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Nonlinear charge transport in bipolar semiconductors due to electron heating

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ABSTRACT

It is known that when strong electric field is applied to a semiconductor sample, the current voltage characteristic deviates from the linear response. In this letter, we propose a new point of view of nonlinearity in semiconductors which is associated with the electron temperature dependence on the recombination rate. The heating of the charge carriers breaks the balance between generation and recombination, giving rise to nonequilibrium charge carriers concentration and nonlinearity.

The study of nonlinear transport deals with physical processes that arise when a sufficiently strong electric field is applied to a semiconductor sample, so that the current deviates from the linear response.

If we have a metal–semiconductor (Ohmic) contact, in an external electric field, the electrons move inside of a semiconductor changing the concentration of carriers in the volume (injection of majority carriers). The current-voltage characteristic (CVC) changes from the linear to quadratic and then back to linear. This effect is known as Mott's law [1]. In the Schottky barrier [2,3], when the equilibrium concentration of charge carriers near the contact is less than the volume concentration, an applied external electric field causes a diode type CVC. Another mechanism that leads to nonlinearity is the minority carrier injection in p–n contact [4,5]. As a consequence of the Peltier and Thompson effect, a mechanism of nonlinearity arises, when an electric field is applied near the contact. We have heating or cooling which generates a nonlinear electrical current in the semiconductor [6]. All these mechanisms of nonlinearity of CVC are due to contacts.

There are other mechanisms of nonlinearity due to the volume.

In bipolar semiconductors, nonequilibrium charge carriers is a mechanism that generates nonlinearity in the density of the current [7]. Previous calculations have been addressed to nonlinearity caused by an impact ionization [8,5], carrier lifetime changes [9], intervalley redistributions of carriers [10].

In semiconductors there are mechanisms of nonlinearity in the density of current associated with mobility (hot electrons). One of these mechanisms is due to the effective mass that depends on the energy, $m^* = m^*(E)$ [11]. Another mechanism is due to the dependence of the momentum relaxation time on energy [12–14].

As a field increases, the average energy of the electrons and holes increases, too (hot carriers). Therefore the system is out of equilibrium, i.e., when the effective temperatures for electrons T_n and holes T_p are greater than the lattice temperature T_{ph}. As a result, electrons and holes tend to occupy higher quantum states in the conduction and valence bands, respectively. The balance between thermal generation and recombination of electrons and holes is broken [12,15,16]. The dependence of the rate of recombination on the temperature of carriers generates a change in the carrier concentration [17]. So, the nonequilibrium concentration for electrons (holes) is connected with the nonequilibrium temperature of carriers which changes the electrical conductivity. Experimental verification of the considered effect is shown in Refs. [18,19].

However, due to the assumption made that the population of the impurity level does not depend on heating, the results turn out to be incorrect if the heating of electrons and holes is not equal (electron and holes temperatures are unequal). However, the question of when this effect takes place was left open. In spite of all these facts, the considered mechanism of nonlinearity has not received further development.

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In general, in semiconductors the effective mass of holes is greater than the effective mass of electrons ($m_p^* > m_n^*$), and the electron–phonon interaction is more quasielastic, it implies that electrons acquire more energy (hot electrons), and their temperature increases above the phonon temperature, i.e., $T_e > T_{ph}$. By contrast, the hole-phonon interaction is less quasielastic. The holes do not obtain energy (not heated), so that the temperature of holes is equal to phonon temperature ($T_p \approx T_{ph} \approx T_0$). It is important to emphasize that the heating only of electrons leads to the appearance of both the nonequilibrium electrons and nonequilibrium holes.

For simplicity we study the case when the electric field is low, in this case we do not have hot electrons but rather a warm electron condition [20,21]. Unfortunately, these publications did not have a clear statement of the problem. So, analyzing the results obtained is very difficult. There were two more articles related to this problem. In publication [22] the statement of the problem was incorrect, and in [23] only intrinsic semiconductor thin films were considered. Under warm electron conditions, the electron temperature $T_n = T_0 + \delta T_n$ with $\delta T_n \ll T_0$. The concentration for electrons and holes are $n = n_0 + \delta n$, $p = p_0 + \delta p$, $\delta n \ll n_0$, $\delta p \ll p_0$.

As was shown in Ref. [24], the recombination rate depends on the electron temperature. In the case of band–band recombination [25], we have:

$$R = \frac{1}{\tau_{bb}} \frac{n_0 p_0}{n_0 + p_0} \left(\frac{\delta n}{n_0} + \frac{\delta p}{p_0} + \frac{1}{\alpha} \left. \frac{\partial \alpha}{\partial T_n} \right|_{T_n = T_0} \delta T_n \right), \tag{1}$$

and τ_{bb} is the effective life time of electrons-hole pair of band–band recombination, defined as:

$$\tau_{bb} = [\alpha (n_0 + p_0)]^{-1}, \tag{2}$$

with α the capture coefficient of electrons by holes.

The recombination rate through the traps can be written as follows [24]:

$$R = \frac{1}{\tau_t} \frac{n_0 p_0}{n_0 + p_0} \left[\frac{\delta n}{n_0} + \frac{\delta p}{p_0} + r \delta T_{\mathrm{n}} \right], \tag{3}$$

where

$$r = \frac{n_1^0}{p_0} \frac{1}{\alpha_{\mathrm{n}}(T_0)} \left. \frac{\partial \alpha_{\mathrm{n}}}{\partial T_{\mathrm{n}}} \right|_{T_{\mathrm{n}} = T_0} \tag{4}$$

and τ_t is the effective life time of electrons-hole pair of doped semiconductors.

$$\tau_t = \left[\frac{\alpha_{\mathrm{n}}(T_0) \alpha_{\mathrm{p}}(T_0) N_t (n_0 + p_0)}{\alpha_{\mathrm{n}}(T_0)(n + n_1^0) + \alpha_{\mathrm{p}}(T_0)(p + p_1^0)} \right]^{-1}, \tag{5}$$

here, N_t is the impurity concentration, $\alpha_{\mathrm{n}}(T_0, T_n)$ and $\alpha_{\mathrm{p}}(T_0)$ are the electron and hole capture coefficients, n_1^0 (p_1^0) the electron (hole) concentration when the Fermi level matches the activation energy of the impurity in equilibrium, $n_1^0 = \nu_n(T_0) \exp[-\varepsilon_t / T_0]$; $p_1^0 = \nu_p(T_0) \exp[\varepsilon_t - \varepsilon_g / T_0]$, ε_t is the impurity energy level, and $\nu_n(T_0) = 1/4(2m_n T_0/h\pi^2)^{3/2}$, $\nu_p(T_0) = 1/4(2m_n T_0/h\pi^2)^{3/2}$ are the densities of state at the bottom of the conduction band and top of the valence band.

If the sample has a finite size along z-axis and the electron system is thermally insulated at the surfaces (adiabatic system), there is not a mechanism for energy relaxation of carriers at the surfaces. If, furthermore, the mechanisms of surface recombination are absent, the density of currents for electrons and holes over the surfaces of the samples is null, $j_{\mathrm{nz}}|_{z=\pm b} = j_{\mathrm{pz}}|_{z=\pm b} = 0$. In the same way the electron heat flux is null over the surfaces [26], $Q_n|_{z=\pm b} = 0$. Under this condition, all parameters of the bipolar semiconductors do not depend on the coordinates.

From the continuity equations [5], $\nabla \cdot j_n = R$ and $\nabla \cdot j_p = -R$ we have $\nabla \cdot j_n = \nabla \cdot j_p = 0$. It implies that the volumetric recombination is zero, $R = 0$, but the effective life time of electron-hole recombination is nonzero, i.e., $\tau_{bb} \neq 0$ and $\tau_t \neq 0$. Another consequence of this consideration is that it does not depend on whether we have weak recombination or strong recombination. The result is the same. Under the condition $R = 0$, we have for band–band recombination

$$\frac{\delta n}{n_0} + \frac{\delta p}{p_0} + \frac{1}{\alpha} \left. \frac{\partial \alpha}{\partial T_n} \right|_{T_n = T_0} \delta T_{\mathrm{n}} = 0, \tag{6}$$

and for the recombination rate through the traps

$$\frac{\delta n}{n_0} + \frac{\delta p}{p_0} + r \delta T_{\mathrm{n}} = 0. \tag{7}$$

Note, that the electric field E_x which was applied along the x-axis, is constant along all the sample. From the Poisson equation [27], we have electroneutrality condition, $\rho = \rho_0 + \delta\rho = 0$.

From condition $\delta\rho \approx 0$, and if the mechanism of recombination is band–band, then $\delta n \approx \delta p$.

In the case of a semiconductor that contains an impurity concentration [24] N_t and under the electroneutrality condition, the nonequilibrium charge carrier concentrations δn, δp and δT_n, are related by [28],

$$\delta p = \zeta_1 \delta n + \zeta_2 \delta T_{\mathrm{n}}, \tag{8}$$

where

$$\zeta_1 = \frac{\alpha_{\mathrm{n}}(N_t n_0 + \frac{n_{t0}^2 n_1^0}{n_0}) + \alpha_{\mathrm{p}} N_t p_1^0}{\alpha_{\mathrm{n}} N_t n_0 + \alpha_{\mathrm{p}}(N_t p_1^0 + n_{t0}^2)},$$

$$\zeta_2 = \left[\frac{n_1^0 n_{t0}^2}{\alpha_{\mathrm{n}} N_t n_0 + \alpha_{\mathrm{p}}(N_t p_1^0 + n_{t0}^2)} \right] \frac{\partial \alpha_{\mathrm{n}}(T_0)}{\partial T_{\mathrm{n}}},$$

where n_{t0} is the equilibrium concentration of electrons located on the impurity levels.

The energy balance equation for electrons is [26],

$$n \nu_{n\varepsilon}(T_n)(T_n - T_0) = \vec{j}_n \cdot \vec{E}, \tag{9}$$

where $n\nu_{n\varepsilon}(T_n)(T_n - T)$ describes the intensity of electron–phonon energy exchange with $\nu_{n\varepsilon}$ the electron energy relaxation frequency, $\vec{E} = (E_x, 0, 0)$ the external electric field, $\vec{j}_n \cdot \vec{E}$ is the Joule effect.

From the energy balance equation for electrons we obtain the nonequilibrium temperature for electrons

$$\delta T_n = \frac{\sigma_{xx}^{n0} E_x^2}{n_0 \nu_{n\varepsilon}(T_0)}, \tag{10}$$

where $\sigma_{xx}^{n0} = n_0 e^2 \tau_n(T_0)/m_n$, and $\tau_n(T_n) = \tau_0 (T_n/T_0)^{q_n}$. The exponent q_n takes different values depending of the mechanism of dispersion (see for example [13,29]). Notice, that $q_n = 1/2$ represents the electron-polarization acoustic phonon interaction, $q_n = 3/2$ represents the electron-charge impurity interaction, $q_n = -1/2$ represents the electron-deformation potential acoustic phonon interaction, $q_n = 0$ represents the electron-neutral impurities interaction.

In the case of band–band recombination we have the nonequilibrium concentration for electrons and holes are equal, $\delta n \approx \delta p$. From equation (6) the relation between the nonequilibrium concentrations and the temperature is

$$\begin{aligned} \delta n = \delta p &= -\frac{n_0 p_0}{n_0 + p_0} \left[\left. \frac{\partial \ln \alpha}{\partial T_n} \right|_{T_n = T_0} \right] \delta T_n \\ &= -\frac{n_0 p_0}{n_0 + p_0} \left[\left. \frac{\partial \ln \alpha}{\partial T_n} \right|_{T_n = T_0} \right] \frac{\sigma_{xx}^{n0} E_x^2}{n_0 \nu_{\varepsilon}(T_0)}. \end{aligned} \tag{11}$$