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Calculation of lifetime and impurity photoconductivity in the development of photodetectors for the gas-discharge cell

Z. Khaydarov

Fergana State University, Murabbiylar str.19, Ferghana 150100, Uzbekistan
email: *zokir_nursuh@mail.ru*

Abstract

This paper presents the results of theoretical calculations of the stationary lifetime and stationary impurity photoconductivity, as well as the time of decline after switching off the light depending on the position of the Fermi level. It is shown that with increasing light intensity, the impurity photoconductivity increases in all regions of equilibrium concentration, and at very high light intensities, the impurity photoconductivity tends to a limiting value. The character of change of the stationary lifetime at high level of optical excitation was observed such that it decreases in the region of weak filling with increasing optical excitation intensity J. And also from the performed calculations, it appears that the relaxation time depends weakly on the light intensity.

***Keywords*:** lifetime, impurity photoconductivity, Fermi level, relaxation time, optical excitation, emitter level.

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1. Introduction

The gas-discharge cell has found quite a wide application in optical photo registration, in particular, spatial and temporal diagnostics of laser radiation and thermal fields of various objects in the infrared (IR) region [1-10]. However, the use of photoelectrodes in a gas-discharge cell with a small value of specific conductivity, less than 10^7 Ohm·cm [5] and at a high level of optical excitation is a difficult task in IR imaging. The absence of theoretical prerequisites for the analysis of photoconductivity with lifetime of equilibrium and nonequilibrium carriers, as well as the concentration of photo carriers at high level of optical excitation from impurity levels makes it more difficult in the development of photodetectors for gas discharge cell in semiconductor photographic ionization chamber (SPIC) [2]. Therefore, it is necessary to analyze the generation and recombination processes in a gas discharge cell with SPIC semiconductor electrodes. In addition, it should be said that in any case it is necessary to provide a temperature range to create photoelectric hysteresis conditions with high resolution and sensitivity of the photographic process in SPIC [2, 3].

In this paper we present the results of theoretical calculations to analyze the lifetime and stationary impurity photoconductivity, as well as the relaxation decay time at high level of optical excitation from the position of the Fermi level. Based on the results of these calculations, the optimal mode of doping of photo electrodes, such as silicon with selenium, sulfur, platinum, gold, manganese and so on, in the SPIC gas-discharge cell is selected. Therefore, the conducted theoretical work is relevant.

2. Results and discussion

The stationary lifetime τ_L of the excess concentration of carriers Δn (electrons) excited to the conduction band by light with intensity J c of impurity levels having concentration M and energy E_M, is expressed by the formula [9-10]

$$\frac{1}{\tau_L} = \gamma\left(N_{cM} + \frac{MN_{cM}}{N_{cM}+n_0} + n_0 + \Delta n\right) + qJ \qquad (1)$$

where n_0 – is the equilibrium concentration of conduction electrons, $N_{cM} = N_c\exp(E_M/kT)$, N_c – density of states in the conduction zone, γ – recombination coefficient, E_M – electron ionization energy, T – thermodynamic temperature.

The value τ_L is also the characteristic time of photoconductivity rise at switching on the light. Decrease after switching off the light goes with time constant τ_d

$$\frac{1}{\tau_d} = \gamma\left(N_{cM} + \frac{MN_{cM}}{N_{cM}+n_0} + n_0 + \Delta n_0\right) \qquad (2)$$

The steady-state concentration is defined by the expression

$$\Delta n = \frac{1}{2}\left(N_{cM} + \frac{MN_{cM}}{N_{cM}+n_0} + \frac{qJ}{\gamma}\right)\sqrt{\left[1 + \frac{4Mn_0qJ}{N_{cM}+n_0}\right] / \left[\gamma\left(N_{cM} + \frac{MN_{cM}}{N_{cM}+n_0} + n_0 + \frac{qJ}{\gamma}\right)^2\right]} \qquad (3)$$

With the help of (1), (2) and (3) equations it is possible to construct the dependences of: stationary lifetime τ_L, relaxation decay time after switching off the light τ_d and stationary carrier concentration Δn on the equilibrium electron concentration no (determining the position of the Fermi level) at different values of optical excitation intensity J.

Figure 1 shows the results of calculation of the dependence of the stationary carrier concentration (impurity photoconductivity) on the position of the Fermi level at different values of the optical excitation intensity J, figure 2 - the stationary lifetime on the position of the Fermi level, and figure 3 - relaxation time from the position of the Fermi level.

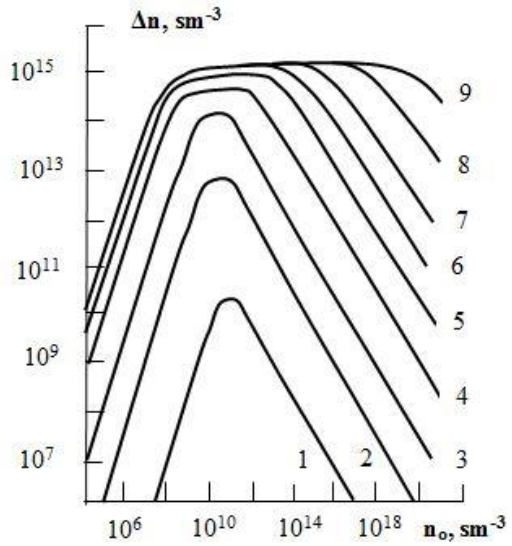

Figure 1. Dependence of impurity photoconductivity on the Fermi level position at different values of excitation light intensity J. J, photon/(sm^2·s):
1 – 10^{13}, 2 – 10^{15}, 3 – 10^{17}, 4 – 10^{19}, 5 – 10^{20},
6 – 10^{21}, 7 – 10^{22}, 8 – 10^{24}, 9 – 10^{26}. Values of design parameters: M = 10^{15} sm^{-3},
N_{cM} = 10^{-9} sm^{-3}, γ = 10^{-10} sm^3/c, q = 10^{-15} sm^2

In these figures, three characteristic regions of variation of Δn, τ_L, and τ_d can be distinguished: 1) the region of weak filling of M levels (in this example, $n_0 \leq 10^8$ sm^{-3}); 2) the region of "medium" filling of M levels ($10^8 \leq n_0 \leq 10^{12}$ sm^{-3}); and 3) the region of strong filling of M levels ($n_0 \geq 10^{12}$ sm^{-3}). As the light intensity increases, Δn increases in all the above regions, and at very high light intensities, the impurity photoconductivity tends to a limit value equal to the equilibrium concentration of electrons at the impurity M levels. The top of the curve $\Delta n(n_0)$ excitation level. With increasing intensity, the "shelf" lengthens toward larger equilibrium concentrations. It is defined by the coordinate

$$n_{0(\max)} = \sqrt{MN_{cM} - N_{cM}^2}, \tag{4}$$

the Fermi level decreases toward the valence band ceiling.

The dependence of $\tau_L(n_0)$ on formula (1) gives an idea of the nature of the change of the stationary lifetime at high excitation level with the change of the position of the Fermi level. The decrease of the lifetime τ_L in the region of weak filling, i.e., when the Fermi level is much higher than the emitter level, is directly related to the last term of the sum in formula (1), $\tau_L \approx 1/(qJ)$. It can be interpreted as the lifetime of the electron at the emitter level with respect to its interaction with the photon flux of intensity J becomes asymmetric and hollow with respect to the position of the maximum at low level of optical excitation.

The following approximate expressions can be written down for individual parts of the equilibrium filling:

1. Low occupancy ($N_{cM} > n_0$)

$$\Delta n \approx \frac{qJ}{\gamma M + qJ}\frac{Mn_0}{N_{cM} + n_0},\ \tau_L \approx \frac{1}{\gamma M + qJ},\ \tau_d \approx \frac{1}{\gamma M}.$$

2. In the area of "medium" filling

$$\Delta n \approx \frac{qJMn_0(N_{cM} + n_0)}{N_{cM}M + qJ(N_{cM} + n_0)},\ \tau_L \approx \frac{N_{cM} + n_0}{\gamma[N_{cM}M + qJ(N_{cM} + n_0)]},\ \tau_d \approx \frac{N_{cM} + n_0}{\gamma MN_{cM}}.$$

3. At full filling and high equilibrium concentration

$$\Delta n \approx \frac{qMJ}{\gamma n_0 + qJ}\frac{n_0}{N_{cM} + n_0},\ \tau_L \approx \frac{1}{\gamma n_0 + qJ},\ \tau_d \approx \frac{1}{\gamma n_0}.$$

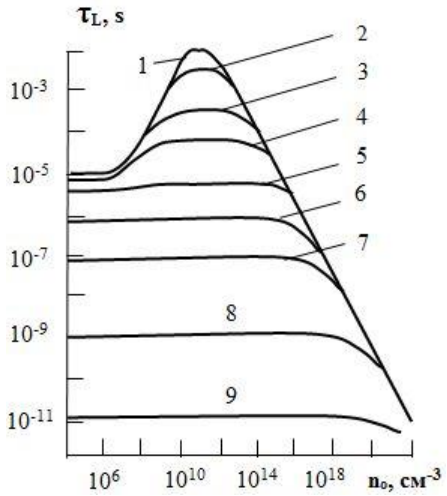

Figure 2. Dependence of the stationary lifetime on the position of the Fermi level for different values of the optical excitation intensity. The values of the calculated parameters are the same as in figure 1.

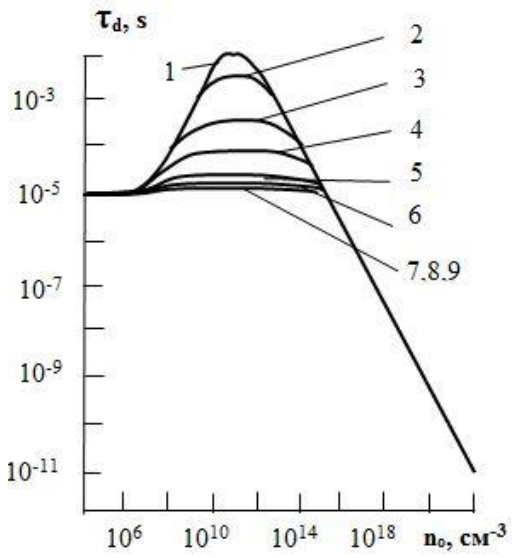

Figure 3. Dependence of the relaxation decay time after switching off the light on the position of the Fermi level for different values of the optical excitation intensity. The values of the calculated parameters are the same as in figure 1

3. Conclusion

The above process determines the rate of steady-state establishment in the case of very strong optical excitation. In contrast to this rapid process of electron exchange between the zone and impurity levels after switching off the illumination, as can be seen from equation (2), recombination, i.e. τ_d relatively weakly depends on the light intensity. In this case, recombination can only change by decreasing the nonequilibrium filling and increasing the concentration of electrons in the conduction band. The limits of both (generation and recombination) processes are limited either by the concentration of *M* levels or by their equilibrium occupancy, i.e., $\Delta n \approx m_0$, so the relaxation of the decline in darkness changes relatively weakly with light intensity.

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