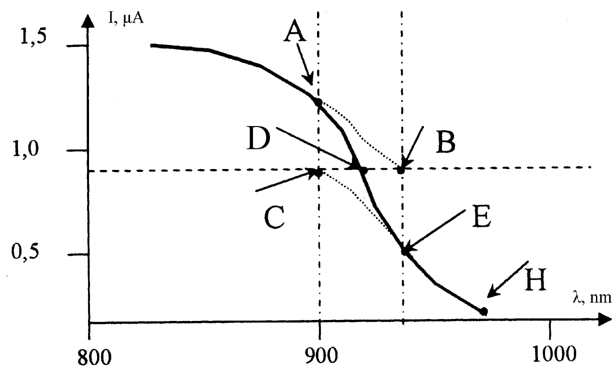

Fig. 2. Shortwave limit of photocurrent IR-quenching

The measurement of quenching curve in section CE without excitation is impossible (similarly to item 2), because the process of quenching kindly requires participation of two light fluxes. But this dependence can be calculated if one considers that curve AB is the change of photocurrent $I_1(\lambda)$ under action of excitation only (see Figure 1a), whereas curve ADE is the result of joint action of excitation and quenching $I_2(\lambda)$. Then, $I(\lambda) = I_1(\lambda) - I_2(\lambda)$. The segment of curve CE (Figure 2) obtained by such procedure shows the behaviour of curve $I_2(\lambda)$ in the vicinity of point D, if the process of crystal excitation with light I_2 was absent.

We have obtained the same result by the other, computation, method. In this section the excitation from basic light (curve AB) is already manifested, but the mechanisms forming the current maximum behind point H are not yet significant. The form for trendline for EXCEL program was used for calculations. In section

EH, function $I(\lambda)$ is approximated by form $I(\lambda) = a\lambda^3 + b\lambda^2 + c\lambda + d$, where $a = 0{,}0002$, $b = -0{,}5$, $c = 499{,}08$, $d = -165663$. Extrapolation of this dependence up to meet with magnitude I1 gives once again the curve CE (dotted line of Figure 2). The curves in section CE, which practically coincide, denote the existence of quenching within spectral range 900—920 nm still up to shortwave limits of IR-effect.

4. In some cases, within the area of bifurcation point we observed complex dependence of curve $I_2(\lambda)$ with one or even two inflections, moreover, both before and after branching point. This is easily explained under assumption that processes of quenching and excitation, acting simultaneously, depend differentially on light colour, and both depend nonlinearly. The prevalence for one of them for each wavelength of incident light gives rise for change in curve nonlinearity.

So, all four arguments produced show that competition of excitation and quenching is characteristic for area at the beginning of photocurrent IR-quenching, moreover, namely in the point D the intensities of these two processes are equal.

When temperature increases, the threshold for IR-quenching of photocurrent shifted towards longer wavelengths (Figure 3).

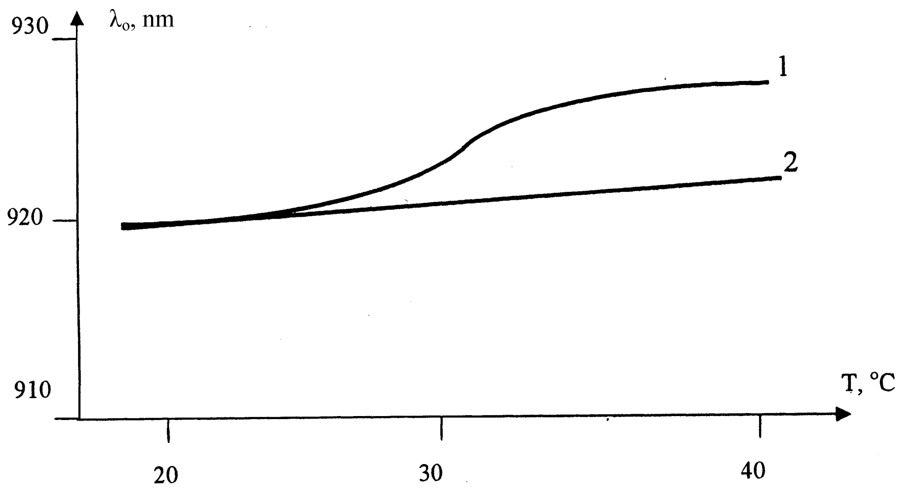

Fig. 3. Coordinate dependence of bifurcation point on temperature at high (2) and inconsiderable (1) intensity of intrinsic light

The range of operation temperatures was chose in such way that the effect of photocurrent temperature quenching did not affect at the selected light intensities. The noticeable decrease of photocurrent was observed beginning from temperatures ~50—55°C. The application of temperature values being sublimit for this effect excludes observation of holes ejection from R-centers to valence band.

Nevertheless, thermal transitions take place here. According to [4], the equilibrium holes, absorbing photons, can transit from basic levels of R-centers with energy 1.1 eV to excited R'-centers with energy 0.9 eV. Here, the occupancy of R-centers with holes decreases and of R'-centers — naturally increases. It has been already noted above, namely this process is responsible, that the first maximum in optical quenching of photocurrent with wavelength about 1040 nm had always been found lower than the second one located at wavelength 1280—1300 nm.

Here, the first maximum as the nearer to bifurcation point influences on spectral position for the beginning in photocurrent IR-quenching. Moreover, according to [5], spectral position for this maximum namely does not change with temperature changes.

When temperature increases from room values and higher, concentration of holes captured at basic states of R-centers decreases. At constant number of photons, that fall on them per unit of time, the decrease in occupancy of these levels is accompanied by decrease in transition of holes to free state.

As a result, at the expense of reduction in quenching mechanism, the equilibrium of bifurcation point gets broken, and it shifts to longer wavelengths. Here, new balance is achieved for lower intensity of photoexcitation, but higher intensity of quenching. This shift will take place until increase in quenching rate does not compensate the losses connected with temperature increase.

The processes are of nonlinear character. This explains the delay for wavelength increase in bifurcation point at temperature increase. As its absolute values increase, the increment manifests in lower degree.

The intensities of illumination during measurement of dependence $\lambda_0(T)$ (curve 1 in Figure 3) were chose in accordance with data in Figure 1. At more considerable illuminations by additional light, the graduated shape of transition disappeared. The curve raised insignificantly (diagram 2 in Figure 3) at magnitudes λ_0 within the range of lower forepart. We explain this by the change in mechanism of basic state emptying for R-centers.

At higher intensities of intrinsic light, more free holes are generated. The occupancy of

R-centers is considerable. Their ejection and, respectively, the intensity of quenching process are controlled only by IR-photon flux. Moreover, the occupancy itself remains stable. The inflow of non-equilibrium holes to R-centers compensates their knockout by photons.

On the contrary, at lower light intensities I1 and, hence, low occupation of R-centers, the process of quenching is defined by concentration of occupied holes, because their number is lower than density of photon flux.

So, the shape of curve $\lambda_0(T)$ is the indicator for change in described mechanism.

The samples investigated show linear volt-current characteristics at shifts within 10–50 V in all range of intrinsic light intensities applied. Within the range of these values, bifurcation point with increase of voltage shifts almost linearly to short wavelengths.

The obtained results correspond to the models developed by us in [6].

Since the intensities of basic and additional light do not change during the experiment, the processes of photoexcitation both majority carriers (electrons through forbidden band) and minority ones (holes from R-centers) remain the same. And concentration of trapped charge in R-centers remains unchanged, respectively.

If applied voltage does not influence practically on concentration of free charge, responsible for current raise, so it changes the rate of its transfer, that affected on current in accordance with dependence $j = env$. Here it is considered, that current raises at the expense of majority carriers, in our case — electrons.

But this is not enough to change the balance of excitation and quenching processes in bifurcation point. The active electric voltage not only accelerates free electrons (recorded current raises), and photoexcited holes (at the expense of recombination enhancement in R-centers the current must decrease). Out of these reasons, the position of bifurcation point at voltage change must not shift.

But one more process is imposed on the observed ones. Photoexcited holes locate about initial R-centers and have the possibility to come back there. As the applied voltage higher, they carried away effectively from their traps. And quantum yield for IR-light increases at the same time [6].

This process can disturb the symmetry. At the expense of additional charge supply, recombination in R-centers enhances. Because of quenching amplification, bifurcation point shifts to shorter wavelengths where the equilibrium is renewed by higher level of excitation.

The behaviour of bifurcation point can be the test for change in quantum yield from R-centers.

With increase in intensity of additional light, threshold of IR-quenching shifted to lower wavelengths. These changes can be easily interpreted out of geometric reasons. In curve of Figure 1, the raise of light intensity I_1 corresponds to increase of horizontal line I_1. Here the dependence of $I_2(\lambda)$ does not change. So, bifurcation point must shift to the left.

In physical sense it means that with increase in initial intensity of intrinsic light the balance of excitation and quenching processes at shortwave threshold of the effect is disturbed. The additional generation of electrons takes place, whereas the number of holes knocked out from R-centers remains the same, because the number of IR-photons absorbed does not change. Since the intensity of basic light does not change here, the equilibrium could be renewed only by certain shift of bifurcation point to shortwave part of spectrum, where light absorbs better.

Note, that the given reasons are valid only within the range for low intensities of light fluxes, when the number of absorbed light quanta on R-centers is smaller than the number of holes captured on them. In the contrary, for example, at very high quenching light and low exciting one, $L_1 << L_2$, the observed pattern can be corrected essentially by occupancy level of R-centers. The limits in application of light flux intensities have been observed particularly by us in works [4,5].

The changes in position of shortwave limit of IR-effect with increase in intensity of basic light resist the simple interpretation. In this case, the horizontal line in Figure 1 remains unchanged, whereas dependence $I_2(\lambda)$ changes nonlinearly. In shortwave part of diagram it raises at the expense of additional absorption of intrinsic light quanta, whereas in longwave part, where band-to-band transitions do not already take place, photocurrent must decrease at the expense of the number of infrared photons absorbed on R-centers.

In bifurcation point the intensity of both processes, excitation and quenching, increases, but in different way. The raise in number of intrinsic light photons causes the direct increase in electron concentration and at the same time more or less linear raise in current. Increase in number of photons absorbed on R-centers can be affected on photocurrent only when the knocked holes will come to S-centers and will cause the additional recombination of electrons. As it was shown in [4], the return of initial center directly after excitation can affect this process. And quantum yield decreases totally, and the process of IR-photon influence is found not effective enough. As the result, the intensity of quenching raise is backward increase of excitation. Balance renewal becomes possible in longer-wave region, when photoexcitation process is lower, but quenching rate increases. Indeed, the shift of bifurcation point to the right was observed experimentally.

The studies carried out show that namely the limit for the beginning of photocurrent infrared quenching brings important information about the nuances of processes taking place. Previously this aspect has remained unstudied.

We have found that competition of photoexcitation and photocurrent quenching is characteristic for this spectral range. Thereby namely, wavelength of shortwave edge in IR-quenching is found sensitive to external effects. Particularly, its change with applied voltage indicates that knockout of holes by IR-photons from R-centers takes place in two stages — the part of photoexcited carriers can come back to initial center, without any participation in infrared quenching.

At increase in intensity of additional light, the limit of the effect shifts to lower wavelengths because of raise in concentration of majority carriers. In the contrary, the raise of basic light leads to movement of the limit to the right at the expense of prevalence in photoexcitation rate over quenching because of low effective ejection of holes from R-levels.

The same changes take place at temperature raise. This is caused by decrease in hole occupancy of basic state of R-centers.

Spectral position of IR-quenching edge can be the test for behaviour of the listed processes.

References

1. *Investigation* of photocurrent relaxation in semiconductor device / Yu. N. Karakis, V. A. Borschak, N. P. Zatovskaya, M. I. Kutalova, A. P. Balaban // Photoelectronics. — 2003. — N 12. — P. 132–135.
2. *Chemeresyuk G. G., Karakis Yu. N.* Investigation in basic electrical characteristics of semiconductors. Methodicals. — Odessa: Preprint of Odessa I. I. Mechnikov State University, 1999. — P. 51.
3. *Novikova M. A., Karakis Yu. N., Kutalova M. I.* Particularities of current transfer in the crystals with two types of recombination centers // Photoelectronics. — 2005. — N 14. — P. 58–61.
4. *Dragoev A. A., Karakis Yu. N., Kutalova M. I.* Peculiarities in photoexcitation of carriers from deep traps // Photoelectronics. — 2006. — N 15. — P. 54–57.
5. *Sensors* of infrared radiation controlled by electric field / A. A. Dragoev, N. P. Zatovskaya, Yu. N. Karakis, M. I. Kutalova // 2nd International Scientific and Technical Conference "Sensors Electronics and Microsystems Technology", Ukraine, Odessa, 26—30 June, 2006: Book of abstracts. Section 1V "Radiation, optical and optoelectric sensors". — Odessa, 2006. — P. 115.

UDC 621.315.592

A. A. Dragoev, Yu. N. Karakis, M. I. Kutalova

STUDIES OF PROCESSES WITHIN SHORT-WAVE THRESHOLD OF PHOTOCURRENT INFRARED QUENCHING

It is shown that spectral position for short-wave threshold of photocurrent infrared quenching can be the indicator for flowing processes of occupation-depletion in recombination traps. It is determined that the competition between photoexcitation and quenching of photocurrent is the characteristic for this spectral region. Thereby, the wavelength of shortwave edge for IR-quenching becomes sensitive to internal exposures. The model explaining the observed changes is developed.

УДК 621.315.592

А. А. Драгоев, Ю. Н. Каракис, М. И. Куталова

ИССЛЕДОВАНИЕ ПРОЦЕССОВ В ОБЛАСТИ КОРОТКОВОЛНОВОГО ПОРОГА ИНФРАКРАСНОГО ГАШЕНИЯ ФОТОТОКА

Показано, что спектральное положение коротковолновой границы инфракрасного гашения фототока может служить индикатором протекающих процессов заполнения-опустошения рекомбинационных ловушек. Установлено, что для этой спектральной области характерна конкуренция фотовозбуждения и гашения фототока. Именно в силу этого длина волны коротковолнового края ИК-гашения оказывается чувствительной к внешним воздействиям. Создана модель, объясняющая наблюдаемые изменения.

УДК 621.315.592

О. О. Драгоєв, Ю. М. Каракіс, М. І. Куталова

ДОСЛІДЖЕННЯ ПРОЦЕСІВ В ОБЛАСТІ КОРОТКОХВИЛЬОВОГО ПОРОГА ІНФРАЧЕРВОНОГО ГАСІННЯ ФОТОСТРУМУ

Показано, що спектральне положення короткохвильової межі інфрачервоного гасіння фотоструму може слугувати індикатором процесів, що відбуваються при заповненні-спустошенні рекомбінаційних пасток. Встановлено, що для цієї спектральної ділянки характерна конкуренція фотозбудження та гасіння фотоструму. Саме завдяки цьому довжина хвилі короткохвильової межі ІЧ-гасіння виявляється чуттєвою до зовнішніх впливів. Створена модель, яка пояснює зміни що спостерігаються.