INSTABILITY OF A NONUNIFORM DISTRIBUTION OF CURRENT AND FIELD

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Abstract

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L. E. GUREVICH, V. I. IOFFE

INSTABILITY OF A NONUNIFORM DISTRIBUTION OF CURRENT AND FIELD

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In ([1]) the instability of an inhomogeneous plasma situated in a magnetic field parallel to the electric field was established. This treatment was extended by Glicksman ([2]) and by us ([3]) to semiconductors with current carriers of both signs. Subsequently we considered other conditions as well, in which there was no magnetic field (nondegenerate semiconductors), and also the cases where the concentration gradient ∇n was produced by illumination, by a temperature gradient ∇T, by an inhomogeneous distribution of impurities, or by Hall currents ([4]-[8]). We called this instability gradient instability. We shall show that instability can be produced not only by a gradient of the concentration of current carriers (as in ([1]-[8])), but also by an inhomogeneity of the external fields E and H or by a mobility gradient. When the concentrations of carriers of both signs are unequal, or in anisotropic semiconductors, the presence of a magnetic field is still not necessary. Instability also occurs in semiconductors with carriers of one sign, where, in contrast to ([1]-[8]), there arise not almost neutral oscillations of concentration and field, but oscillations of charge and current as well. In this paper we shall confine ourselves to those manifestations of gradient instability which occur in semiconductors. Gradient instability (occurring in the presence of an electric field and at a process frequency much lower than the collision frequency) requires conditions opposite to those under which the "drift" instability investigated by A. A. Galeev, B. B. Kadomtsev, A. B. Mikhailovskii, L. I. Rudakov, R. Z. Sagdeev, V. N. Oraevskii, and A. V. Timofeev ([9]) is possible: a temperature gradient or strong nonisothermality of the plasma, a strong external magnetic field, and the absence of an electric field and insignificance of collisions.

In considering gradient instability we shall assume that the inhomogeneities are such that the WKB approximation may be applied. This requires no discussion in the case of an inhomogeneity of the mobility of the fields, and in the case of a gradient of the concentration of current carriers caused by illumination, Hall currents, temperature gradients, and impurity distribution; but in the case of injection of carriers, in order that the concentration gradient be of the same order over the entire length of the crystal, it is necessary that the drift length be greater than the diffusion length and greater than, or of the order of, the length of the sample in the direction of the current. (These conditions are easily realized experimentally.) In those cases where the dependence of the stationary concentration on the coordinate is exponential (Hall currents or temperature inhomogeneity), the WKB approximation is not required at all, and a simple transformation reduces the equations to equations with constant coefficients.

In a conducting medium situated in external electric and, generally speaking, magnetic fields, a new branch of the electromagnetic spectrum appears; the excitations of this branch we have called galvanomagnetic waves. Under certain conditions these waves are weakly damped, and in the presence of inhomogeneity they can become unstable.

In the case when the inhomogeneity exists only in the direction parallel to the current,

$$\mathbf{I} = \hat{\sigma}\mathbf{E} - e[\hat{D}_-\nabla n_- - \hat{D}_+\nabla n_+] = \text{const}, \qquad \mathbf{E} \neq \text{const}. \tag{1}$$

Linearizing the continuity equations

$$\partial n'_\pm/\partial t + \operatorname{div}\{-\hat{D}\nabla n \pm \hat{\mu}\hat{\sigma}^{-1}\mathbf{I}n\}_\pm = -\nu_\pm(n-N)_\pm$$

(N are equilibrium concentrations, ν^{-1} are the lifetimes of nonequilibrium carriers) and putting $n'_+ = n'_- = n'$, $E' \sim \exp i\int k\,dr$, we obtain expressions for the frequency and the increment

$$\omega = (\mathbf{kw}) = \frac{(\mathbf{k}\hat{\mu}n\mathbf{k})_+(\mathbf{k}\hat{\mu}_-\mathbf{E}) - (\mathbf{k}\hat{\mu}n\mathbf{k})_-(\mathbf{k}\hat{\mu}_+\mathbf{E})}{(\mathbf{k},\ \hat{\mu}_+n_+ + \hat{\mu}_-n_-,\ \mathbf{k})},$$

$$\gamma = -(\nabla\mathbf{w}) - \nu - \frac{(\mathbf{k}\hat{D}_+\mathbf{k})(\mathbf{k}\hat{D}_-\mathbf{k})(n_+ + n_-)}{(\mathbf{k},\ \hat{D}_+n_+ + \hat{D}_-n_-,\ \mathbf{k})}.$$

In deriving these expressions, terms of order $1/kL$ ($L = n/\nabla n,\ \mu/\nabla\mu,\ H/\nabla H$ is the inhomogeneity length) were retained only if they were multiplied by the quantity $eE/Tk \gg 1$. In doing so, the terms containing derivatives of k drop out.

For $(\nabla\mathbf{w})' = 0$ the waves are weakly damped if

$$\nu + \frac{(\mathbf{k}\hat{D}_+\mathbf{k})(\mathbf{k}\hat{D}_-\mathbf{k})(n_+ + n_-)}{(\mathbf{k},\ \hat{D}_+n_+ + \hat{D}_-n_-,\ \mathbf{k})} < (\mathbf{kw}).$$

If the inhomogeneity is transverse to the current, then an analogous calculation should be carried out by expressing from (1) $\mathbf{I}$ through $\mathbf{E}$ and putting $\dot{\mathbf{E}} = \text{const}$.

In crystals with current carriers of one sign, linearizing the continuity equation and Poisson' s equation and taking into account that the electron temperature is determined by the value of the field at the given instant, we find

$$\omega = (\mathbf{k}\hat{\mu}\mathbf{E}), \qquad (\nabla\hat{\mu}\mathbf{E}) > (\mathbf{k}\hat{D}\mathbf{k}) + 4\pi ne\,(\mathbf{k}\hat{\mu}\mathbf{k})/\varepsilon k^2$$

or

$$E > E_{\text{cr}} = Tk^2 L/e + 4\pi neL/\varepsilon.$$

For $E > E_{\text{cr}}$, waves are excited with $k \leq k_{\max} = \sqrt{ms^2/T}\sqrt{1/Ll}$ and $\omega \leq \omega_{\max} = s\sqrt{eE/TL}$ (s is the speed of sound, T_{-} is the electron temperature, l is the mean free path, m is the mass). Estimates show that an instability of this type is possible only in bodies with a small concentration of carriers.

Let us consider several specific cases of gradient instability.

1. Let $\mathbf{H} \parallel \mathbf{E} \parallel z$, $\partial H/\partial x \neq 0$, $|kH/\nabla H| \gg 1$ (the x-axis is perpendicular to the plate). In [4] it was shown that E_{cr} is minimal for $k_y \simeq k_z \simeq k_x = \sqrt{\gamma/Dd}$ (γ is the coefficient of surface recombination, d is the plate thickness). Taking this into account, we find that

$$\text{for } \frac{\mu_{\pm}H}{c} < 1 \qquad E_{\text{cr}} = \frac{T}{e}\frac{N_{\max}}{N_{\min}}\frac{\gamma}{Dd\,|\nabla\ln H|}\frac{c^2}{\mu_{-}^2 H^2},$$

$$\text{for } \frac{\mu_{-}H}{c} > 1 > \frac{\mu_{+}H}{c} \qquad E_{\text{cr}} = \frac{T}{e}\frac{N_{\max}}{N_{\min}}\frac{\gamma}{Dd\,|\nabla\ln H|}\frac{c}{\mu_{-}H},$$

when

$$\frac{\mu_{\pm}H}{c} > 1 \qquad E_{\text{cr}} = \frac{T}{e}\frac{N_{\max}}{N_{\min}}\frac{\gamma}{Dd\,|\nabla\ln H|}\frac{c^3}{\mu_{-}^3 H^3}.$$

2. In the case of an inhomogeneous electric field, instability can arise only in the presence of a magnetic field that is not parallel to the electric field. In this case the Hall current and diffusion fluxes will lead to ∇n, which, along with the inhomogeneity of E, may be the cause of the instability. Analogously to (5), one can show that instability is possible only for a small angle between $\mathbf{E}$ and $\mathbf{H}$. In a weak magnetic field the terms due to ∇n are, in order of magnitude, equal to $\left[\frac{eE}{T}\frac{\mu H}{c}\right]^2$, while the terms due to the inhomogeneity of E are equal to $\frac{eE}{T}\frac{\mu H}{c}|\nabla\ln E|$, and the latter are substantial when $|\nabla\ln E| > \frac{eE}{T}\frac{\mu H}{c}$, and

$$E_{\text{cr}} = \frac{T}{e}\frac{\gamma}{Dd}\frac{c}{\mu H}\frac{1}{|\nabla \ln E|}.$$

In a strong magnetic field, when $\frac{\partial E}{\partial y} \neq 0$, the terms associated with ∇n are unimportant, and

$$E_{\text{cr}} = \frac{T}{e}\frac{\gamma}{Dd}\frac{1}{|\nabla \ln E|}c^2\mu^{-2}H^{-2}.$$

3. Suppose that in an impurity semiconductor a current I flows parallel to $\nabla\mu$, produced by ∇T or by an inhomogeneity in the impurity distribution.

In this case the instability condition takes the form

$$T_{\text{cr}} = \frac{T}{e}\frac{\sigma\mu_-\mu_+}{|\nabla\mu_-\mu_+|}\left|\frac{n_+ + n_-}{n_+ - n_-}\right|\left(\frac{\pi m}{L_0}\right)^2$$

(L_0 is the length of the specimen, $m = 1, 2, ...$).

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