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Longitudinal bulk emf due to inhomogeneities in a many-valley semiconductor

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1. One of the present authors showed in Ref. 1 that a bulk emf can occur in a many-valley semiconductor with inhomogeneities. The emf due to inhomogeneities is related to an intervalley redistribution of electrons in nonheating electric fields. The orientation and frequency dependences of the emf were studied in Ref. 2 for a smooth variation of the carrier density n(x). As in the case of the hot-electron thermo-emf, the emf in question is proportional to the square of the amplitude of the electric field in weak fields and it exhibits a more marked orientation dependence than the thermo-emf. For orientations in which the emf is large, it is considerably greater than the thermoelectric power; i.e., a factor of τ/τ_ε greater, where τ and τ_ε are the intervalley and energy relaxation times of carriers.

A transverse intervalley emf (Refs. 1 and 2) was observed in Refs. 3–5 in which the orientation and field dependences of the total bulk emf due to inhomogeneities were measured.[1)] A strong anisotropy of the total emf was observed (more than a factor of 3 in weak fields[5)]), which was in agreement with the results of Refs. 1 and 2. It should be noted that the measurements of Refs. 3–5 were carried out at a frequency of the electromagnetic field $f \sim 10^{10}$ GHz, corresponding to $\omega\tau \gg 10$ for n-type Ge with $n = 3 \cdot 10^{13}$–$8 \cdot 10^{13}$ cm^{-3} (at a temperature of 77°K) used in Ref. 5. It follows from Ref. 2 that, under such conditions, the transverse intervalley emf is much smaller than its low-frequency value (to estimate $\omega\tau$, we have used the values of τ from Ref. 6).

Experiments similar to those carried out in Refs. 3 and 5 represent a simple method of measurement of the intervalley relaxation times (much simpler, for example, than the acoustoelectric measurements of Ref. 6). Therefore, it is of interest to study such effects in the whole range in which they may manifest themselves.

We shall investigate the longitudinal intervalley emf arising in an electric field parallel to the gradient of the electron density.[2)] The aforementioned emf is linearly absent in static fields and, therefore, in contrast to the transverse emf, it cannot be studied in the limit $\omega\tau_M \to 0$ (see Ref. 2; τ_M is the Maxwellian relaxation time). At microwave frequencies (used in Refs. 3–5), the induced emf is of the order of the transverse intervalley emf (see Refs. 1 and 2). We shall assume that the quantity $\omega\tau_M$ is finite and study the cases of a smooth variation of n(x) and also the case of an abrupt n^+-n junction in the limit $\tau_M > \tau$.

2. For simplicity, we shall study only the case of two types of carrier (type 1 and 2 electrons) with different values of the longitudinal diffusion coefficient ($D_{1xx} \neq D_{2xx}$) since other components of the diffusion tensors are not required (the indices xx will be omitted). The emf under study can be obtained from the following system of equations.

a) Poisson's equation

$$\frac{\partial \mathcal{E}}{\partial x} = -\frac{e^2}{\varepsilon_d kT}(\lambda_1 n_1 + \lambda_2 n_2 - \mathfrak{N}(x)), \tag{1}$$

where $\mathcal{E} = eE/kT$, E is the x component of the electric field vector (in the y and z directions, the problem is assumed to be uniform), n_1 and n_2 are the densities per valley of electrons of types 1 and 2, λ_1 and λ_2 are the numbers of valleys occupied by the electrons of types 1 and 2, $\mathfrak{N}(x)$ is the donor concentration (it is assumed that the semiconductor under study retains its type of conduction), ε_d is the permittivity, and T is the temperature.

b) Two equations of continuity for the currents of electrons of types 1 and 2,

$$\frac{\partial j_{1,2}}{\partial x} = -\lambda_{1,2}\frac{\partial n_{1,2}}{\partial t} - \lambda_1\lambda_2\frac{n_{1,2}-n_{2,1}}{\tau}, \tag{2}$$

where τ is the intervalley relaxation time and $j_{1,2}$ are the total currents of electrons of types 1 and 2, given by

$$j_{1,2} = -\lambda_{1,2}D_{1,2}\left(\frac{\partial n_{1,2}}{\partial x} + n_{1,2}\mathcal{E}\right). \tag{3}$$

The equation (3) is written under the assumption that the semiconductor is nondegenerate (Einstein's relation is satisfied) and that $\tau \gg \tau_\varepsilon$. Therefore, deviations of the spherically symmetric component of the distribution function from its equilibrium value can be neglected.

Our calculations refer to the constant total current conditions

$$I(t) = -e(j_1 + j_2) + \frac{\varepsilon_d kT}{e}\frac{\partial \mathcal{E}}{\partial t}. \tag{4}$$

We shall consider separately two limiting cases: 1) a very smooth variation of $\mathfrak{N}(x)$, when all the derivatives with respect to x can be neglected in Eqs. (1)-(3) in the zeroth approximation; 2) a more rapid variation of $\mathfrak{N}$ (for $\tau_M > \tau$), when a considerable space charge is created ($n^+ - n$ junction).

3. For a smooth variation of $\mathfrak{N}(x)$, all the unknown quantities ($n_{1,2}$ and $\mathcal{E}$) can be expanded in powers of $d\mathfrak{N}/dx$; the effect under study is obtained in the first order with respect to this quantity. The constant component of the electric field arising due to a current $I(\omega)$ is given by

$$\bar{\mathcal{E}}(\omega) = \mathcal{E}_1(\omega) + \mathcal{E}_2(\omega),$$

where

$$\mathcal{E}_1(\omega) = \frac{\omega_M^2}{2}\left(\frac{I_{eff}(\omega)}{I_s(x)}\right)^2\left[1 + \frac{a^2\omega^2\lambda_1\lambda_2}{\omega_0^2+\omega^2}\left(1+\frac{\omega_0}{\omega_M}\right)\right]\frac{d}{dx}\left(\frac{1}{\omega^2+\omega_M^2(x)}\right), \tag{5}$$

$$\mathcal{E}_2(\omega) = -\left(\frac{I_{eff}(\omega)}{I_s(x)}\right)^2\frac{\lambda_1\lambda_2 a\omega_0\omega_M}{\omega_0^2+\omega^2}\frac{da}{dx}, \tag{6}$$

$I_{eff}(\omega)$ is the effective current, which is assumed to be a sinusoid of frequency ω; $I_s(x) = eD\mathfrak{N}(x)/l_d(x)$, $l_d^2(x) = \varepsilon_d kT/e^2\mathfrak{N}(x)$; $\omega_M(x) = 1/\tau_M = D/l_d^2(x)$ (ω_M is the Maxwellian frequency, l_d is the Debye radius); $\omega_0 = (\lambda_1 + \lambda_2)/\tau$ and $D = (\lambda_1 D_1 + \lambda_2 D_2)/(\lambda_1 + \lambda_2)$ is the diffusion coefficient of electrons. The parameter $a = (D_1 - D_2)/(\lambda_1 D_1 + \lambda_2 D_2)$ measures effectively the difference between the electron anisotropy in different values.

The first term in brackets in Eq. (5) corresponds to the "standard" rectification due to a concentration gradient and is independent of the many-valley nature of the carrier spectrum. The second term and the field $\mathcal{E}_2(\omega)$, yield the effect under study. The field $\mathcal{E}_2(\omega)$ is due to a doping-induced change in the anisotropy of the mobility in a valley (i.e., due to a change in the ratio of the principal components of the relaxation time tensor). In the cases of interest; i.e., for weak doping, the aforementioned effect is weak and, therefore, will not be discussed.

For $\omega_0 \ll \omega_M$, the second term in brackets in Eq. (5) is much smaller than unity provided $\omega^2 \ll \omega_0^2$ and becomes equal to $a^2\lambda_1\lambda_2[1 + (\omega_0/\omega_M)] \sim 1$ for $\omega^2 \gg \omega_0^2$. Therefore, the intervalley emf "corrects" the "standard" emf at high frequencies and approximately doubles it. For $\omega_0 \gg \omega_M$, the intervalley emf at high frequencies $\omega^2 > \omega_0\omega_M$ becomes dominant and is greater by a factor of $B \sim \omega_0/\omega_M$ than the standard emf provided $\omega^2 > \omega_0^2$. We shall study in the limit $\omega_0 \gg \omega_M$ frequencies such that the condition $\omega^2 \gg \omega_M^2$ is satisfied for all x. The semiconductor then behaves as an insulator and the electric field in the semiconductor is nearly uniform.

$$\mathcal{E}_{eff}(\omega) = \frac{eI_{eff}(\omega)}{\omega\varepsilon_d kT}.$$

Equation (5) then yields

$$\mathcal{E}_1(\omega) = \frac{(\mathcal{E}_{eff}(\omega)\, l_d(x))^2}{2\omega^2}\left[1 + \frac{a^2\lambda_1\lambda_2\omega^2\omega_0}{(\omega_0^2+\omega^2)\,\omega_M}\right]\frac{d}{dx}(\omega_M^2). \tag{7}$$

It follows from Eq. (7) that, for $\omega_0\omega_M \ll \omega_0^2$, there is a region in $\mathcal{E}_1(\omega)$ which is frequency-independent (for a given $\mathcal{E}_{eff}$); neglecting the dependence D(x), we find that the following expression holds for such a plateau:

$$\mathcal{E}_1(\omega) = \mathcal{E}_{eff}^2 L_0^2 a^2\lambda_1\lambda_2\frac{1}{\mathfrak{N}}\frac{d\mathfrak{N}}{dx}, \tag{8}$$

where $L_0 = \sqrt{D/\omega_0}$ is the diffusion length during the intervalley relaxation time. With an accuracy up to a factor c the order of unity, Eq. (8) reduces to the corresponding expression for the transverse field given in Ref. 1, i.e., both effects can be of the same order of magnitude.

4. We have assumed in the derivation of Eq. (7) that $\mathfrak{N}(x)$ varies slowly over all the characteristic lengths of the problem; i.e., the Debye radius l_d and the intervalley diffusion length L_0. It is clear that, in the high-frequenc limit $\omega^2 \gg \omega_M^2$, when the field $\mathcal{E}(t)$ is uniform, it is not necessary to require a slow variation of $\mathfrak{N}$ over the lengtl l_d. Therefore, Eqs. (7) and (8) are also applicable under weaker conditions: a slow variation of $n(x)$ over the leng L_0. The latter length is shorter than l_d in the limit $\omega_0 \gg \omega_M$. The last inequality is assumed to be satisfied in the derivation of Eqs. (7) and (8). It is now necessary to replace in the expressions for $\omega_M(x)$, $l_d(x)$, and Eq. (8) the quantity $\mathfrak{N}(x)$ by the total equilibrium electron density $\bar{\mathfrak{N}}(x) = \mathfrak{N}(x) - \frac{\varepsilon_d kT}{e^2}\frac{d\mathcal{E}^{(0)}}{dx}$, where $\mathcal{E}^{(0)}$ is the diffusion field

5. Finally, we would like to point out that, like the transverse effect, the longitudinal intervalley emf is strongly anisotropic but the respective orientation depen dences are quite different. For example, for n-type ger manium and for a gradient $\mathfrak{N}(x)$ in the [100] direction, th longitudinal emf is zero and the transverse emf reaches a maximum; for a gradient of the concentration in the [111] direction, both emf are nonzero and the longitudina emf reaches a maximum. For n-type Si, the longitudina emf vanishes for $\nabla\mathfrak{N}\parallel[111]$ and reaches a maximum for $\nabla\mathfrak{N}\parallel[100]$. In the latter case, the transverse emf is equa to zero.

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[1]In Refs. 4 and 5, the inhomogeneity was achieved by doping and, in Ref. 6, by optical excitation.
[2]The existence of such an emf was pointed out in Ref. 2.

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