Electrostatic plasma instability of photoexcited electrons in semiconductors

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It has been demonstrated theoretically that an electrostatic plasma instability of photoexcited electrons can be produced in semiconductors at a low lattice temperature in crossed, constant electric and magnetic fields.

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Electrostatic plasma instabilities (EPI) are well-known effects produced in a gaseous plasma. Analogous effects can occur in a semiconductor plasma of hot electrons. These effects have been analyzed theoretically in a number of papers, e.g., in Refs. 1–4. These types of instabilities, however, have not been detected experimentally. This is attributable primarily to the difficulty of constructing a beam-type, nonmonotonic distribution function (DF) and the fact that there is a strong interaction between the electrons and the lattice in semiconductors.

We shall show in this letter that the essential conditions for the occurrence of EPI of photoexcited electrons can be established by using a constant electric field E_0 and a constant, unquantized magnetic field H_0 at right angles to it in the presence of fast electron recombination. We shall analyze the characteristics of the predicted EPI.

At a low lattice temperature T_0 the electron scattering in the passive region (PR) of the momentum space, in which the electron energy is lower than the optical-phonon energy $\hbar\omega_0$, is weak. Because of this, the effect of scattering on EPI of electrons, which are concentrated in the PR, is minimal. We shall demonstrate that a beam DF of photoelectrons can be produced in the PR. Let us examine electron photoexcitation by a monochromatic light from the impurity levels. We shall assume that the electron concentration in the absence of photoexcitation is negligible. During excitation, the photoelectron DF has the shape of a sphere $f(v) \sim \delta(V^2 - V_0^2)$, where V_0 is the absolute photoelectron velocity. If the photoelectron energy is slightly lower than $\hbar\omega_0$, then the DF can be converted to a three-beam distribution by applying crossed E_0 and H_0 fields. If $\pi\nu \ll \omega_c$, where ν is the scattering frequency and the PR and ω_c is the cyclotron frequency, then the trajectories in the momentum space will have the shape of circles whose center is displaced perpendicularly to E_0 and H_0. If we select the values of E_0 and ω_c in an appropriate way, the photoelectrons with sufficiently large velocity components at right angles to H_0—a specific interval of the cyclotron period—will have an energy higher than $\hbar\omega_0$, which they will lose almost completely after a rapid emission of the optical photon. As a result, the DF in the direction of H_0 has a three-beam shape. It has been established that the average lifetime of carriers in semiconductors is of the order of 10^{-10} sec at helium temperatures.[5,6] The calculations of the cascade capture of electrons in impurity levels with the participation of acoustic phon-

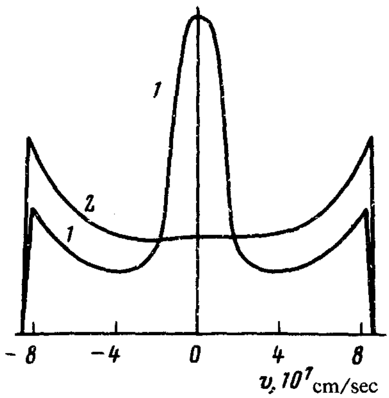

FIG. 1. Steady-state distribution function of photoelectrons in the direction of the magnetic field for n-InSb at $E_0 = 40$ V/cm and $\omega_c = 4.4\times10^{12}$ sec^{-1}. 1–$\nu_R = 10^{10}$ sec^{-1}; 2–$\nu_R(V) = 3\times10^{48}|V|^{-5}$.

ons[7,8] show that the capture frequency ν_R depends on the electron velocity as $\nu_R(V)\sim|V|^{-5}$.[8] Because of this, we can expect the formation of a beam-type, steady-state DF (if the EPI are ignored) as a result of a continuous photoexcitation of electrons in the passive region.

This assumption is confirmed by the numerical calculations of the evolution of the DF, which were carried out by us using the many-particle Monte Carlo method for the n-InSb model (Ref. 9) at $T_0 = 4.2$ K. The energy of the generated photoelectrons was 0.024 eV ($\hbar\omega_0 = 0.0244$ eV). The calculations showed that the steady-state DF is formed during a time of the order of the cyclotron period. At ν_R = const = 10^{10} sec^{-1} the steady-state DF has a three-beam shape and at $\nu_R(V)\sim|V|^{-5}$ it has a two-beam shape (Fig. 1). Allowance for the scattering by ionized impurities in the Conwell-Weisskopf approximation did not change appreciably the shape of the DF at an ionized-impurity concentration $N\leqslant10^{14}$ cm^{-3}.

We shall analyze the predicted EPI in the linear approximation with allowance for the recombination. In contrast to Ref. 2, we shall consider the dependence of N on the coordinate x and the time t, which arises as a result of electron recombination. For simplicity, we shall ignore the scattering by phonons and impurities and assume that in the absence of plasma perturbations the DF is a one-dimensional, steady-state function $f_0(V)$ in the direction of H_0 and that the electron density has been established. Thus the system of equations has the form

$$\frac{\partial f}{\partial t} + V\frac{\partial f}{\partial x} + \frac{eE}{m}\frac{\partial f}{\partial V} = g(V) - \nu_R(V)f,$$

$$\frac{\partial N}{\partial t} = \int[g(V) - \nu_R(V)f]\,dV, \tag{1}$$

$$\frac{\partial E}{\partial x} = \frac{e}{\epsilon\epsilon_0}\left[\int f\,dV - N\right].$$

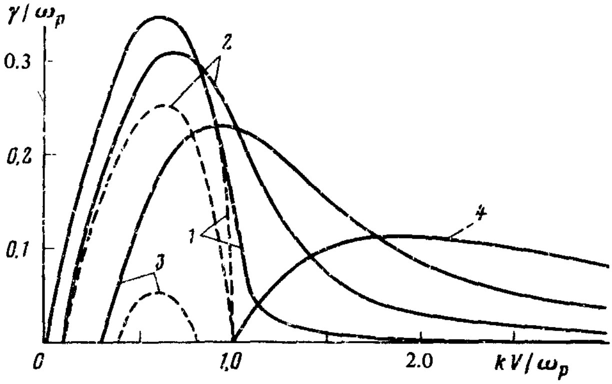

FIG. 2. Growth rate of electrostatic plasma instabilities for different values of ν_R. 1–$\nu_R/\omega_p = 0.01$; 2–0.1; 3–0.3; 4–1.0.

Here E is the field of the space charge, and $g(V)$ is the effective production rate, which takes into account the photoproduction, cyclotron rotation and optical-phonon emission. We shall linearize Eq. (1) for perturbations such as $\exp[i(kx - \omega t)]$, assuming that the unperturbed DF and the density are

$$f_0(V) = g(V)/\nu_R(V), \qquad N_0 = \int f_0(V)dV. \tag{2}$$

Thus we derive from Eq. (1), with allowance for Eq. (2), the following dispersion equation:

$$\frac{\omega_p^2}{N_0}\int \frac{f_0(V)\left[+ \frac{i}{\omega}\left(\nu_R(V) - V\frac{\partial \nu_R(V)}{\partial V}\right)\right]}{(\omega - kV + i\nu_R(V))^2} dV = 1, \tag{3}$$

where ω_p is the plasma frequency. For $f_0(V) = (N_0/2)[\delta(V+V_0) + \delta(V-V_0)]$ (curve 2 in Fig. 1 represents an idealized DF) the dependence of the growth rate of EPI on the wave number k for different values of ν_R = const, which was obtained by solving Eq. (3), is illustrated in Fig. 2 by the solid curves. The dashed curves were calculated in accordance with Ref. 2, in which the dependence of N on x and t was ignored.

The simulation of EPI carried out by us in the nonlinear regime using flat plates, showed that a continuous EPI regime occurs in the presence of a fast recombination. After the linear regime is established, the electron density, the DF and the electric field of the space charge will oscillate continuously at a frequency close to ω_p (at $N = 1.3 \times 10^{14}$ cm^{-3}, $\omega_p/2\pi = 200$ GHz) without attentuation in time. The EPI under consideration can therefore be used to generate electromagnetic waves in the short-wave part of the superhigh-frequency range.

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