Turk J Phys
25 (2001) , 513 – 521.

Impurity Conductivity in Semiconductors Resulting from Radiant Excitation

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Received 06.09.1999

Abstract

This paper deals with the derivation of common formulae for induced impurity photosensibility with an arbitrary set of energy levels in the semiconductor gap. We give the expression for the real recombinational situation with two types of impurity levels as well. The basic properties and certain common peculiarities concerning induced photoconductivity in semiconductors are under consideration.

1. Introduction

Impurity photoconductivity of semiconductors related with several types of energy levels in the gap is discussed in Reference [1]. These energy levels influence the generation rate, as well as the life time of the current carriers. One of the interesting manifestation of this level interaction is the sensitivity of impurity concentration longwave photoconductivity under short wavelength lighting [2]. Short wavelength on lighting not only widens the photosensitivity to the longer range of the spectrum, but also changes the dark resistance of the photoconductor a process that is of great practical importance, and has not been investigated until now.

This paper exhibits a derivation of common expressions for induced impurity photoconductivity (IPS) and for a real recombinational situation with two types of levels.

2. Kinetic equations for IPS of semiconductors in the case of a two-level model.

We consider a semiconductor with r-types of local levels and the following parameters:

K-k-type levels concentration;

ΔE_k is the energy levels with respect to the bottom of the conduction band;

$q_k(\lambda)$ is the crossection of the photon capturing by electron at k-type level, the crossection depends on exciting light wavelength, m_k-electrons concentration at k-type level;

p_k is the holes concentration (vacant states of K-level);

$N_{ck}=N_c \cdot \exp(-\Delta E_k/kT)$ describes the density of states in the conducting band; and

N_c is the effective density of states in the conduction band.

Unipolar impurity photoconductivity results when thermal electronic exchange of levels with the valence band is neglected. The second condition for unipolar IPS realization is the absence of transitions. The regiment is met when exciting light energy quantum is less than the half of the gap ($h\nu < Eg/2$). In the present case, the kinetics of electronic transitions maybe described by the following set of differential equations:

$$\frac{dn}{dt} = \sum q_k m_k J + \sum \gamma_k m_k n_{ck} - n \sum \gamma_k p_k, \tag{1}$$

$$\frac{dm_k}{dt} = -q_k m_k J - \gamma_k m_k N_{ck} + \gamma_k n p_k. \tag{2}$$

Under particle conservation,

$$n + \sum m_k = N = const. \tag{3}$$

Constant value N is equal to the sum of all electrons at local states in the gap, as well as the number of electrons in the conduction band at the absolute zero temperature.

Carriers concentration n, m_k, p_k is represented by the equilirium parts n_o, m_{ok}, $p_o k$ and the nonequilibrum addings Δn, Δm_k, Δp_k due to lighting, so $n = n_o + \Delta n$, $m_k = m_{ok} + \Delta m_k$, $\Delta m_k = -\Delta p_k$.

With these as supplements, Equations (1-3) maybe rewritten in the form:

$$\frac{d\Delta n}{dt} = \sum \{q_k m_{0k} J - \gamma_k (p_{0k} + \Delta p_k) \Delta n - [q_k J + \gamma_k (N_{ck} + n_0)] \Delta p_k\} \tag{4}$$

$$\frac{d\Delta p_k}{dt} = q_k m_{0k} J - [q_k J + \gamma_k (N_{ck} + n_0 + \Delta n)] \Delta p_k - \gamma_k p_{0k} \Delta n \tag{5}$$

$$\Delta n = \sum \Delta p_k \quad (k = 1, 2, ..., r). \tag{6}$$

The resulting system consists of $(r+1)$ differential equations as in (4-5) with the additional particle conservation condition (6).

The system (4-6) maybe linearized in two cases. The first is the low level of excitation ($\Delta n << n_o$) and the arbitrary filling of local levels. The second is the arbitrary level of excitation, but poor equilibrium filling of local levels ($\Delta p_k << p_{ok}$). To make the total analysis of the processes related with the lighting we discuss the scheme of electronic transitions shown in Figure l. The scheme consists of two levels in the gap; the M-level,

located upper than the Fermi level and filled poorly in equilibrium, and the K-level, filled high in equilibrium. For the chosen real scheme of electronic transitions (Figure 1) the system of differential equations (4-6) maybe written in the following form:

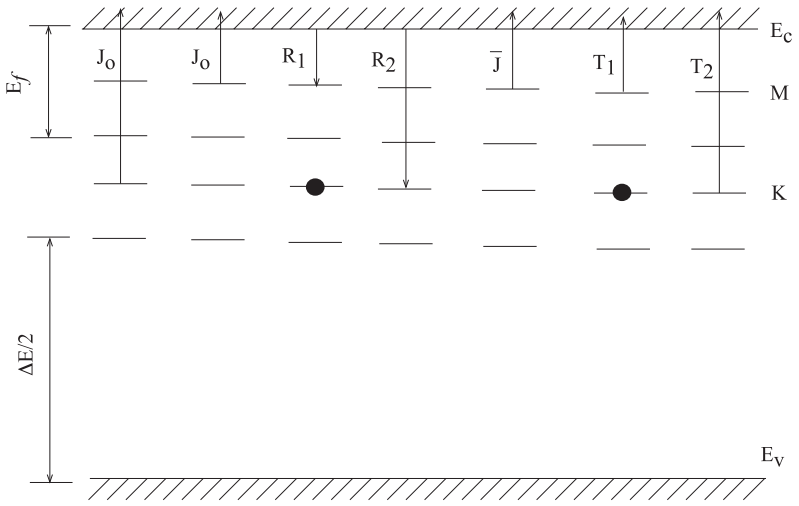

Figure 1. The scheme of electronic transitions.

J_o- lighting intensity
J - impurity light intensity
R_1, R_2- recombination factors
T_1, T_2 - factors of thermal throw of electrons into the zone M, K - energy levels of the first and second types correspondingly.

$$\frac{d\Delta n}{dt} = q_m m_{0m} J - \gamma_m \left(p_{0m} + \Delta p_m\right) \Delta n - [q_m J + \gamma_m \left(N_{cm} + n_o\right)]\Delta p_m + q_k m_{0k} - \gamma_k \left(p_{0k} + \Delta p_k\right) \Delta n - [q_k J + \gamma_k \left(N_{ck} + n_0\right)]\Delta p_k \tag{7}$$

$$\frac{d\Delta p_m}{dt} = q_m m_{0m} J - [q_m J + \gamma_m \left(N_{cm} + n_0 + \Delta n\right)]\Delta p_m - \gamma_m p_{om} \Delta n \tag{8}$$

$$\frac{d\Delta p_k}{dt} = q_k m_{0k} J - [q_k J + \gamma_k \left(N_{ck} + n_0 + \Delta n\right)]\Delta p_k - \gamma_k p_{0k} \Delta n \tag{9}$$

$$\Delta n = \Delta p_m + \Delta p_k. \tag{10}$$

The resultant system is basic for further analysis of the problem. One can consider the stationary state, when all time derivatives are equal to zero:

$$\frac{d\Delta n}{dt} = \frac{d\Delta p_m}{dt} = \frac{d\Delta p_k}{dt} = 0.$$

Consider a light beam of short wavelength, that excites electrons from both the M and K levels. The first problem is to determine the electrons concentration in the conduction zone and at the local levels as a result of J_0 lighting (that is to find Δn, Δp_m, Δp_k). From Eqns. (8) and (9) we have

$$\Delta p_m = \frac{q_m m_{0m} J_0 - \gamma_m p_{0m} \Delta n}{q_m J_0 + \gamma_m \left(N_{cm} + n_0 + \Delta n\right)}. \tag{11}$$

In the same way, from (8) we have

$$\Delta p_k = \frac{q_k m_{0k} J_0 - \gamma_k p_{0k} \Delta n}{q_k J_0 + \gamma_k \left(N_{cm} + n_0 + \Delta n\right)}. \tag{12}$$

Using (9) we get the equation

$$\Delta n = \frac{q_m m_{om} J_0 - \gamma_m p_{0m} \Delta n}{q_m J_0 + \gamma_m \left(N_{cm} + n_0 + \Delta n\right)} + \frac{q_k m_{0k} J_0 - \gamma_k p_{0k} \Delta n}{q_k J_0 + \gamma_k \left(N_{ck} + n_0 + \Delta n\right)}. \tag{13}$$

Supposing $\Delta n << n_o + N_{cm}$ and $\Delta n << n_o + N_{ck}$, and remarking the letter symbols as $\Delta n = n_c$; $n_o = n_T$; $m_{om} = m_{Tm}$; $m_{ok} = m_{Tk}$; $p_{om} = p_{Tm}$; $p_{ok} = p_{Tk}$, we get:

$$n_c = \frac{q_m m_{Tm} J_o}{\gamma_m p_{Tm} + \left[q_m J_0 + \gamma_m \left(N_{cm} + n_T\right)\right] \frac{\gamma_k p_{Tk}}{q_k J_0 + \gamma_k (N_{ck} + n_T)}} + \frac{q_k m_{Tk} J_0}{\gamma_k p_{Tk} + \left[q_k J_0 + \gamma_k \left(N_{ck} + n_T\right)\right] \frac{\gamma_m p_{Tm}}{q_m J_0 + \gamma_m (N_{cm} + n_T) + 1}}, \tag{14}$$

where

n_T is equilibrium dark concentration of electrons in the conducting zone;

n_c is the electron concentration in the conduction zone due to permanent short range lighting J_0;

m_{Tm} is the equilibrium concentration of electrons at M-levels;

m_{Tk} is the equilibrium concentration of electrons at K-levels;

m denotes the M-levels density;

k denotes the K-levels density;

N_{cm}, N_{ck} are factors of thermal transition from M and K-levels, respectively, to the conducting band:

$$N_{cm} = N_0 \exp\left(-\frac{\Delta E_m}{kT}\right);$$

$$N_{ck} = N_0 \exp\left(-\frac{\Delta E_k}{kT}\right);$$

N_c is the effective density of states in the conduction band;

ΔE_m, ΔE_k denote the M-and K - levels energies with respect to the bottom of the conducting band;

p_{Tm} is the concentration of vacant states at M-level in equilibrium (p_{Tm}= M-m_{Tm});

p_{Tk} is the concentration of vacant states at K-level in equilibrum (p_{Tk}=K-m_{Tk});

q_m, q_k are the crossections of photoionization from M and K-levels, respectively;

γ_m,γ_k are recombination factors at M- and K-levels, respectively.

The relation between the main equilibrium concentrations can be expressed by the relations:

$$m_{Tm} = \frac{Mn_T}{N_{cm} + n_T} \tag{15}$$

$$m_{Tk} = \frac{Kn_T}{N_{ck} + n_T} \tag{16}$$

$$p_{Tm} = \frac{MN_{cm}}{N_{cm} + n_T} \tag{17}$$

$$p_{Tk} = \frac{KN_{ck}}{N_{ck} + n_T}. \tag{18}$$

Let us consider the situation when, despite the short-range lighting J_0, there is also Long-range lighting J. Long-range lighting spectrum corresponds to the light absorbtion at M-level, and is characterized by interaction factor q_m. When there is no direct ab sorbtion at K-level, q_k=0, where q_m is the crossection of electron interaction (photoionization) at M-level under lighting J. Let us find the surplus concentration Δn under lighting J. After the proper calculations we have the following expression for the induced impurity photosensitivity Δn resulting from simultaneous affect of Long-range beam J and permanent shortrange lighting J_0:

$$\Delta n = \frac{q_m \left(m_{Tm} + m_{cm}\right) J}{\gamma_m \left(p_{Tm} + p_{cm}\right) + \left[q_m J_0 + q_m J + \gamma_m \left(N_{cm} + n_T + n_c\right)\right] G}. \tag{19}$$

Here,

$$G = 1 + \frac{\gamma_k \left(p_{Tk} + p_{ck}\right)}{q_k J_0 + \gamma_k \left(N_{ck} + n_T + n_0\right)} and \tag{20}$$

m_{cm} is the electrons concentration at M-levels due to permanent lighting J_o;

p_{cm} is the vacant states concentration at M-levels, resulting from lighting J_0; and

p_{ck} is the vacant states concentration at K-level due to lighting J_0.

The relationship between concentrations in the conducting band and M-, K-levels is given by the following expressions:

$$m_{Tm} + m_{cm} = \frac{\left(n_T + n_c\right) M}{N_{cm} + \left(n_T + n_c\right) + \frac{q_m J_0}{\gamma_m}} \tag{21}$$

$$p_{Tm} + p_{cm} = \frac{M}{1 + \frac{(n_T + n_c)}{N_{cm} + \frac{q_m J_0}{\gamma_m}}} \tag{22}$$

$$p_{Tk} + p_{ck} = \frac{K}{1 + \frac{(n_T + n_c)}{N_{ck} + \frac{q_k J_0}{\gamma_k}}}. \tag{23}$$

The resulting formulas are basic for further detailed analysis of the properties of induced impurity photosensitivity and its difference from equilibrium impurity photosensitivity in our simplified scheme of electronic transitions.

3. Some peculiarities of induced IPS in semiconductors

Without shortrange lighting (J_0=0), and in complete equilibrium (p_{Tk}=0), formula (19), has the form:

$$\Delta n = \frac{q_m m_{Tm} J}{\gamma_m p_{Tm} + q_m J + \gamma_m \left(N_{cm} + n_T\right)}. \tag{24}$$

This form is quite the same as the formula for the impurity photoconductivity due to one independent level in the semiconductors gap. Comparison of these formulae allows one to conclude the following:

1. Permanent lighting affects the rate of carrier generation. So, if the equilibrium filling of level M is low ($m_{Tm} << M$, m_{Tm}=0), there will be no notable photoresponce due to negligable rate of optical generation $q_m m_{Tm} J \to 0$.

In such a state the photoconductor practically has no sensibility in the Long-range spectrum J.

If shortrange lighting J_0 is added in such a case, according to Eqn. (19), the rate of optical generation under longrange illumination J rises sharply as $q_m(m_{Tm}+m_{cm})$ $J=q_m m_{cm} J$ because $m_{Tm} << m_{cm}$.

In so doing, permanent lighting makes the photoconductor optically sensitive in the longrange spectrum. More pronounced the sensitivity, the less there is equilibrium filling of level M, and its degree can reach several orders.

2. As follows from Eqn. (19), permanent lighting affects not only the rise of generation rate from level M, but the inverse process as well; transition of electrons from level M to the band. This is the irradiative effect of sensitivity irradiation and greater the crossection of M-level electrons interaction with lighting irradiation (q_m) greater the effect. In the Eqn. (19) this effect is represented by the value $q_m J_0$ in the denominator and the value $\gamma_m p_m$ depending on permanent lighting in a complex way.

We note that, under low intensive lighting and low temperature, irradiative effect of lighting may be negligible, but the dominant effect is level filling by lighting. The last gives rise to the optical spectral photoconductivity sensitivation in the longrange spectrum J.

3. Specific influence of K-levels, represented by the G-factor in Eqn. (19), and is a strong mechanism of stationary photosensitivity and carriers lifetime decrease with respect to illumination J under lighting J_o. G-factor changes from minimum value, equal 1, to very high values, determined by the ratio of capture probabilities at K-levels.

Value $q_k J_o + \gamma_k(N_{ck} + n_T + n_c)$ is the probability of thermal and optical transitions from these levels to the conductivity band. So, less the level filling, in darkness under permanent lighting, deeper is the location and the lower the temperature and dark concentration of electrons in the band $(n_T + n_c)$, - the greater is the G-factor and the greater the influence of K-levels existance on Δn.

As a first approximation, the physical sense of this influence is in opening and strengthening of a new recombination channel for electrons exiting the M-levels to the conduction band via irradiation J. The last shortens the lifetime of free elections in a steady state. So, the G-factor modifies the addend, that characterizes the probability of optical and thermal transitions from M-level. It shortens the lifetime and stationary value of the photoresponse by $[\ q_{mo} J_0 + q_m J + \gamma(N_{cm} + n_T + n_c)]$. This effect is in principle destructive for impurity photoconductivity. It is similar to the trapping levels and is typical show of levels mutual interaction in the recombination process of impurity photoconductivity [3, 4].

We have to note that for intrinsic photoconductivity there is no such evident interaction or it takes place in a peculiar case.

Under intensive illumination extitJ carriers transitioning from M- to K-levels may result in the lowing of generation rate $q_m\ (m_{Tk} + m_{ck})$ J and may be responsible for the "flash-like" character of photoresponse kinetics.

Moreover, the analysis of G-factor influence (see formula 24) shows that the transition process is always "flash-like" for induced impurity photoconductivity while turning on the light. So, at the initial stage Δn value corresponds to the case of recombination-generation. Let us consider certain regularities of induced photoeffect.

Figure 2 shows Δn(J) dependence for several values of permanent lighting J_0 intensity (and small range of J values).

Calculations (19, 20, 14) have been done with the following values of main parameters:
$M = 10^{13}\ \mathrm{cm}^{-3}$; $K = 2{\cdot}10^{14}\mathrm{cm}^{-3}$; $N_{\mathrm{cm}} = 9{,}24{\cdot}10^{10}\mathrm{cm}^{-3}$;
$N_{ck} = 3{,}48{\cdot}10^{-2}\mathrm{cm}^{-3}$; $n_T = 6{\cdot}10^{9}\mathrm{cm}^{-3}$; $q_m = 4{,}9{\cdot}10^{16}\mathrm{cm}^{2}$;
$\gamma_m = 1{,}5{\cdot}10^{-7}\mathrm{cm}^{3}/s$; $q_k = 10^{-16}\mathrm{cm}^{2}$; $\gamma_k = 3{,}4{\cdot}10^{-8}\mathrm{cm}^{3}/s$.

There are two parts to the plot: the range of low intensity and the saturation regime, corresponding to practically complete optical ionization of emitters level.

Photoresponse grows proportionally with lighting intensity J_o. So, in linear assumption and rather small range of lighting intensity J_o, induced impurity photosensibility is quite similar to the ordinary impurity photoconductivity, where permanent lighting plays the role of implantation by filling the level and increasing dark photoconductivity.

Figure 3 represents the total free electrons concentration $(n_T + n_c + \Delta n)$ dependance on the intensity of emitters level exitation for several values of permanent lighting intensity in the small range (about one order).

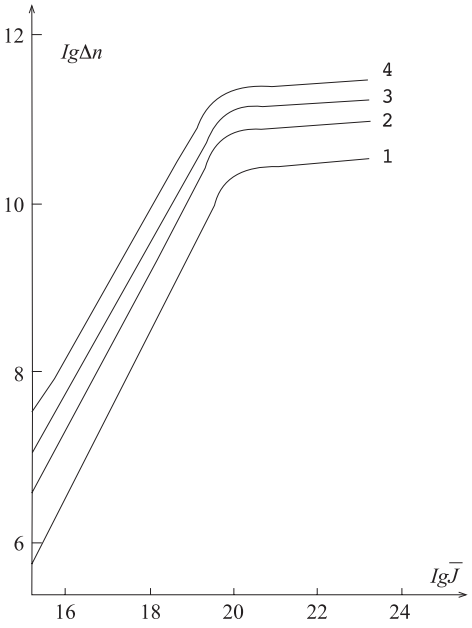

Figure 2. Logarithm Δn dependence on illumination J intensity under the different values of lighting J_o ($quantum/cm^2$):
1 - 10^{16}, 2 - $4{\cdot}10^{16}$, 3 - $8{\cdot}10^{16}$, 4 - $1.2{\cdot}10^{17}$

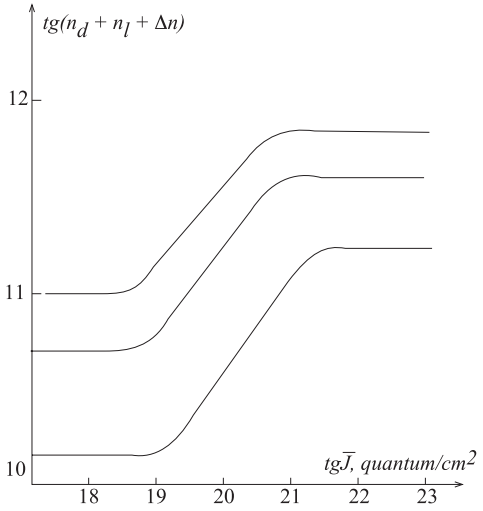

Figure 3. Dependence of total electrons concentration in the conductivity zone against illumination intensity under different values of lighting J_o($quantum/cm^2$):
1 - 10^{16}, 2 - $4{\cdot}10^{16}$, 3 - $8{\cdot}10^{16}$

In calculations in addition to the above represented main features we used the following values:

J_o=$10^{16}\div1{,}2{\cdot}10^{17}$ $quanta/cm^2$; J=$10^{17}\div1{,}2{\cdot}10^{23}$ $quanta/cm^2$

The represented curves show that dynamical range region is limited by the carriers concentration in the band (steady and permanent lighting induced) from the low intensity and by transition into the regime of complete optical ionization of emitters level from the high intensity.

Figure 4 shows the photoresponse multiple dependence on illumination J for different values of lighting $J_o$in the small range of intensity. This curve grows up lineary in the wide range and then saturates, because of complete ionization of levels.

Figure 5 shows the calculated ratio $\Delta n/J$ dependence on J, corresponding to amperwatt photosensibility of photoresponse. In the limits of linear photoconductivity, sensibility is constant and it grows up with permanent lighting intensity. Under the regime of complete M-levels ionization and hence saturation, sensibility drops off. As it follows from the curves shown in figures 2-5, photoresponse behaviour due to the illumination J in the case of induced impurity photosensibility, commonly corresponds to the known regularities of ordinary photoconductivity for the case of optical exitation of impurity

level filled of equilibrium current carriers.

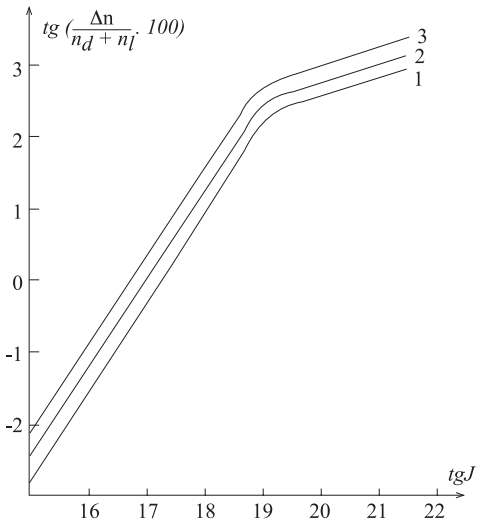

Figure 4. Photoresponce multiple $\Delta n/(n_d+n_l)$ dependence on J under different $J_o(quantum/cm^2)$: 1 - 10^{16}, 2 - $4{\cdot}10^{16}$, 3 - $8{\cdot}10^{16}$

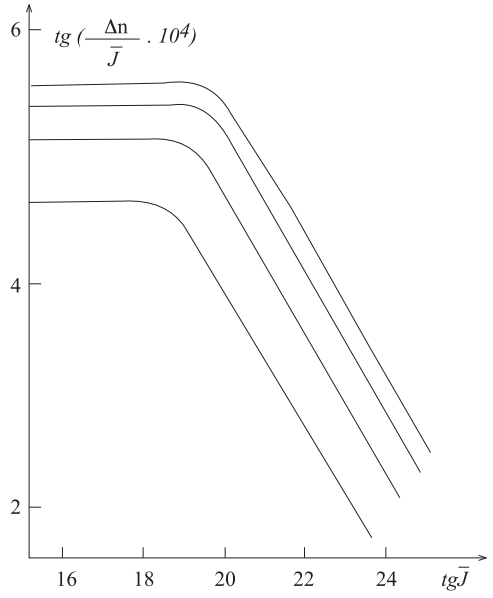

Figure 5. Dependence of photoresponce amper - watt sensibility $(\Delta n/J)$ on J under different $J_o(quantum/cm^2)$: 1 - 10^{16}, 2 - $4{\cdot}10^{16}$, 3 - $8{\cdot}10^{16}$, 4-1.2$\cdot$ 10^{17}.

In this context the use of permanent shortrange lighting resulting in the increase of electrons concentration in the conductivity band $n_c$and at the emitters level m_c to a certain extent is similar to the equilibrium implantation of photoreceiver with shallow impurities that are thermally ionized completely at the operating temperature.

Therefore the use of permanent lighting for photoreceiver with given set of levels in the gap can be thermed as optical implantation.

The last is of particular importance for photoreceivers used in the image formation in semiconductive photographic system and images transformers of ionizational type.

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