Propagation of magnetosonic wave in ion implanted semiconductor: Effects of nano-sized grains

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Abstract. We have derived a linear dispersion relation for magnetosonic wave (MSW) in compensated semiconductor plasma, like Ge, embedded with nano-sized grains (NSGs) of ions. These NSGs are bombarded by electrons and holes in the plasma medium and usually acquire net negative charge on account of higher mobility of electrons as compared to that of the holes [1]. The process of charging of NSGs depletes the electron density and creates a charge imbalance, which modifies the propagation characteristics of MSW even if NSGs do not participate in wave perturbation.

1. Introduction

The MSW is a low-frequency electromagnetic wave that propagates perpendicular to magnetic field at the frequency well below the ion-cyclotron frequency. Herlofsen [2] was the first to discover and study MSW in strongly magnetized plasma.

In semiconductor, if ions are implanted at high fluency, they may agglomerate to form nano-sized grains (NSGs). In recent years, there has been growing interest on the study of linear and nonlinear optical properties of NSGs of implanted ions in solids [4, 5-8]. These NSGs can be synthesized within the host material by ion implantation followed by an appropriate annealing process [9]. The shape and size of the NSGs is determined by various factors such as ion fluence, annealing treatment, etc. The metallic NSGs buried in glasses are promising bistable materials because they exhibit ultrafast nonlinear response at plasmon frequency [8], which make them potentially attractive candidates for device applications in the various fields including photonics, nonlinear optics, optoelectronics, etc [5, 6, 9, 10].

Like dust in dusty plasmas, the NSGs in semiconductors might acquire a net negative charge that would change the balance between electron and hole densities in an otherwise compensated semiconductor. This, in turn, gives rise to several novel phenomena. Salimullah et. Al. [11], first time, predicted the possible lattice formation in piezoelectric semiconductors. Later, in the same medium, the role of electron-phonon coupling in the formation of plasma crystal was also reported [12].

A survey of the available literature reveals that the study on properties of NSGs in solids has been hotly pursued in the recent years; however, their effects on the properties of host material have not been explored. We firmly believe that by interacting with the carriers and by creating charge imbalance of the carrier concentration, the NSGs would modify properties of host material. Since a study on wave propagation through host material can provide tremendous insight regarding its properties, comprehensive efforts in this direction are needed.
Motivated by this in the present paper, we have focused our attention on the study of propagation properties of MSW in the ion-implanted-group-IV semiconductor. The choice for the MSW stems from the fact that it is a fundamental electromagnetic mode observed in laboratory and space plasmas and can render an effective tool for material diagnosis [12, 13].

An MSW propagates perpendicular to the magnetic field in gaseous plasma (without any dust contamination) and obey the dispersion relation

\[ \frac{\omega^2}{k^2} = c^2 \frac{v_s^2 + v_{A}^2}{v_{A}^2 + c^2}, \tag{1} \]

where \( v_s \) is the speed of acoustic wave, \( v_A \) is the speed of Alfvén wave and \( c \) is the speed of light.

The paper is organized in the following manner. In section 2, we outline the basic equations describing MSW propagation. In section 3, we derive a dispersion relation for the MSW in the implanted semiconductor plasma. In section 4, we present analytical investigation of the dispersion relation for the MSW followed by discussions.

2. The basic equations

We consider compensated semiconductor plasma i.e. \( n_e = n_h = n_0 \) embedded with NSGs. The electrons and holes from all directions bombard on the NSGs and get stick onto them. However, owing to high mobility of electrons, greater number of electrons bombards the NSGs as compared to holes in given time interval. If we consider equal probability of sticking of electrons and holes onto the NSGs, the later acquire net negative charge and consequently, the electron density depletes. Thus, the charge neutrality condition reads

\[ n_{h0} = n_0 = \bar{n}_{e0} + zn_n, \tag{2} \]

with \( \bar{n}_{e0} \) being the depleted electron density, \( z \) the number of electrons that reside onto an NSG and \( n_n \) their density in the medium. The charge imbalance so created may be measured in terms of parameter

\[ \delta = \frac{\bar{n}_{e0}}{n_{0h}} = \frac{\bar{n}_{e0}}{n_0}. \tag{3} \]

Let the semiconductor be immersed in a strong magnetic field \( B_0 = zB_0 \) and MSW propagates across the external magnetic field, so let \( k = yk \). For MSW, the term \( \mathbf{E} \times \mathbf{B}_0 \) is along \( k \) so that plasma is compressed and released during oscillations in the course of wave propagation. Therefore, we keep pressure gradient term via the density gradient term in our analysis. The propagation of MSW in the medium may be described by Maxwell’s equations ignoring the displacement current and the dynamics of electrons and holes in semiconductor plasma with immobile NSGs may be described by the respective continuity and momentum equations for the species \( \alpha = e, h \) as

\[ \frac{\partial n_\alpha}{\partial t} + \nabla (n_\alpha v_\alpha) = 0, \tag{4} \]

and

\[ \frac{\partial v_\alpha}{\partial t} + (v_\alpha \nabla) v_\alpha = \frac{q}{m_\alpha} (\mathbf{E} + v_\alpha \times \mathbf{B}_0) - \gamma_\alpha kT_\alpha \nabla n_\alpha, \tag{5} \]

here, \( m_\alpha, \gamma_\alpha, T_\alpha \) and \( v_\alpha \) are the mass, specific heat ratio, temperature and the first-order velocity of the species.

3. Dispersion relation

A dispersion relation for MSW may be deduced by linearizing Eqs. (4-5), which leads us to expressions for \( x \)-components of first-order perturbed velocities of electrons and holes:

\[ v_\alpha \left(1 - \frac{\omega_e^2 / \omega^2}{1 - G} \right) = -\frac{ie}{m_e \omega} E_x, \tag{6a} \]
and \( v_{hx} \left( 1 - \frac{\Omega_e^2}{\omega^2} \right) = \frac{i e}{m_h \omega} \mathbf{E} \). \[(6b)\]

Here, \( \omega_e = -\frac{eB_0}{m_e} \) and \( \Omega_e = \frac{eB_0}{m_e} \) are the respective electron and hole cyclotron frequencies, with
\[
G = \frac{k^2}{\omega^2} \frac{K_T}{m_e} \text{ and } S = \frac{k^2}{\omega^2} \frac{K_T}{m_h} \text{ being the dimensionless parameters.}
\]

Now, using expressions for \( v_{ex} \) and \( v_{hx} \) in Maxwell’s equations, we get
\[
\omega^2 - c^2 k^2 = \omega_p^2 \left[ \frac{1 - G}{1 - G} \left( \frac{\omega_e^2}{\omega^2} \right) + \Omega_p^2 \left( \frac{1 - S}{1 - S} \left( \frac{\Omega_e^2}{\omega^2} \right) \right) \right], \[(7)\]

With \( \omega_p^2 = \left( \frac{n_e e^2}{m_e \epsilon_0} \right)^{0.5} \) and \( \Omega_p^2 = \left( \frac{n_e e^2}{m_h \epsilon_0} \right)^{0.5} \), being the electron and hole plasma frequencies.

Under the assumption \( \omega < \omega_e, \Omega_e \), and neglecting the factors \((1 - G)\) and \((1 - S)\) relative to \( \omega_e^2/\omega^2 \) and \( \Omega_e^2/\omega^2 \), respectively. With these assumptions, Eq. (10) reduces to dispersion relation for MSW in compensated semiconductor plasma embedded with immobile NSGs as
\[
\frac{\omega^2}{k^2} = c^2 \left[ \frac{\nu_A^2 (1 + m \delta)}{\nu_A^2 + c^2 (1 + m \delta)} \right], \[(8)\]

where \( m = \left( m_e/m_h \right) \), the electron to hole mass ratio, and \( \nu_A = \frac{B_0}{\sqrt{\mu_0 n_0 m_h (1 + m \delta)}} \), the Alfvén velocity and \( \nu_s \), the sound speed. We notice from above equation that the presence of charged NSGs in compensated semiconductor plasma alters the Alfvén velocity and modifies the dispersion relation for MSW through charge imbalance parameter \( \delta \) in the medium. It is evident that, with rise in temperature, the acoustic velocity \( \nu_s \) increases and so does the influences of charged NSGs on the dispersion characteristics of the MSW. Also, by considering positive ions in place of holes and dust in place of NSGs i.e. \( n = \left( m_e/m_i \right) \to 0 \) in above formulation, we can recover dispersion relation (Eq. (1)) form Eq. (8).

4. Results and discussion

In this section, by employing the dispersion relation Eq. (8), we present analytical investigation on the effects of the NSGs on the propagation characteristics of MSW. The set of parameters used are given in [14]. The results are displayed in the form of graphs in Figures 1 and 2.

Figure 1 illustrates dispersion characteristics of the MSW for different values of charge imbalance parameter \( \delta = 1, 0.8 \) and \( 0.6 \) in group IV semiconductor. The graph reveals that MSW propagates without any dispersion, irrespective of the amount of charge residing on the NSGs. As the charge on the NSGs increases, the electron concentration falls. This reduces inertia of the plasma fluid, which results in slightly increase in phase velocity of MSW. The effect of charged NSGs is negligible for small values of \( k \) but increases as \( k \) assumes higher values.

Figure 2 displays variation of phase velocity of MSW as a function of hole density in semiconductor plasma for magnetic field \( B_0 = 1, 2 \) and \( 3 \) Tesla. An increase in hole density of plasma increases inertia of the plasma fluid and thus, the phase velocity decreases. It is also evident that with increase in magnetic field, the strength of compression and release of plasma increases during course of oscillations and so does the consequent phase velocity of MSW. Therefore, the MSW travels at higher phase velocity in a strongly magnetized plasma with lower hole concentration.
Figure 1. Dispersion characteristics of magnetosonic wave for charge imbalance parameter $\delta=1$, 0.8 and 0.6.

Figure 2. Variation of phase velocity $v_p$ of magnetosonic wave with hole concentration $n_{0h}$ in semiconductor plasma for magnetic field $B_0=1$, 2 and 3T.

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