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Original Research Article

Modeling acoustic spectra in inhomogeneous semiconductors with embedded nanoparticles

Ajit Singh*
Assistant Professor, Department of Physics, Government College, Kalka – 133302 (Panchkula) Haryana, India
*Corresponding author, E-mail: ajitnehra2010@gmail.com

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ABSTRACT
Semiconductors embedded with nanoparticles have gained significant attention among material scientists due to their potential applications in developing advanced nano-electronic devices. While much of the current research focuses on the thermal characteristics of these materials, their acoustic properties are equally important and warrant detailed investigation. In this study, we analyze the acoustic spectra of an inhomogeneous semiconductor containing a single nanoparticle. A macroscopic model of piezoelectric media, combined with a fluid model of plasmas, is employed to derive the corresponding dispersion relation. The effects of the medium's density gradient and the presence of the nanoparticle on acoustic wave gain are examined as functions of the velocity ratio v_0/v_s, carrier density η_{0e}, and wave frequency ω. It is observed that the point of transition $v_0/v_s = 1$ from attenuation to amplification is strongly influenced by the density gradient, whereas it remains largely unaffected by the inclusion of the nanoparticle. Furthermore, the density gradient shifts this crossover point toward higher velocity ratios and decreases the overall gain magnitude.

1. Introduction

Nanoparticle (NP) embedded semiconductor structures have emerged as a highly active and intriguing area of research. Numerous theoretical and experimental studies have explored both the growth mechanisms and the significant changes in physical and chemical properties induced by nanoparticles. For example, Zide et al. [1] fabricated composite epitaxial materials consisting of semi-metallic ErAs nanoparticles embedded in a semiconducting $In_{0.53}Ga_{0.47}As$ matrix. They observed that these nanoparticles increase the free electron concentration while preserving relatively high electron mobilities. Additionally, the theoretically calculated Seebeck coefficients showed good agreement with experimental measurements, suggesting that metallic NPs embedded in a semiconductor matrix could serve as foundational elements for efficient thermoelectric materials. Schultz and Palmstrom [2] studied the growth of ErAs on GaAs surfaces through an embedded growth mode and demonstrated that the resulting surface morphologies depend on structural characteristics, thermodynamic factors, and diffusion properties. Kawasaki et al. [3] investigated the atomic and electronic structures of ErAs nanoparticles within a GaAs matrix using cross-sectional tunneling microscopy and spectroscopy. Choudhary [4] theoretically analyzed the thermoelectric figure of merit in nanostructured materials and reported that embedding nanoparticles leads to significant modifications in the thermal properties of the system.

The studies discussed above indicate that nanoparticle (NP) embedded semiconductors provide a promising platform for detailed investigation. Such media are valuable for developing new materials aimed at improving nanoelectronic device performance, making them highly attractive to material scientists. Building on this concept, several research groups [5, 6] examined longitudinal phonon–plasmon interactions in piezoelectric semiconductors containing either a single NP or a collection of NPs. In those studies, acoustic gain was observed only when the ratio of the drift velocity to the acoustic velocity (v_0/v_s) exceeded unity. The transition point from attenuation to amplification ($v_0/v_s \approx 1$) was found to be independent of the presence of nanoparticles. However, notable changes in the acoustic gain characteristics were observed due to the inclusion of NPs in an otherwise homogeneous semiconductor plasma. These changes are attributed to the restoring force generated by displacements in the electron cloud surrounding the nanoparticles. Under an applied external electric field, the electrons in this cloud undergo collective oscillations similar to the plasma oscillations of free electrons in the homogeneous medium. This phenomenon effectively alters the spring constant of the system, resulting in a modified plasma frequency.

It is well recognized that complete homogeneity in a plasma system is rarely achieved under various field configurations due to the influence of external forces. In practice, inhomogeneities can also arise from nonuniform doping or exposure to uneven radiation. Experimentally, producing a perfectly homogeneous semiconductor remains highly challenging. When a system exhibits gradients in density, temperature, pressure, or magnetic field, a plasma current or particle drift naturally occurs; even in the presence of an electrostatic field, these gradients enhance particle drift. This drift plays a key role in determining the amplification characteristics of acoustic waves propagating through the semiconductor medium. To date, the combined effect of carrier-density gradients and the presence of nanoparticles on phonon–

plasmon coupling, and consequently on the propagation and gain properties of acoustic waves in NP-embedded inhomogeneous semiconductors, has not been systematically studied. Therefore, a comprehensive investigation of plasmon–phonon interactions in such inhomogeneous nanoparticle-embedded semiconductor plasmas is highly relevant.

2. Theoretical formulation

To investigate the influence of a density gradient on plasmon–phonon interactions in a nanoparticle (NP) embedded piezoelectric semiconductor plasma, specifically n-type CdS, we consider a metallic nanoparticle with an electron cloud of density n_{0n} embedded within the medium. The semiconductor is assumed to be subjected to an electrostatic field $\vec{E}_0$ along the negative z-direction, which causes the free electrons in the medium to drift with a velocity $\vec{v}_0$ in the positive z-direction. A density gradient ∇n_{0e} is also assumed along the z-axis, which may arise from nonuniform doping or uneven exposure to radiation, introducing inhomogeneity in the system.

When a density gradient ∇n_{0e} is present in the medium, the first-order momentum transfer equation can be expressed as:

$$\frac{\partial \vec{v}_1}{\partial t} + v_0 \frac{\partial \vec{v}_1}{\partial z} = \left(-\frac{e}{m}\right) E_1 - \nu v_1 - v_0^2 \frac{\partial}{\partial z}\left(\frac{n_1}{n_{0e}}\right). \tag{1a}$$

Assuming that all perturbations vary as $\exp[i(\omega t - kz)]$, we obtain:

$$[i(\omega - kv_0)\nu] v_z = \left(-\frac{e}{m}\right) E_z + i v_0^2 \left(\frac{n_1}{n_{0e}}\right) k\,. \tag{1b}$$

For the current field configuration, by solving the above equation in the quasistatic limit (i.e., $k^2 C_L^2 >> \omega^2$, where C_L is the speed of light in the material), the velocity of the free electrons in the medium can be expressed as:

$$v_{1z} = \frac{i(e/m)}{F_1(\omega,k)} E_z\,, \tag{2}$$

where $F_1(\omega,k) = \omega - kv_0 - i\nu - \dfrac{D\nu k^2(1+i\delta/k)}{\omega - kv_0(1-i\delta/k)}$

and $\delta = \nabla n_{0e}/n_{0e}$.

Equation (2) has been derived under the local approximation, assuming that $\vec{k}$ is independent of $\hat{z}$. This approximation is physically justified when the wavelength is much smaller than the density decay length δ^{-1} [7, 8]. Under this assumption, the resulting velocity $v_z = v_{1z} + v_{np}$ of electrons in the inhomogeneous medium can be expressed as:

$$v_z = i\left(\frac{e}{m}\right)\left[\frac{1}{F_1(\omega,k)} + \frac{\omega}{\omega^2 - \omega_{pn}^2/3}\right] E_z\,. \tag{3}$$

Here, $\omega_{pn} = \sqrt{\dfrac{e^2 n_{0n}}{m\varepsilon}}$ represents the plasma frequency of the electrons within the nanoparticle's electron cloud.

The continuity equation for the free electrons in the inhomogeneous semiconductor medium can be expressed as:

$$\frac{n_1}{n_{0e}} = \frac{v_z(k+i\delta)}{\omega - v_0(k-i\delta)}\,. \tag{4}$$

By combining Equations (3) and (4), the electron displacement in an inhomogeneous semiconductor containing a nanoparticle can be determined as:

$$D_z = \frac{-ien_{0e}v_z}{\omega - kv_0} = \frac{\varepsilon\omega_{pe}^2(1+i\delta/k)}{\omega - kv_0(1-i\delta/k)}\left[\frac{1}{F_1(\omega,k)} + \frac{\omega}{\omega^2 - \omega_{pn}^2/3}\right] E_z \tag{5}$$

Here, $\omega_{pe} = \sqrt{\dfrac{e^2 n_{0e}}{m\varepsilon}}$ denotes the plasma frequency of the free electrons in the semiconductor plasma medium.

By comparing Equation (5) with Equation (3) of Ref. [5], we obtain the dispersion relation describing the phonon–plasmon interaction in an inhomogeneous semiconductor plasma containing a nanoparticle as:

$$(\omega^2 - k^2 v_s^2)\left[1 - \frac{\omega_{pe}^2(1+i\delta/k)}{\omega - kv_0(1-i\delta/k)}\left(\frac{1}{F_1(\omega,k)} + \frac{\omega}{\omega^2 - \omega_{pn}^2/3}\right)\right] = K^2 k^2 v_s^2\,. \tag{6}$$

The right-hand side of Equation (6) includes $K^2 = \dfrac{\beta^2}{C\varepsilon}$, a dimensionless electromechanical coupling coefficient. In the case of a non-piezoelectric medium (i.e., $\beta = 0$), the coupling term disappears, resulting in two independent modes, which are:

$$(\omega^2 - k^2 v_s^2) = 0 \tag{7a}$$

$$\left[1 - \frac{\omega_{pe}^2(1+i\delta/k)}{\omega - kv_0(1-i\delta/k)}\left(\frac{1}{F_1(\omega,k)} + \frac{\omega}{\omega^2 - \omega_{pn}^2/3}\right)\right] = 0\,. \tag{7b}$$

Equation (7a) corresponds to the conventional acoustic mode propagating through an elastic medium, while Equation (7b) represents the electrokinetic mode, which is modified by the presence of a nanoparticle through the electron cloud plasma frequency ω_{pm} and the density gradient via the term δ. Following the method proposed by Steele and Vural [9], the dispersion relation (Equation 6) has been solved under the collision-dominated limit as:

$$\omega^2\left(1 - \frac{k^2 v_s^2}{\omega^2}\right)\left[1 - \frac{\omega_{pe}^2(1+i\delta/k)}{\omega - kv_0(1-i\delta/k)}\left(\frac{\omega - kv_0(1-i\delta/k)}{-i\nu[\omega - kv_0(1-i\delta/k)] - D\nu k^2(1+i\delta/k)} + \frac{\omega}{\omega^2 - \omega_{pn}^2/3}\right)\right] = K^2 k^2 v_s^2\,.$$

By applying the standard approximation $kv_s/\omega = 1 + i\alpha$, where $\alpha(<<1)$ is the gain per radian, we can rewrite the above equation as:

$$\omega^2\left(1-(1+i\alpha)^2\right)\left[1-\frac{\omega_{pe}^2(1+i\delta/k)}{\omega-kv_0(1-i\delta/k)}\left(\frac{\omega-kv_0(1-i\delta/k)}{-i\nu[\omega-kv_0(1-i\delta/k)]-D\nu k^2(1+i\delta/k)}+\frac{\omega}{\omega^2-\omega_{pn}^2/3}\right)\right]=K^2k^2v_s^2 .$$

Under the condition $\alpha << 1$, the above relation simplifies to:

$$-2i\alpha\left[1-\frac{\omega_{pe}^2(1+i\delta/k)}{\omega-kv_0(1-i\delta/k)}\left(\frac{\omega-kv_0(1-i\delta/k)}{-i\nu[\omega-kv_0(1-i\delta/k)]-D\nu k^2(1+i\delta/k)}+\frac{\omega}{\omega^2-\omega_{pn}^2/3}\right)\right]=K^2 .$$

Following rationalization and further mathematical simplifications, the gain per radian can be expressed as:

$$\alpha=\frac{K^2\omega_R(\omega\gamma-Dk\delta)}{\left[(\omega\gamma-Dk\delta)\left(1+\frac{\nu\omega_R}{\gamma X}\right)\right]^2+\left[\omega_R+Dk^2\delta\left(1+\frac{\nu\omega_R}{\gamma X}\right)\right]^2}, \qquad (8)$$

where $\omega_R=\frac{\omega_{pe}^2}{\nu}$, $\gamma=\frac{v_0}{v_s}-1$, $X=\omega^2-\omega_{pn}^2/3$.

In the above equation, the term X represents the influence of the nanoparticle on the acoustic gain α, as it depends on the plasma frequency ω_{pn} of the nanoparticle's electron cloud, while δ accounts for the effect of the medium's inhomogeneity.

3. Result and discussion

To numerically analyze the acoustic gain characteristics in an inhomogeneous piezoelectric semiconductor medium doped with a nanoparticle, we consider n-type CdS at 300 K with the following physical parameters: $m_e = 0.17m_0$, $\varepsilon_l = 9.35$, $\beta = 0.21$ C/m^2, $\mu = 0.035$ m^2/V/s, $\rho = 4820$ kg/m^3.

Using parameters listed above in Eq. (8), the dependence of acoustic gain α on the velocity ratio v_0/v_s, wave frequency ω, and carrier density n_{0e} for piezoelectric, inhomogeneous n-type CdS at room temperature has been evaluated numerically and is illustrated graphically in Figures 1 through 6.

Figure 1 illustrates the variation of acoustic gain α\alphaα with the velocity ratio v_0/v_s in the presence of a nanoparticle for different values of the density gradient δ. From the curves, it can be observed that for δ = 0 (homogeneous medium), the crossover point for acoustic wave amplification occurs at a velocity ratio of unity, consistent with the experimentally established condition for gain. Consequently, in this scenario, acoustic waves experience attenuation when the velocity ratio is below unity. However, introducing inhomogeneity into the medium shifts the crossover point to values greater than unity. The figure also shows that increasing the inhomogeneity decreases the magnitude of the acoustic gain while simultaneously raising the crossover value for amplification.

Figure 2 depicts the dependence of gain per radian α\alphaα on the velocity ratio v_0/v_s for both the presence and absence of a nanoparticle at δ = 100. It is observed that the inclusion of a nanoparticle enhances the acoustic gain. In both cases, the crossover point for amplification shifts above unity (v_0/v_s = 1.2), indicating that electrons in the medium require a higher drift velocity to achieve acoustic wave amplification. Additionally, the presence of a nanoparticle reduces the rate at which the acoustic gain increases with the velocity ratio v_0/v_s.

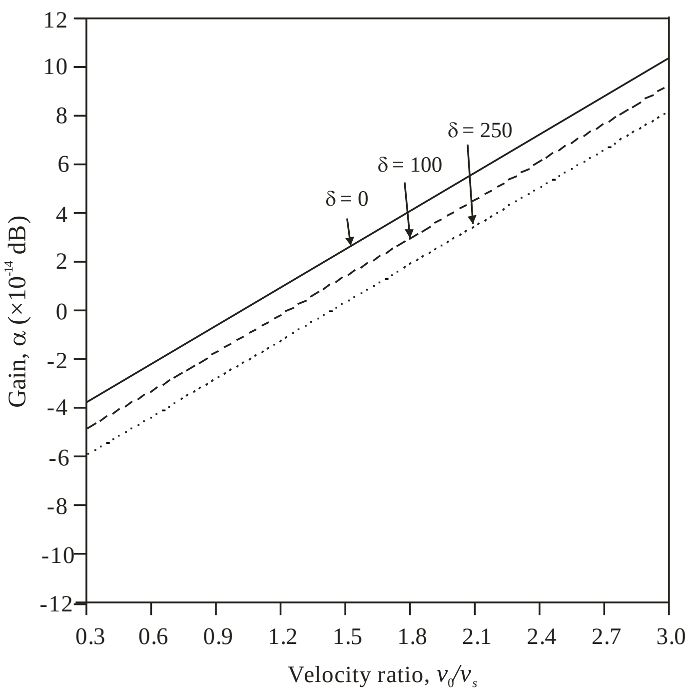

Figure 1: Acoustic gain α as a function of the velocity ratio v_0/v_s in the presence of a nanoparticle at $\omega = 5\times10^7$ s^{-1} and $n_{0e} = 10^{18}$ m^{-3}.

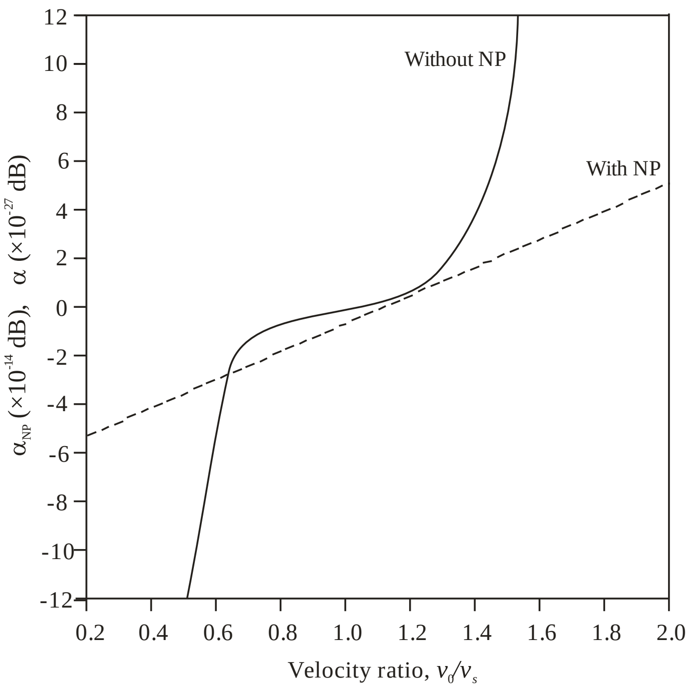

Figure 2: Dependence of acoustic gain α on the velocity ratio v_0/v_s at δ = 100, $\omega = 5\times10^7$ s^{-1}, and $n_{0e} = 10^{18}$ m^{-3}.

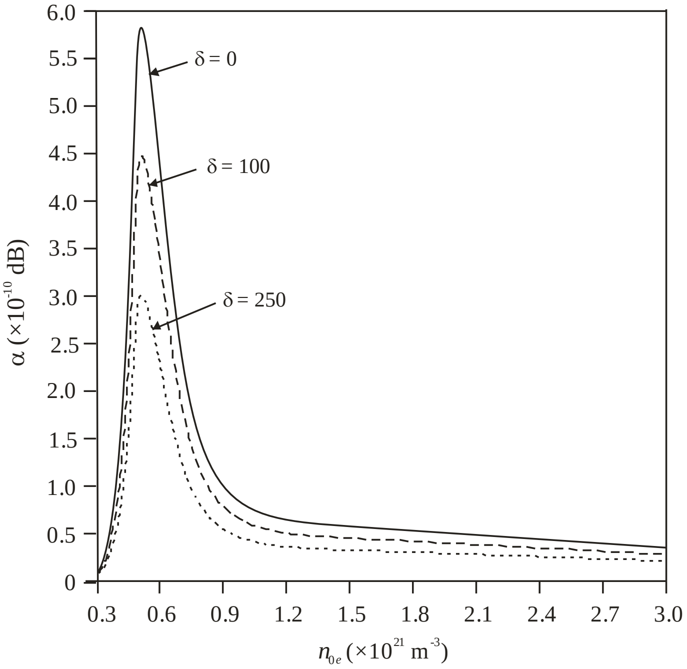

Figure 3: Variation of acoustic gain α with free electron density n_{0e} in the presence of a nanoparticle at $\omega = 5\times10^{7}\ s^{-1}$ and $v_0/v_s = 1.944$.

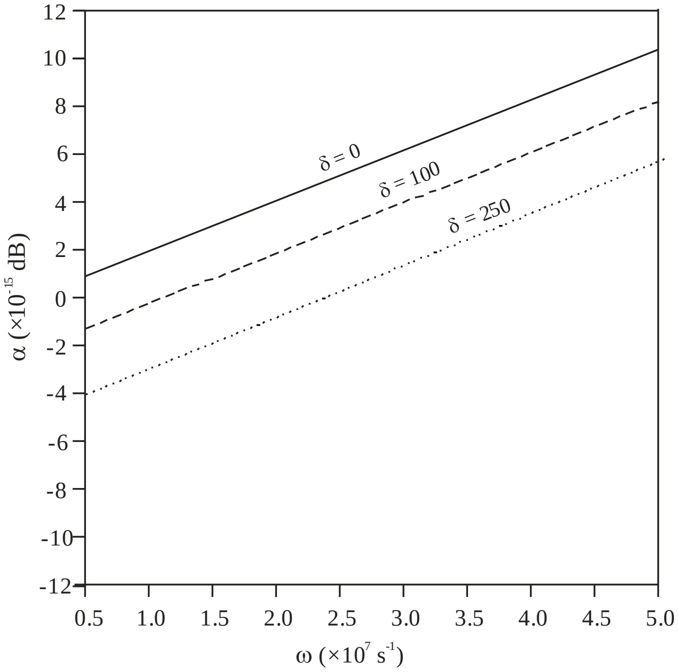

Figure 5: Acoustic gain α as a function of wave frequency ω in the presence of a nanoparticle at $n_{0e} = 10^{24}\ m^{-3}$ and $v_0/v_s = 1.944$.

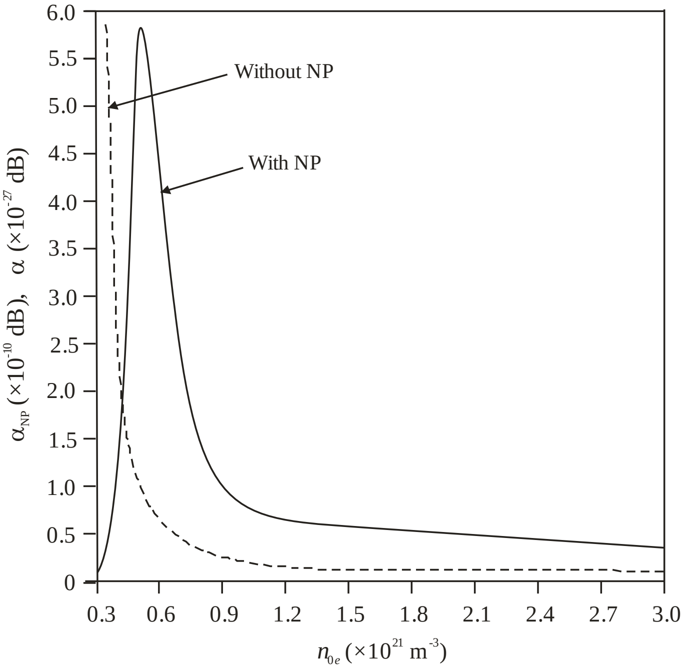

Figure 4: Dependence of acoustic gain α on carrier density n_{0e} at δ = 100, $\omega = 5\times10^{7}\ s^{-1}$, and $v_0/v_s = 1.944$.

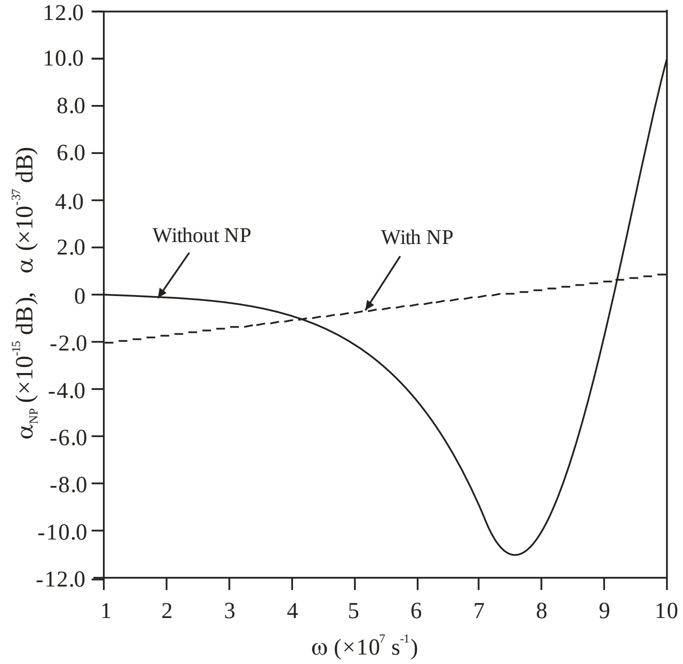

Figure 6: Variation of acoustic gain α with wave frequency ω at δ = 100, $n_{0e} = 10^{24}\ m^{-3}$, and $v_0/v_s = 1.944$.

Figure 3 illustrates the variation of acoustic gain α\alphaα with the free electron density n_{0e} in the presence of a nanoparticle for different values of the density gradient δ. The results indicate that the acoustic gain increases rapidly in the low-density regime, reaching a maximum around $n_{0e} \approx 0.43\times10^{21}\ /m^3$. Beyond this point, further increases in electron density lead to a sharp decrease in gain, which eventually vanishes at higher densities, suggesting enhanced stability of the plasma wave at elevated electron concentrations. The curves also show that higher values of δ correspond to a lower maximum gain, indicating that increasing inhomogeneity reduces the achievable peak amplification.

Figure 4 depicts the dependence of gain per radian α on the free electron density n_{0e} at δ = 100, both in the presence and absence of a nanoparticle. It is observed that embedding a nanoparticle in the medium enhances the acoustic gain. In the presence of a nanoparticle, the gain exhibits a trend similar to that shown in Figure 3 for δ = 100. In contrast, when no nanoparticle is present, the acoustic gain reaches its maximum at a lower electron density and then decreases sharply, eventually dropping to zero at higher n_{0e} values.

Figure 5 illustrates the variation of acoustic gain α\alphaα with wave frequency ω in the presence of a nanoparticle for different values of the density gradient δ. In all three cases, the acoustic gain increases approximately linearly with ω. For a homogeneous medium (δ = 0), the acoustic mode is amplified across the entire frequency range considered. As the inhomogeneity of the medium increases, the threshold frequency at which amplification begins also rises. Specifically, for $\delta = 100$, amplification occurs for $\omega > 9.5\times10^6$ s^{-1}, while for $\delta = 250$, amplification is observed only for $\omega > 2.39\times10^7$ s^{-1}. The figure further shows that higher inhomogeneity reduces the overall magnitude of acoustic gain, indicating that the density gradient exerts a stabilizing effect on the propagating acoustic wave.

Figure 6 presents a comparative analysis of acoustic gain in the presence and absence of a nanoparticle at $\delta = 100$. When no nanoparticle is present, the acoustic mode undergoes attenuation for $\omega \leq 9.4\times10^6$ s^{-1}. The attenuation coefficient increases with angular frequency up to $\omega > 7.5\times10^6$ s^{-1}, after which it begins to decrease, reaching zero at $\omega \approx 9.4\times10^6$ s^{-1}. Beyond this frequency, the acoustic mode becomes amplifying, with the amplification coefficient increasing as ω rises. In contrast, when a nanoparticle is embedded within the medium, the acoustic mode experiences attenuation across the entire frequency range, with the attenuation coefficient decreasing linearly with increasing frequency.

4. Conclusion

This study focused on the phonon-plasmon interactions in an inhomogeneous semiconductor medium embedded with a nanoparticle. The primary objective was to examine how the presence of a nanoparticle and medium inhomogeneity, represented by a density gradient, affect the acoustic gain characteristics. The acoustic gain was analyzed as a function of the velocity ratio v_0/v_s, wave frequency ω, and free electron density n_{0e} of the semiconductor. For the velocity ratio, it was observed that the nanoparticle shifts the attenuation-to-amplification crossover point from $v_0/v_s = 1$ to a higher value. Regarding carrier density, the presence of a nanoparticle broadens the gain spectrum and enhances the overall magnitude of acoustic gain. The density gradient also plays a significant role: it shifts the crossover point to higher velocity ratios and reduces the peak gain value. While the position of the maximum gain remains largely unaffected by the density gradient, the gain magnitude at that point decreases. Overall, both the nanoparticle and inhomogeneity exhibit notable effects on the acoustic gain profile, indicating their potential as control parameters for tuning wave amplification in semiconductor plasmas.

The frequency-dependent analysis indicates that inhomogeneity in the medium restricts the range of frequencies over which acoustic amplification can occur. This study demonstrates that both the presence of a nanoparticle and the density gradient in the semiconductor significantly enhance the resonant interaction between acoustic phonons and the modified plasmon mode. These findings provide valuable insights into the fundamental mechanisms of phonon-plasmon interactions in inhomogeneous semiconductor media and may serve as a basis for further exploration and applications.

References

[1] J.M. Zide, D.O. Klenov, S. Stemmer, A.C. Gossard, G. Zeng, J.E. Bowers, D. Vashaee, A. Shakouri, Thermoelectric power factor in semiconductors with buried epitaxial semimetallic nanoparticles, *Appl. Phys. Lett*. **87** (2005) 112102.

[2] B.D. Schultz, C.J. Palmstrom, Embedded assembly mechanism of stable metal nanocrystals on semiconductor surfaces, *Phys. Rev. B* **73** (2006) 241407(R).

[3] J.K. Kawasaki, R. Timm, K.T. Delaney, E. Lundgren, A. Mikkelsen, C.J. Palmstrom. Local density of states and interface effects in semimetallic ErAs nanoparticles embedded in GaAs, *Phys. Rev. Lett*. **107** (2011) 036806.

[4] K.K. Choudhary, Phonon scattering mechanism for size-dependent thermoelectric properties of Bi_2Te_3 nanoparticles, *J. Nanopart. Res*. **15** (2013) 1362.

[5] P. Dubey, S. Ghosh, Modified longitudinal phonon-plasmon interactions in nanoparticle doped piezoelectric semiconductors, *Acta Acust. United Ac* **102** (2016) 436-440.

[6] S. Ghosh, P. Dubey, Phonon-plasmon interactions in piezoelectric semiconductors doped with a nanoparticle (NP) cluster, *Int. J. Mod. Sci. Eng. Tech*. **2** (2015) 28-34.

[7] M. Singh, A. Sangwan, Sanjay, M. Singh, Parametric oscillation of acoustical phonon mode in magnetized doped III–V semiconductors, *J. Opt*. **50** (2021) 209–222.

[8] J. Gahlawat, M. Singh, S. Dahiya, Piezoelectric and electrostrictive contributions to optical parametric amplification of acoustic phonons in magnetized doped III–V semiconductors, *J. Optoelectron. Adv. Mater*. **23** (2021) 183–192.

[9] M.C. Steele, B. Vural: *Wave Interactions in Solid State Plasmas*, Mc-Graw Hill, New York (1969) pp. 136-140.

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