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PECULIARITIES OF NONLINEAR STABILIZATION OF PLASMA-BEAM INSTABILITY IN SEMICONDUCTOR GaAs

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ABSTRACT

The excitation of nonlinear plasma oscillations by a monoenergetic electron beam of low density moving through a semiconductor is considered by the particle-in-cell method. An electron beam is assumed to be a sequence of electron bundles with constant density. It has been assumed that the electron collision frequency in a semiconductor is greater than the hydrodynamic increment of instability in collisionless plasma but less than plasma electron frequency is investigated. The influence both of nonparabolicity of electron dispersion law and intervalley electron transitions on the plasma-beam instability is taken into account. The nonparabolicity is shown to lead to the decrease of the maximum of the electric field amplitude while the intervalley electron transitions lead to the appearance a plateau on the temporal dependence of the slow amplitude of the electric field.

PHYSICAL MODEL

We consider a homogeneous semiconductor GaAs placed in the strong magnetic field. Let the x-axis be directed along the direction of the magnetic field, which is parallel to the direction of a nonrelativistic monoenergetic beam moving with the velocity $v_0 << c$ (where c is the speed of light in empty space). Hereinafter we consider a one-dimensional problem. We assume that the collision frequency in the semiconductor ν satisfies the following condition:

$$\gamma_0 < \nu < \Omega_p , \qquad (1)$$

where $\Omega_p = \sqrt{4\pi e^2 N_0 / \varepsilon_0 m}$ is the electron Langmuir frequency in the semiconductor plasma, e is the charge of an electron, N_0 is the equilibrium electron density in the semiconductor plasma, $\varepsilon_0 = 12.53$ is the dielectric constant of the crystal lattice of the semiconductor, $m = 0.067 m_0$ is the effective mass of an electron in the semiconductor, $\gamma_0 = \sqrt{3}/2^{4/3}\Omega_p (n_0 / N_0)^{1/3}$ is the maximum growth rate of hydrodynamic instability, n_0 is the equilibrium electron density in an electron beam. In the case under consideration the most unstable oscillations are characterized by the frequency $\omega \approx \Omega_p \approx k_0 v_0$ and the growth rate of hydrodynamic instability $\gamma = \sqrt{\omega_b^2 \Omega_p / 2\nu} < \gamma_0$ [1]. Here $\omega_b = \sqrt{4\pi e^2 n_0 / m_0}$ is the electron Langmuir frequency of electron beam and k_0 is the wave vector of the most unstable mode.

The case described above can be realized in the highly compensated semiconductor GaAs at the liquid helium temperature. Let us consider a sample of GaAs with an n-type impurity concentration of about $N_d = 5 \cdot 10^{17}\,\text{cm}^{-3}$ and the electron concentration of $N_0 = 4 \cdot 10^{15}\,\text{cm}^{-3}$ ($\Omega_p \approx 4.0 \cdot 10^{12}\,\text{s}^{-1}$). In GaAs in a thermodynamic equilibrium state the majority of electrons occur in the valley with a minimum energy at the center of the Brillouin zone (the <000> valley). The next several higher valleys with minimum energies in the <100> directions are separated from the <000> valley by the energy gap $\Delta \approx 0.36\,\text{eV}$. The effective electron mass in higher valleys is $m_{<100>} \approx 75 m_{<000>}$. Since the density of states is proportional to $m^{3/2}$, the density of states for the valley in <100> directions is higher than for the <000> valley. Therefore it far more probable for electron whose temperatures exceeds Δ to occur in the <100> valleys than in the <000> valley. The emission or absorption of optical phonons accompanies the electron transitions between the valleys. The relaxation frequency of an electron momentum changes abruptly from $\nu \approx 5 \cdot 10^{11}\,\text{s}^{-1}$ to $\nu \approx 10^{12}\,\text{s}^{-1}$.

NONLINEAR STABILIZATION

With the aid of the particle-in-cell method [1] we have obtained that the valley-to-valley transitions cause the considerable changes in the temporal dependence of the slow amplitude of the wave electric field $E_s(t)$ (i.e., $|dE/dt| << \Omega_p E$). The dependence $E_s(\tau)$ (where $\tau = \gamma t$) is shown in Fig.1.

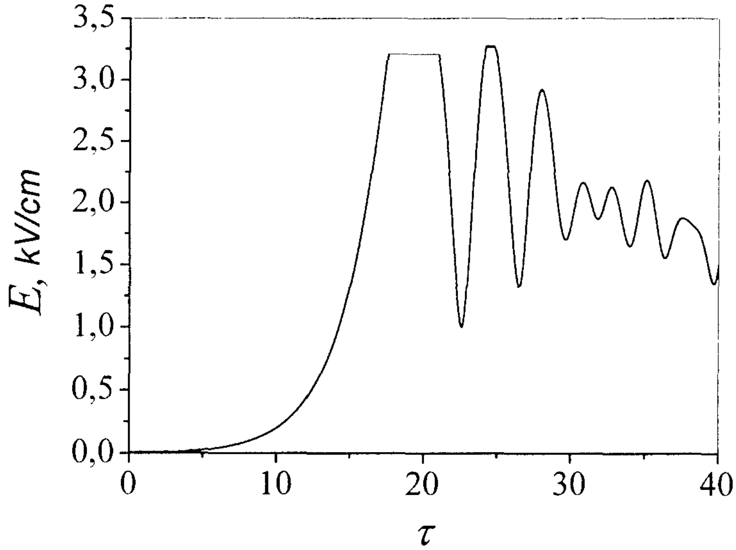

Fig. 1

The plateaus in Fig.1 appear due to the frequency ν increases abruptly. This increase causes the abrupt decrease the growth rate of hydrodynamic instability γ. This situation continues until the most of beam electrons are trapped.

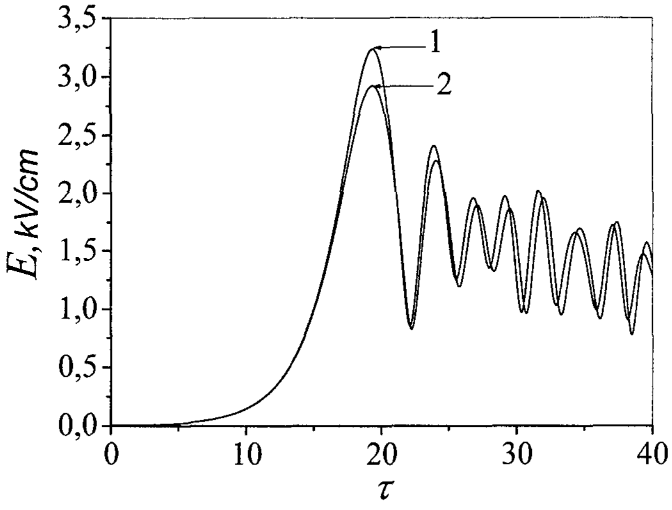

Fig. 2

The influence of nonparabolicity of electrons dispersion law in GaAs is shown in fig.2.

In this figure the curve "1" corresponds to the dependence $E_s(\tau)$ without taken into account the nonparabolicity and the curve "2" corresponds to the opposite case. The influence mentioned above is taken into account with the help of the dependence of the electron effective mass on their temperature $m(T_e)$:

$$m^*(T_e) = m\sqrt{1 + \frac{4T_e(E_s)}{\theta_g}}, \tag{2}$$

where θ_g is the energy gap between the valence and conduction bands. Fig.2 shows that the nonparabolicity causes the decrease of the maximum of E_s in which the most of the beam electrons are trapped by the wave.

REFERENCES

[1] A. A. Ivanov, V. V. Parail, and T. K. Soboleva, *Zh. Eksp. Teor. Fiz.* Vol.63, 1678 (1972).