THE INFLUENCE OF TRAPPING LEVELS ON THE KINETICS OF ELECTRONIC PROCESSES IN \(p\)-\(n\) JUNCTIONS

Academician of the Academy of Sciences of the Uzbek SSR É. I. ADIROVICH and E. M. KUZNETSOVA

1962

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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

THE INFLUENCE OF TRAPPING LEVELS ON THE KINETICS OF ELECTRONIC PROCESSES IN p–n JUNCTIONS

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PHYSICS

1. J. Haynes and J. Hornbeck ([1]) established the photoconductivity decay effect in silicon and germanium caused by trapping levels. F. M. Berkovskii, S. M. Ryvkin, and N. B. Strokan ([2]) showed that β-traps (trapping levels with a small effective cross section), while substantially increasing the photoconductivity relaxation time, have practically no effect on the inertia of the short-circuit current in photodiodes, whereas α-traps (multiple-trapping levels) must give inertial "tails." The results obtained were generalized to electronic processes occurring in p–n junctions without illumination. However, the injection effect and the associated transport phenomena that create a current through the p–n junction were not considered directly and were replaced by consideration of the kinetics of electronic processes in a homogeneous semiconductor under homogeneous excitation. In the present article a theory is developed for a p–n junction in semiconductors with trapping levels possessing arbitrary values of effective cross section and binding energy.

Fig. 1

2. The kinetics of minority charge carriers in the base region ($0 \leq x \leq w$) of a p–n junction (for definiteness we consider holes in an n-type base) is described by the following system of equations (see Fig. 1):

$$\frac{\partial p}{\partial t} - D\frac{\partial^2 p}{\partial x^2} = -\frac{p - p_n}{\tau} + Bp_\ell - Ap\left(N_\ell - p_\ell\right), \qquad \frac{\partial p_\ell}{\partial t} = Ap\left(N_\ell - p_\ell\right) - Bp_\ell. \tag{1}$$

Here, as in ([2]), quantum transitions between the band and the trapping levels are written explicitly, while the recombination process is represented through the lifetime τ. The solution has the form $p = p_n + p_{\mathrm{st}} + p'$; $p_\ell = p_{\ell n} + p_{\ell \mathrm{st}} + p'_\ell$;

$i = i_{\text{st}} + i'$, where quantities with subscript n correspond to thermodynamic equilibrium, quantities with subscript st are the concentrations of nonequilibrium holes and the current under a stationary bias V applied to the p–n junction, and quantities with a prime subscript are additional changes in the nonequilibrium concentrations and current* caused by the signal $v' = v'_0 e^{j\omega t}$:

$$p' = \frac{qp_n}{kT} e^{qV/kT} \frac{\operatorname{sh} \dfrac{w-x}{L}\gamma}{\operatorname{sh} \dfrac{w}{L}\gamma} v'_0 e^{j\omega t}, \qquad p'_\ell = \frac{\dfrac{N_\ell}{N_v} e^{(\varepsilon_\ell - \varepsilon_v)/kT}}{1 + j\omega/B} p',$$

$$i' = \frac{q^2 D p_n}{kTL} S e^{qV/kT} \gamma \operatorname{cht}\left(\frac{w\gamma}{L}\right) v'_0 e^{j\omega t}. \tag{2}$$

* Here and below $N_v = 2\left(\dfrac{2\pi m^* kT}{h^2}\right)^{3/2} = 4.82\cdot 10^{15}\left(\dfrac{m^*}{m}T\right)^{3/2}$; $i = -qDS \left.\dfrac{\partial p}{\partial x}\right|_{x=0}$;

$i_s = S\dfrac{qDp_n}{L} \operatorname{cth} \dfrac{w}{L}$; $L = \sqrt{D\tau}$; S is the area of the p–n junction; w is the extent of the base region.

Here

$$\gamma = \left\{1 + j\omega\tau \left[1 + \frac{N_l}{N_v} \frac{e^{(\varepsilon_l - \varepsilon_v)/kT}}{1 + j\omega/B}\right]\right\}^{1/2} =$$

$$= \left\{\frac{1 + \omega^2\tau_l^2(1 + \tau/\tau_{\text{pr}})}{1 + \omega^2\tau_l^2} + j\omega\tau \frac{1 + \omega^2\tau_l^2 + \tau_l/\tau_{\text{pr}}}{1 + \omega^2\tau_l^2}\right\}^{1/2}, \tag{3}$$

where

$$\tau_l = 1/B, \qquad \tau_{\text{pr}} = 1/AN_l. \tag{4}$$

The solution was obtained under the boundary conditions

$$p_{\text{st}}\big|_{x=0} = p_n\left(e^{qV/kT} - 1\right); \qquad p_{\text{st}}\big|_{x=w} = 0;$$

$$p'\big|_{x=0} = p_n e^{qV/kT} \frac{qv'_0}{kT} e^{j\omega t}; \qquad p'\big|_{x=w} = 0, \tag{5}$$

specified at the boundary of the base region with the space-charge region ($x = 0$) and at the ohmic contact ($x = w$).

It follows from (2) and (3) that, when the trapping effect of minority charge carriers in the base region is taken into account, the complex differential conductance of the p—n junction is

$$G = \frac{i'}{v'} = \frac{1}{r_{i0}} \frac{\gamma \operatorname{cth} \frac{w}{L}\gamma}{\operatorname{cth} \frac{w}{L}}, \tag{6}$$

where $r_{i0} = kT/q(i_{\text{st}} + i_S)$ is the differential resistance of the p—n junction at low frequency. Formula (6) differs from the expression for the conductance of a p—n junction without trapping levels ([3], [4]) in that γ enters it instead of $\sqrt{1 + j\omega\tau}$. In the limiting cases of a thick ($w \gg L$) and a thin ($w \ll L$) base, the conductance is respectively equal to

$$G = \frac{\gamma}{r_{i0}}; \qquad G \simeq \frac{1}{r_{i0}} \left[1 + \left(\frac{w}{L}\right)^2 \frac{\gamma^2 - 1}{3}\right]. \tag{7}$$

As is seen from (3) and (6), the complex differential conductance of the p—n junction depends on three relaxation times: 1) the recombination lifetime of a hole in the valence band τ; 2) the characteristic trapping time of a free hole τ_{pr}; 3) the lifetime of a hole at the trapping level τ_l. In the course of the solution, the known general relation between the probabilities of direct and reverse quantum transitions in a crystal ([5]) was used:

$$\frac{B}{AN_l} \equiv \frac{\tau_{\text{pr}}}{\tau_l} = \frac{N_v}{N_l} e^{-(\varepsilon_l - \varepsilon_v)/kT}. \tag{8}$$

3. In the limiting case of very small effective capture cross sections of holes at the trapping levels, $B \to 0$. In this case $\gamma \to \sqrt{1 + j\omega\tau}$ and $\tau_{\text{eff}} = \tau$. In the other limiting case, when the effective capture cross sections are very large, $B \to \infty$ and

$$\gamma \to \left[1 + j\omega\tau \left(1 + \frac{N_l}{N_v} e^{(\varepsilon_l - \varepsilon_v)/kT}\right)\right]^{1/2},$$

i.e.

$$\tau_{\text{eff}} = \left(1 + \frac{N_l}{N_v} e^{(\varepsilon_l - \varepsilon_v)/kT}\right) \tau.$$

These results coincide with the conclusions of F. M. Berkovskii, S. M. Ryvkin, and N. B. Strokan on the characteristic relaxation times of the current in a p—n

junction when holes are trapped, respectively, by β-traps and by α-traps ([2], [6]). However, such a conclusion on the basis of the limiting assumptions $B \to 0$ and $B \to \infty$, or even the more precise

$$\tau \ll \theta \equiv \frac{\tau_{\text{pr}}\tau_l}{\tau_{\text{pr}} + \tau_l}; \qquad \tau \gg \theta \equiv \frac{\tau_{\text{pr}}\tau_l}{\tau_{\text{pr}} + \tau_l}, \tag{9}$$

coinciding with the definition of β- and α-traps in ([6]), is not sufficiently rigorous. Indeed, in the general case it follows from (3) that

$$\operatorname{tg} 2\varphi_\gamma = \omega\tau \frac{1 + \omega^2\tau_l^2 + \tau_l/\tau_{\text{pr}}}{1 + \omega^2\tau_l^2(1 + \tau/\tau_{\text{pr}})}, \tag{10}$$

whence we find the general expression for the effective lifetime*:

$$\tau_{\text{eff}} = \tau \frac{1 + \omega^2\tau_l^2 + \tau_l/\tau_{\text{pr}}}{1 + \omega^2\tau_l^2(1 + \tau/\tau_{\text{pr}})}. \tag{11}$$

If the fraction in expression (11) does not change in order of magnitude, then one may assume that $\tau_{\text{eff}} \approx \text{const}$. It follows from (11) that this occurs if and only if

$$\frac{\tau + \tau_l}{\tau_{\text{pr}}} \ll 1,$$

i.e. (see (4) and (8)) when the condition

$$N_l \ll \frac{1}{A\tau + \frac{1}{N_v} e^{(\varepsilon_l - \varepsilon_v)/kT}} \tag{12}$$

is satisfied.

In this case $\tau_{\text{eff}} \approx \tau$. Consequently, inequality (12) is the necessary and sufficient condition for the smallness of the concentration of sticking centers for minority charge carriers. If it is violated, the sticking effect influences the effective lifetime and the inertia of electronic processes in the p–n junction.

At large concentrations of sticking centers, the p–n junction has a frequency-independent effective lifetime in two separate frequency ranges:

$$\text{a)} \quad \omega^2\tau_l^2 \ll \frac{\tau_{\text{pr}}}{\tau + \tau_{\text{pr}}} \qquad \text{b)} \quad \omega^2\tau_l^2 \gg \frac{\tau_l + \tau_{\text{pr}}}{\tau_{\text{pr}}}. \tag{13}$$

In the frequency region (13b), it follows from (11) that

$$\tau_{\text{eff}} = \frac{\tau\tau_{\text{pr}}}{\tau + \tau_{\text{pr}}}. \tag{14}$$

In this case, for β-traps $\tau_{\text{eff}} = \tau$. However, for α-traps $\tau_{\text{eff}} = \tau_{\text{pr}}$, which does not coincide with the formula $\tau_{\text{eff}} = \tau(1 + \tau_l/\tau_{\text{pr}})$ obtained in [2,6]. In the low-frequency region (13a),

$$\tau_{\text{eff}} = \tau(1 + \tau_l/\tau_{\text{pr}}) \tag{15}$$

independently of the magnitude of the ratio τ/θ, i.e. not only for α-traps, but also for β-traps. At these frequencies α-traps and β-traps do not differ in their influence on the kinetics of electronic processes in the base region of the p–n junction.

4. Let us clarify the reason for the discrepancy between these results and the conclusions drawn in [2], which coincide with the asymptotic consideration of γ. On the leading edge of a rectangular voltage, current, or illumination pulse, the character of the relaxation process is determined by the ratio of the times τ and θ. According to [2], when $\tau \ll \theta$ (β-traps), the excess concentration of free holes relaxes almost completely in a time τ, after which its residual quasistationary value, relaxing with time τ_l, is very small and is practically not detected. When $\tau \gg \theta$ (α-traps), in a time of order θ a quasistationary regime of the sticking levels is established, after which a joint relaxation of p' and p'_l occurs over the time

$$\tau\left(1 + \frac{N_l}{N_v} e^{(\varepsilon_l - \varepsilon_v)/kT}\right).$$

The factor

* According to (7), for a diode with a thick base $\varphi_\gamma = \varphi_G$, i.e. in the voltage-generator regime φ_γ is the phase shift between the current and the applied voltage. In the current-generator regime, when the current is in phase with the generator voltage, the phase of the voltage transfer coefficient is $\varphi_k = -\varphi_\gamma$. Direct measurement of τ_{eff} can be carried out by means of the phase method proposed in [7].

$1 + \frac{N_l}{N_v} e^{(\varepsilon_l - \varepsilon_v)/kT}$ expresses the prolongation of the duration of the recombination process caused by the entry of holes into the zone with sticking levels.

Such a course of relaxation processes will occur only for an infinitely sharp front of the P-pulse. In general, one must also take into account one more time parameter—the duration of the front of the pulse generating the nonequilibrium concentration of holes p'. The influence of this parameter is also revealed when considering the kinetics of electronic processes carried out with a small harmonic signal.

If $\omega \ll 1/\theta$ (more precisely, this condition is expressed by inequality (13a)), then at each instant of time a quasi-equilibrium has time to be established between the band and the sticking levels, i.e., any sticking centers behave as α-traps, and the kinetics of the $p-n$ junction is characterized by the relaxation time $\tau(1 + \tau_l/\tau_{np})$. If, however, $\omega \gg 1/\theta$ (more precisely, this condition is expressed by inequality (13b)), then α-traps and β-traps must affect the kinetics of the current in a $p-n$ junction in different ways. For $\tau \ll \theta$, the sticking of periodically injected or light-generated free holes practically ceases. Therefore the relaxation and the phase shift caused by it are determined, for β-traps, only by the recombination lifetime τ. If $\tau \gg \theta$, then the relaxation of nonstationary holes is determined not by τ, but by the faster sticking process. Therefore, in the frequency range (13b), the effective relaxation time for a material with α-traps is equal to τ_{np}, and not to $\tau\left(1 + \frac{N_l}{N_v} e^{(\varepsilon_l - \varepsilon_v)/kT}\right)$.

The dependence of τ_{eff} on frequency, caused by the processes of sticking and thermal liberation of holes, means that the equivalent parameters r_i and C, corresponding to the modeling of the $p-n$ junction by a cell r_iC;

$G = 1/r_i + j\omega C$, must possess a frequency dependence superimposed on the frequency dependence

$$G = \frac{1}{r_{i0}} \sqrt{1 + j\omega\tau} \tag{3}$$

or arising in a lower-frequency region.

5. Inequality (12) leads to curious quantitative estimates. At $T \sim 300°$K, $A \sim 10^{-8}$ cm^{3}sec^{-1}, $m^* \sim m$, $\varepsilon_l - \varepsilon_v \sim 0.04$ or 0.01 eV and $\tau \gtrsim 10^{-11}$ sec, the condition that the concentration of sticking centers be small takes the following form: $N_l \ll 1/A\tau$. If the recombination lifetime is $\tau \sim 10^{-8}$ sec, then sticking increases the relaxation duration for $N_l \gtrsim 10^{16}$ cm^{-3}; if $\tau \sim 10^{-5}$ sec, then for $N_l \gtrsim 10^{13}$ cm^{-3}. Consequently, the effect of hole sticking on an acceptor impurity in silicon and germanium of n-type (or of electrons on a donor impurity in p-type) in many real cases affects the magnitude of the effective lifetime.

Physicotechnical Institute
Academy of Sciences of the Uzbek SSR

Received
10.III 1962

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Note: Figure translations are in progress. See original paper for figures.