Instability of Drift Waves in Two-Component Solid-State Plasma

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Abstract—The instabilities of longitudinal waves in infinite semiconductor plasma containing charge carriers of two types are considered under the assumption that the thermal velocity of electrons slightly exceeds that of holes. The main result of this study is that instability can occur in intrinsic semiconductors if the electron drift velocity is lower than the thermal velocity. Drift wave instabilities are studied in intrinsic semiconductors and semiconductors with identical plasma frequencies of electrons and holes. The influence of dissipation on the instability of these waves is also considered. © 2005 Pleiades Publishing, Inc.

1. INTRODUCTION

In modern microwave engineering, bands of short millimeter and submillimeter waves are the most poorly understood. In these regions, tube-based devices can no longer be used, and solid-state structures efficiently operate as solid-state lasers only at shorter wavelengths, i.e., in the infrared and visible regions. At the same time, short millimeter and submillimeter waves are of significant interest for modern communication, medical research, and studies of the physical properties of materials [1, 2]. Therefore, the search for materials and physical effects to be applied in the development active devices in the millimeter and submillimeter ranges is obviously an important problem.

One conventional approach is the study of the possibility of developing solid-state devices demonstrating a prolonged interaction between an electromagnetic traveling wave and carriers drifting in dc fields in semiconductor plasma. Surveys of this problem are published from time to time, one example being the excellent review paper [3]. Paper [1] is also of considerable interest. In particular, this paper describes an experiment in which instability was observed in the millimeter range during the interaction of carriers drifting in a semiconductor layer with a periodic structure such as a dielectric waveguide with a periodic wall of complex shape. In our opinion, however, the mechanism of this instability is not completely clear. Finally, review [4] shows that study of the possibility of inducing instabilities in short-wavelength ranges and developing solid-state oscillators and amplifiers using these instabilities is of great interest to many researchers.

To date, great progress has been achieved in the technology of solid-state semiconductor periodic structures such as superlattices. These structures are new artificial materials whose properties can significantly differ from those of natural crystals. If the layer thicknesses are about 1–3 µm, then, in the millimeter and terahertz ranges, such structures represent a continuous semiconductor medium. By selecting semiconductors with different types of conductivity in their superlattice layers, one can obtain a material in which plasma frequencies, drift velocities, etc., for different carriers are of the same order of magnitude. At the same time, instabilities in semiconductors and plasma have been studied taking into account the significant difference in the parameters of the electron and hole components. The objective of this study was to examine the possibility of obtaining instability in electron–hole plasma consisting of a homogeneous semiconductor with a drift velocity smaller than the thermal velocity of carriers. In order to simplify the formulas, we do not consider the transition from a layered periodic structure to a homogeneous medium; these problems were considered in [5, 6].

The papers [7–11] of the late 1950s to early 1960s dealt with the instabilities induced by the carrier drift in plasma generated under external electric fields. In [12], these instabilities were considered in the kinetic and hydrodynamic approximations.

It has previously been shown that two-component plasma becomes unstable if the electron drift velocity with respect to ions is fairly high. The conditions for the instability onset were studied in [7–9] for plasma formed by electrons and ions with equal temperatures. It was shown that plasma becomes unstable if the electron drift velocity \( v_{0e} \geq 1.32 v_{Te} \). When the electron temperature is much higher than the ion temperature, the drift velocity at which instability occurs decreases \( v_{0e} \leq (m_e/m_p)^{1/2} v_{Te} [10] \).

The interaction of drift waves with plasma waves in semiconductors was considered in [11], where the two-stream instability caused by carrier drift in an external electric field was studied in the kinetic approximation. Dispersion relations were obtained for two modes of collective oscillations: a high-frequency optical mode,

\[ \omega^2 = \left( \frac{\omega_{0e}^2 + \omega_{0p}^2}{\epsilon_0} \right). \]
in which electrons and holes move out of phase, and a low-frequency acoustic plasma mode

\[ \omega = \frac{m_e}{m_p} k \nu_{Te}, \]

in which electrons and holes move in phase. In these formulas, the following notation is used: \( \omega_{0e,p} \) are the Langmuir frequencies of electrons and holes, \( m_{e,p} \) are their masses, \( \nu_{Te,p} \) is the thermal velocity of electrons, \( k \) is the wave number, and \( \varepsilon_0 \) is the lattice component of the permittivity. These solutions were derived in the following approximations:

\[ \frac{\omega_{0p}}{\omega_{0e}} < 1, \quad \frac{\omega_{0p} \nu_{Te}}{\omega_{0e} \nu_{Tp}} \gg 1. \]

It follows from these inequalities that the thermal velocity of electrons should significantly exceed the hole velocity. At the same time, for many semiconductors, the electron thermal velocity only slightly exceeds the hole velocity; i.e., the second inequality is violated. This factor is taken into account in this study. We consider the interaction of plasma oscillations of electrons and holes (see [13]),

\[ \omega^2 = \omega_{0e}^2 \varepsilon_0 + k^2 \nu_{Te}^2, \]

\[ \omega^2 = \omega_{0p}^2 \varepsilon_0 + k^2 \nu_{Tp}^2, \]

in the presence of carrier drift. It will be shown below that a specific feature of these waves is that they have regions of negative phase velocity, where the resonant interaction of the hole and electron drift waves with negative phase velocity is possible.

Significant attention was paid to the instability of spatially separated electron–hole streams in the studies of Romanov et al. [14–18]. The analysis was carried out in the quasi-hydrodynamic approximation and took into account the thermal velocity and collision frequency of carriers. The main aim of those studies was to find out if it was possible to decrease the drift velocity at which the instability occurs. The studies were carried out in a wide range of drifting carrier parameters, and the results were compared to the data presented in [11].

The existence of two carrier streams significantly complicates the problem; accordingly, we use the hydrodynamic approximation. It is known that the hydrodynamic equations are valid for the frequencies \( \omega \gg \nu \) (collisionless plasma [19]) and \( \omega \ll \nu \) only if the collective dynamics of the particles is studied and effects such as Landau damping are disregarded. The effect of thermal motion of the carriers can also be taken into account in the hydrodynamic approximation. As was shown in [20], the error of the hydrodynamic description (compared to the kinetic approach) does not exceed 10%, even at \( \nu \lambda^2 / 2 \pi \nu \gg 3 \) (\( \lambda \) is the wavelength). Using the plasma frequencies \( \omega_0 = (4 \pi e^2 n_i / m_0 \varepsilon_0)^{1/2} = 10^{11–10^{13}} \text{s}^{-1} \), effective masses \( m = 10^{28–10^{29}} \text{g} \), and collision frequencies \( \nu = 5 \times 10^{10–10^{13}} \text{s}^{-1} \) at temperatures from 4.2 to 300 K [21], which are typical of semiconductors, we obtain the thermal velocities \( \nu_T = 10^7–10^8 \text{cm/s} \), Debye length \( R_D = \nu T / \omega_0 \approx 10^{-4} \text{cm} \), and carrier free paths \( l = \nu_T / \nu \approx 10^4–10^5 \text{cm} \). Thus, our approach is valid for the frequencies \( \omega = 10^{10–5} \times 10^{13} \text{s}^{-1} \). It should also be taken into account that, compared to the kinetic approximation, in the hydrodynamic approximation, a numerical coefficient slightly exceeding unity appears at the term \( k^2 \nu_T^2 \) in relation (1).

2. BASIC EQUATIONS

Let us consider an infinite two-component solid-state plasma formed by electrons and holes. Let us assume that an external dc electric field causes electron drift with the velocity \( \nu_{0e} \) and hole drift with the velocity \( -\nu_{0p} \). We direct the \( 0x \) axis along electron drift direction. The electromagnetic processes in such a structure are described by Maxwell’s equations, as well as constitutive equations for electrons and holes,

\[ \frac{\partial \varepsilon_0}{\partial t} + (\nu_{0e} \text{grad}) \varepsilon_e = -\frac{e}{m_e} E - \frac{\nu_{0e}^2}{n_{0e}} \text{grad} n_e - \nu_e \varepsilon_e, \]

\[ \frac{\partial n_e}{\partial t} + \text{div} (n_{0e} \varepsilon_e + n_e \nu_{0e}) = 0, \]

\[ \frac{\partial \nu_e}{\partial t} - (\nu_{0p} \text{grad}) \nu_p = \frac{e}{m_p} E - \frac{\nu_{0p}^2}{n_{0p}} \text{grad} n_p - \nu_p \nu_p, \]

\[ \frac{\partial n_p}{\partial t} + \text{div} (n_{0p} \varepsilon_p - n_p \nu_{0p}) = 0, \]

where \( n_{0e} \) and \( n_{0p} \) are the equilibrium electron and hole concentrations; \( \varepsilon_e \) and \( \nu_e \) are collision frequencies; \( \nu_{0e} \) and \( \nu_{0p} \) are thermal velocities; and \( n_e, n_p, \varepsilon_e \) and \( \nu_p \) are the variable concentrations and velocities of carriers.

In order to determine the components of the permittivity tensor, we use the following relation for the electric displacement:

\[ \mathbf{D} = \varepsilon_0 \mathbf{E} + \frac{4 \pi}{\omega} (-en_{0e} \varepsilon_e - en_e \varepsilon_{0e} + en_{0p} \nu_p - en_p \nu_{0p}). \]