Instability of hot electrons in two-valley semiconductors

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A new type of plasma instability with a frequency of $\sim 10^{13}$ Hz is predicted in semiconductors in which the lower valley has a small effective mass and the higher-energy valleys have a large effective mass. The instability can be realized experimentally in the A^3B^5 and A^2B^6 compounds with a strong intervalley scattering.

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The effects of hot electrons in semiconductors are promising in the development of submillimeter-range, electromagnetic-wave generators. One such effect can be an inversion of the distribution function (DF) of hot electrons in a direction transverse to a strong, constant electric field E. Favorable conditions for the inversion can be obtained in polar semiconductors (n-GaAs, n-InP, n-CdTe, etc.) in which the lower valley has a small effective mass, the upper valleys have a large mass, and there is a strong intervalley scattering. A DF inversion in a light valley in a strong field E was determined by numerical calculations in n-GaAs[1] and in n-CdTe.[2] It was pointed out in Ref. 1 that the DF inversion may lead to a negative differential mobility at high frequencies. This problem was examined in detail in Ref. 3.

In this paper we report that a DF inversion in a light valley and the presence of electrons in heavy valleys produce an electrostatic instability in the hot electron plasma. First, we shall show that a DF inversion with respect to velocities $V_\perp$ transverse to the field can occur in a light valley $\bar{f}_1(V_\perp)$, which was integrated over all the values of $V \| E: \bar{f}_1(V_\perp) = \int f_1(V_\perp)\, dV_\|$. The examined instability can occur only as a result of inversion of $\bar{f}_1(V_\perp)$, since the $f_1(V_\perp)$ inversion obtained in Ref. 1 at $V_\perp = 0$ is insufficient. The DF calculations performed in this paper by the Monte Carlo method, using a three-valley n-GaAs model with constants taken from Refs. 4 and 5, showed that the $\bar{f}_1(V_\perp)$ inversion appears only at $E \geqslant 60$ kV/cm (Fig. 1), whereas the $f_1(V_\perp)$ inversion at $V_\| = 0$ occurs at $E = 15$ kV/cm.[1] We shall idealize $f_1(V_\perp)$ by assuming that it is a circle of radius V_0 in the transverse direction to the field, i.e., that $f_1(V_\perp) = \delta(V_\perp^2 - V_0^2)$, where $V_0 = (2\epsilon_0/m_1)^{1/2} \sim 10^8$ cm/sec and ϵ_0 is the energy gap between the valleys with a light m_1 and heavy m_2 masses.

Let us examine the instability of small, electrostatic perturbations $\sim \exp[i(\omega t - kr)]$ for an idealized DF. We assume that in the absence of perturbations the heavy electrons have zero velocity and the light electrons are comprised of an infinite number of beams whose unperturbed velocities are equal to $V_0 \cos\phi$, where ϕ is the angle between the velocity vector of the corresponding beam and the direction of the wave. Thus, the dispersion equation, which follows from the corresponding equation for a multibeam plasma, has the form

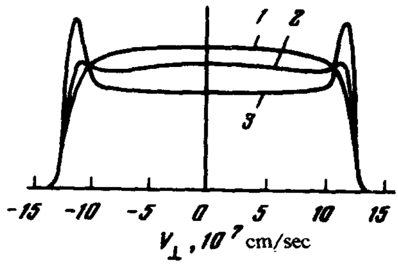

FIG. 1. Dependence of the DF of electrons in a light GaAs valley on $V_\perp$ at: 1, $E=40$; 2, $E=60$; 3, $E=100$ kV/cm. The DF was integrated over all the values of $V_\parallel$.

$$\frac{\omega_1^2}{2\pi}\int_0^{2\pi}\frac{d\phi}{(\omega-kV_0\cos\phi)(\omega-kV_0\cos\phi-i\nu_1)}=1-\frac{\omega_2^2}{\omega(\omega-i\nu_2)}. \tag{1}$$

Here ω_1, ω_2, and ν_1, ν_2 are the plasma frequencies and the scattering frequencies of the light and heavy electrons, respectively. In the absence of collisions, $\nu_1=\nu_2=0$, after integration of Eq. (1) obtain

$$\frac{\omega_1^2\ \omega\ \mathrm{sign}\left(|\omega/kV_0+\sqrt{(\omega/kV_0)^2-1}\,|-1\right)}{[\omega^2-(kV_0)^2]^{3/2}}=1-\frac{\omega_2^2}{\omega^2}. \tag{2}$$

Equation (2) was solved numerically relative to the complex frequency. The solution of Eq. (2) for the instability is shown in Fig. 2. We note that for an instability to occur there must be both a DF inversion in the light length and a simultaneous presence of electrons in the heavy valleys, since separately the distribution $\bar{f}_1=\delta(V_1^2-V_0^2)$ is stable, which is indicated by the solution of Eq. (2) whose-right hand side is equal to unity.

Let us estimate the effect of collisions on the instability excitation. We assume that $\nu_1 \ll |\omega|$. Thus, after integration of (1), expansion in ν_1 of the left-hand side of the obtained equation, limiting ourselves to the linear term, we obtain

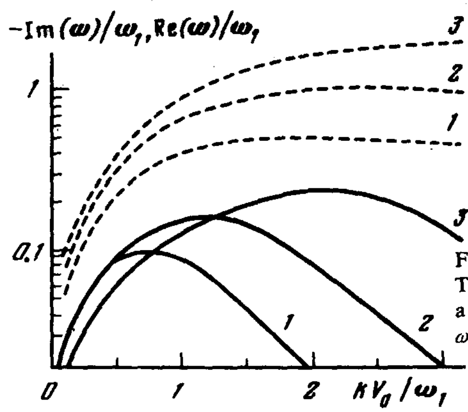

FIG. 2. Solution of Eq. (2) corresponding to the instability. The solid curves represent the increment of the instability and the dashed curves denote the frequency. 1, $\omega_2/\omega_1=0.5$; 2, $\omega_2/\omega_1=1$; 3, $\omega_2/\omega_1=2$.

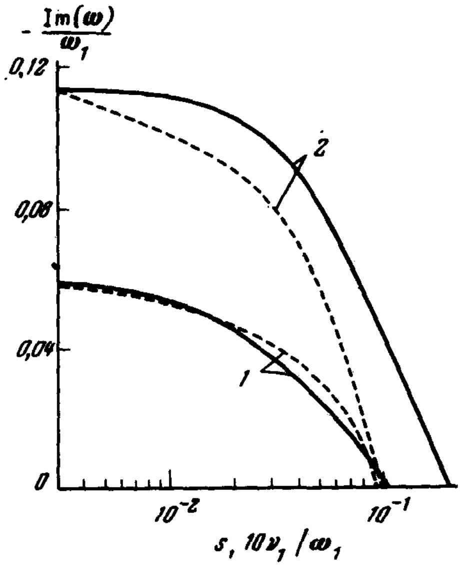

FIG. 3. Dependence of the increment of the instability on ν_1 at $\nu_2 = 2\nu_1$ and $s = 0$ (solid curves) and on s (dashed curves) at $\nu_1 = \nu_2 = 0$; 1, $kV_0/\omega_1 = 0.3$; 2, $kV_0/\omega_1 = 0.6$; $\omega_1 = \omega_2$.

$$\omega_1^2 \,\mathrm{sign}\left(\left|\omega/kV_0 + \sqrt{(\omega/kV_0)^2 - 1}\right| - 1\right)\left[\omega\left(\omega^2 - (kV_0)^2\right)^{-3/2} + i\nu_1\left(\omega^2 + (kV_0)^2/2\right)\left(\omega^2 - (kV_0)^2\right)^{-5/2}\right] = 1 - \omega_2^2/[\omega(\omega - i\nu_2)]. \quad (3)$$

The dependence of the increment $\gamma = -\mathrm{Im}(\omega)$ on ν_1, obtained by solving Eq. (3), is shown in Fig. 3, in which it can be seen that for the instability to occur the plasma frequencies must exceed the collision frequencies.

As seen in Fig. 1, idealization of the DF of light electrons by using the delta function even at $E = 100$ kV/cm is crude. Let us determine the effect of the background of light electrons whose velocity is different from V_0. To do this, we assume that the DF of light electrons is comprised of two parts: electrons with the DF in the form of a delta function and background elelctrons with the distribution function independent of V at $V < V_0$ and equal to zero at $V > V_0$. In this case, disregarding the collisions, the dispersion equation has the form

$$\frac{\omega_1^2\,\omega\,\mathrm{sign}\left(\left|\omega/kV_0 + \sqrt{(\omega/kV_0)^2 - 1}\right| - 1\right)}{[\omega^2 - (kV_0)^2]^{3/2}}\left[1 - s\left(\frac{kV_0}{\omega}\right)^2\right] = 1 - \frac{\omega_2^2}{\omega^2}, \quad (4)$$

where s is the ratio of the concentration of background electrons to the total concentration of light electrons. The dependence of γ on s obtained from Eq. (4) is shown in Fig. 3, from which it follows that at $s \lesssim 0.8$ there should be an instability.

We give numerical estimates corresponding to *n*-GaAs. At $E = 100$ kV/cm, as the Monte Carlo calculations show, $\omega_1 \approx \omega_2$, which corresponds to curves 2 in Fig. 2. The values of ν_1 and ν_2 in the energy dependence of the electron are in the limits 10^{12}–10^{13} sec^{-1}. Thus, according to the inequality $\omega_{1,2} > \nu_{1,2}$, the lower limit of the electron density is of the order of 10^{17} cm^{-3}. The value of s is close to 0.6. The electrostatic oscillation frequency in this case is of the order of 10^4 GHz. An analogous situation apparently also occurs in other semiconductors such as A^3B^5 and A^2B^6.

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