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INTERACTION OF A NONRELATIVISTIC ELECTRON BEAM WITH A SEMICONDUCTOR CYLINDER IN AN EXTERNAL MAGNETIC FIELD

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ABSTRACT

The paper presents a theoretical study of electrostatic oscillations in a cylindrical system, which represents an electron beam surrounded by a semiconductor of finite thickness, adjacent to a dielectric or a perfectly conducting metal. The system is placed in a finite axial magnetic field. The results of the analysis show that space charge waves (the drift waves) and cyclotron waves could be unstable. It is also shown that, as the external magnetic field or the collision frequency of electrons increases the growth rates of the instabilities decrease.

INTRODUCTION

Investigating interactions of charged particles beams with natural oscillations in plasmas is among the important topics of microwave plasma electronics. By now there is a great number of papers devoted to the electron beam-plasma interaction. Interactions of this kind are of considerable interest since they can be used for amplification and generation of electromagnetic oscillations of various wavelengths [1]. Also they can bring ample information on physical properties of the medium. In current literature, great attention is focused on the interaction of electron beams with the eigenmodes in plasmas of cylindrical and tubular geometry. The reason is that plasma amplifiers and generators are chiefly built around plasma formations of cylindrical geometry [2].

The interaction of electron beams with tubular solid-state plasmas of finite thickness without external magnetic field was already studied [3]. However, at conditions of experiment, the beam-plasma systems are always situated in an external magnetic field, which prevents lateral motions of electrons in the beam. This paper is aimed at investigating oscillatory processes in a cylindrical structure representing a quasi-neutral charged particle beam surrounded by a semiconductor of finite thickness adjacent to a dielectric or a perfectly conducting metal. Collisions of electrons in the semiconductor are taken into account.

PROBLEM FORMULATION. DISPERSION RELATIONS

Let the spatial domain $a \le \rho \le b$ in a cylindrical coordinate system (ρ, φ, z) be occupied by a semiconducting material. The spatial domain $0 \le \rho < a$ is filled with a dielectric of permittivity ε_{d1}, while the domain $\rho > b$ is filled with another dielectric of permittivity ε_{d2} or with a perfectly conducting metal. The structure under analysis is infinite along the z-axis and is situated in a finite strength axial magnetic field $\vec{H}_0$. We will analyse the interaction of a straight, quasi-neutral nonrelativistic electron beam propagating trough the domain $0 \le \rho < a$, with electrostatic magnetoplasma oscillations existing in the cylindrical semiconductor structure.

Making use of Maxwell's equations, equations of motion, continuity equations for each region of the structure, boundary conditions at $\rho = a$ and at $\rho = b$, and taking into account that the field magnitude should be finite at the axis of the cylindrical structure and (infinitely) far from it, we can find the dispersion relation to describe the interaction of magnetoplasma waves in the structure with the beam under analysis. The dispersion relation has the form

$$F(a,b,q,l,\omega,\nu,\omega_p,\omega_{Hs},\omega_b,\omega_{Hb},V_0) = 0, \qquad (1)$$

where q and l are, respectively, the axial and the azimuthal wavenumbers; ω is the signal frequency; ν is the effective collision frequency of electrons in the semiconductor; ω_p, ω_{Hs} and ω_b, ω_{Hb} are, respectively, the plasma frequencies and the cyclotron frequencies in the semiconducting material and in the beam; V_0 is the equilibrium velocity of electrons in the beam.

If the semiconductor borders on a metal at $\rho = b$ or if $b >> a$, then the dispersion relation takes the more simple form.

NUMERICAL RESULTS AND DISCUSSION

(1) was solved numerically using values of parameters appropriate for n-type InSb, i.e., the permittivity of the crystal lattice $\varepsilon_0 = 16$; the effective mass of electrons $m^* = 0.015m$; the equilibrium concentration $N_0 = 5\times10^{13}\text{cm}^{-3}$. Throughout the discussion $a = 10^{-1}\text{cm}$, $d = (b-a) = 10^{-3}\text{cm}$, $\omega_b = 10^9\text{s}^{-1}$, $V_0 = 3\times10^9\text{cm/s}$.

A numerical solution of (1) shows (see Fig. 1), that the interaction of charged particle beam with magnetized collisional solid-state plasmas gives rise to a broad-band instabilities of the space-charge waves ($\omega = qV_0$) and the cyclotron waves ($\omega = qV_0 - \omega_{Hb}$). The growth rate of any considered instability attains its maximum value under resonance conditions, when the frequency of the unstable wave coincides with that of natural oscillations of the semiconductor cylinder.

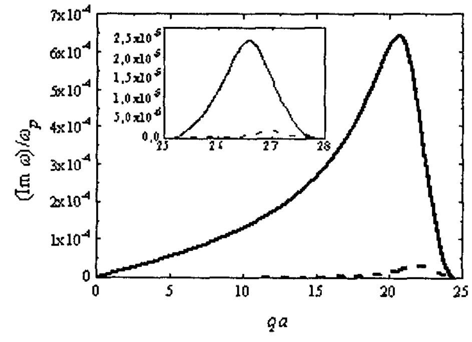

Fig. 1. The growth rates of unstable space-charge waves (solid line) and cyclotron waves (dashed line) for the structure under consideration: $l = 0$; $\Delta = \omega_{Hs}/\omega_p \approx 0.9$; $\Gamma = \nu/\omega_p = 0.1$

Account of two boundaries to the solid-state plasma (tubular geometry of the plasma) shows the domain of instability to be in fact divided into bands of stable and unstable states.

The growth rates of the instabilities are strongly influenced by the external magnetic field and the effective collision frequency. As the magnetic field or collision frequency increases, the growth rate of the instability decreases (see Fig. 2 and Fig. 3).

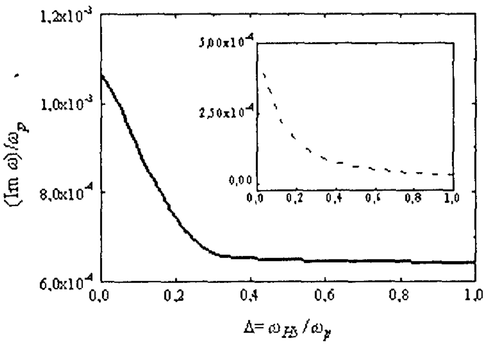

Fig. 2. The growth rates of unstable space-charge waves (solid line) and cyclotron waves (dashed line) as functions of parameter $\Delta = \omega_{Hs}/\omega_p$: $l = 0$; $\Gamma = \nu/\omega_p = 0.1$

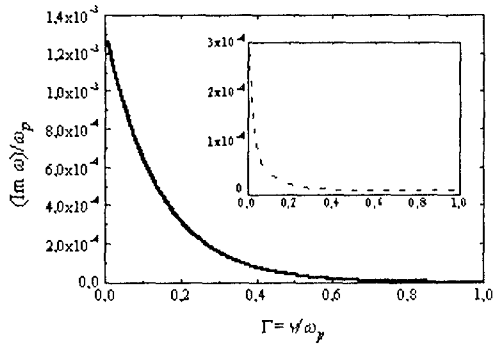

Fig. 3. The growth rates of unstable space-charge waves (solid line) and cyclotron waves (dashed line) as functions of parameter $\Gamma = \nu/\omega_p$: $l = 0$; $\Delta = \omega_{Hs}/\omega_p \approx 0.9$;

Fig. 4 shows that the maximum value reached by the growth rate at the negative values of the azimuthal wave number is higher than at the positive values of the azimuthal wave number.

If the cyclotron frequency in the semiconductor is greater than the plasma frequency, then the surface waves in considered semiconductor structure don't exist. In this case, electrons of the beam interact only with spatial oscillations of the semiconductor plasma. The growth rates of the instabilities for this kind of interaction are much less, than in the case of interaction with surface oscillations.

In order to observe the amplification effect for the space-charge wave, it is necessary to preliminary modulate the charge-particle beam.

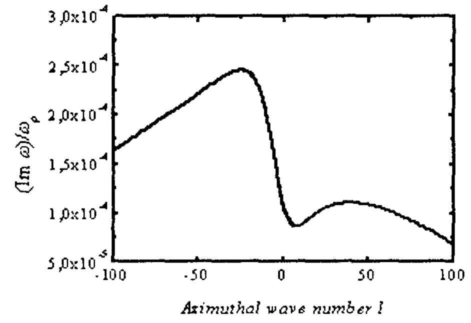

Fig. 4. The growth rate of unstable space-charge waves as a function of the azimuthal wave number l: $\Delta = \omega_{Hs}/\omega_p \approx 0.9$; $\Gamma = \nu/\omega_p = 0.1$

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