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Longitudinal Phonon-Plasmon Interactions in Nanoparticle Doped Piezoelectric Semiconductors: Effect of Density Gradient

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Summary
Nanoparticle embedded semiconductors are nowadays becoming friendlier to material scientists because of being useful for processing new materials used in fabrication of advanced nano-electronic devices. Researchers are concentrating especially over thermal properties of these materials. But acoustical properties are also very important parameter to be studied. Hence we have presented our study of acoustical spectra in an inhomogeneous semiconductor embedded with a single nanoparticle. We have used macroscopic model of piezoelectric media and fluid model of plasmas to derive the dispersion relation. The effect of density gradient and presence of nanoparticle on acoustic wave gain has been reported with varying velocity ratio ϑ_0/ϑ_s, medium carrier density η_{0e} and wave frequency ω. The attenuation to amplification crossover point $\vartheta_0/\vartheta_s = 1$ is found to be greatly altered due to density gradient of the medium whereas it is found independent of the presence of nanoparticle. The density gradient in the medium shifts the crossover point to higher velocity ratio and reduces the gain magnitude.

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1. Introduction

Nanoparticle (NP) embedded semiconductor structure is becoming one of the most fascinating and active areas of research. There are numerous theoretical and experimental reports on the growing mechanism and the noticeable modifications in physical and chemical properties of these materials. Zide *et al.* [1] have grown composite epitaxial materials that consist of semimetallic ErAs NPs embedded in a semiconducting In0.53Ga0.47As matrix. They found that the presence of these particles increases the free electron concentration in the material while maintaining relatively high mobilities. Theoretically calculated Seebeck coefficients are found in reasonable agreement with experimentally measured ones for several sample structures. They suggested that embedded metallic NPs in a semiconductor matrix can serve as a building block for creating efficient thermoelectric materials. Schultz and Palmtrom [2] have grown ErAs on GaAs surfaces that occurred by an embedded growth mode. They have shown that the surface morphologies obtained from their growth mode depend on structural differences, thermodynamics and diffusion properties. Kawasaki *et al.* [3] have examined the atomic and electronic structures of ErAs NPs embedded within GaAs matrix via cross sectional tunneling microscopy and spectroscopy. They found that the local density of states exhibits a finite minimum at the Fermi level, demonstrating that the NPs remain semimetallic despite the predictions of previous models of quantum confinement in ErAs. A theoretical analysis on thermoelectric figure of merit enhanced by nanostructuring of thermoelectric materials was presented by Choudhary [4]. He has reported significant modifications in all thermal parameters of the system due to embedded NPs.

From the above discussed reports, it is clear that, NP embedded semiconductor is an appealing medium to be considered for detailed study. This kind of media is useful for processing new materials to fabricate improved nanoelectronic devices and hence, becoming friendlier to material scientists. Previously, following the same idea, we have reported longitudinal phonon-plasmon interactions in piezoelectric semiconductors embedded with a single [5, hereafter referred as paper I] and a group of NPs [6]. We obtained acoustic gain only when the ratio of drift velocity to acoustic velocity ϑ_0/ϑ_s is greater than one. This attenuation to amplification crossover point ($\vartheta_0/\vartheta_s \approx 1$) is found independent of the presence of NP. We found interesting modifications in acoustic gain characteristics due to the presence of NPs within the homogeneous semiconductor plasma medium. These modifications may be attributed to the resulted restoring force due to the displacement in the electron cloud of NPs. Under the influence of an external electric field, electrons from the cloud start collective oscillations identical to plasma oscillations of free electrons of homogeneous semiconductor media. This effect is responsible to modify the spring constant and therefore leads to a modified plasma frequency.

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It is well established observation that under several field configurations complete homogeneity of a plasma system cannot be achieved due to the applied external forces. On the other side, the inhomogeneity may be induced in a material by nonuniform doping or by exposing it to nonuniform radiation. Experimentally, it is very difficult to grow a complete homogeneous semiconductor. Now, if the system has gradients of density, temperature, pressure, magnetic field etc. a plasma current or a particle drift exists; otherwise in the presence of electrostatic field, the gradients enhance the particle drift. This particle drift is the only parameter which actually decides the amplification characteristics of the acoustic wave propagating through a semiconductor medium. We found that the problem of how the carrier-density gradient and presence of NP influence the coupling of phonon and plasmon, and therefore the propagation and gain characteristics of acoustic wave in NP embedded inhomogeneous semiconductors has not been reported yet. Thus, it is pertinent to make a detailed and systematic analysis of plasmon-phonon interactions in the inhomogeneous semiconductor plasma embedded with a NP.

2. Theoretical formulation

To study the possible signature of density gradient on plasmon-phonon interactions in a NP embedded piezoelectric semiconductor plasma medium (n-CdS), we consider a metallic NP of electron cloud density η_{0n} to be present within the medium. We assume that the medium is subjected to an electrostatic field $\vec{E}_0$ (along negative z-direction) due to which free electrons of the medium get drifted with velocity $\vec{\vartheta}_0$ along the positive z-direction. The density gradient ∇n_{0e} is taken in the z-direction which could be induced in the medium by nonuniform doping or by exposing it to nonuniform radiation.

In presence of density gradient ∇n_{0e} in the medium, the first order momentum transfer equation may be written as

$$\frac{\partial \vartheta_1}{\partial t} + \vartheta_0 \frac{\partial \vartheta_1}{\partial z} = \Big(-\frac{e}{m}\Big)E_1 - \nu\vartheta_1 - \vartheta_0^2 \frac{\partial}{\partial z}\Big(\frac{n_1}{n_{0e}}\Big). \tag{1a}$$

Considering that all perturbations vary as $\exp[\mathrm{i}(\omega t - kz)]$, we get

$$\big[\mathrm{i}\big(\omega - k\vartheta_0\big)\nu\big]\vartheta_z = \Big(-\frac{e}{m}\Big)E_z + \mathrm{i}\vartheta_0^2\Big(\frac{n_1}{n_{0e}}\Big)k. \tag{1b}$$

For present field geometry, on solving above equation under quasistatic limit (i.e., $k^2C_L^2 \gg \omega^2$, C_L is speed of light in the material) we may obtain the velocity of free electrons of the medium as

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

where

$$F_1(\omega, k) = \omega - k\vartheta_0 - \mathrm{i}\nu - \frac{D\nu k^2(1 + \mathrm{i}\delta/k)}{\omega - k\vartheta_0(1 - \mathrm{i}\delta/k)}$$

and

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

We have derived equation (2) under local approximation by assuming $\vec{k}$ independent of $\hat{z}$. This approximation is physically valid when wavelength is much smaller than density decay length δ^{-1} [7, 8]. Now, the resultant velocity $\vartheta_z = \vartheta_{1z} + \vartheta_{np}$ of electrons present within the inhomogeneous medium may be obtained as

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

in which $\omega_{pn} = \sqrt{e^2 n_{0n}/m\varepsilon}$ is the plasma frequency of electrons present within the nanoparticle cloud.

The continuity equation for free electrons of the inhomogeneous semiconductor medium may be written as

$$\frac{n_1}{n_{0e}} = \frac{\vartheta_z(k + \mathrm{i}\delta)}{\omega - \vartheta_0(k - \mathrm{i}\delta)}. \tag{4}$$

Using equations (3) and (4), one may deduce electron displacement in inhomogeneous semiconductor embedded with a NP as

$$\begin{aligned} D_z &= \frac{-\mathrm{i}en_{0e}\vartheta_z}{\omega - k\vartheta_0} \\ &= \frac{\varepsilon\omega_{pe}^2(1 + \mathrm{i}\delta/k)}{\omega - k\vartheta_0(1 - \mathrm{i}\delta/k)}\left[\frac{1}{F_1(\omega, k)} + \frac{\omega}{\omega^2 - \omega_{pn}^2/3}\right]E_z. \end{aligned} \tag{5}$$

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

Comparing equation (5) with equation (3) pf paper I, we obtain the dispersion relation that represent the phonon-plasmon interaction in inhomogeneous semiconductor plasma embedded with a NP as

$$\begin{aligned} \big(\omega^2 - k^2\vartheta_s^2\big)\Bigg[1 - \frac{\omega_{pe}^2(1 + \mathrm{i}\delta/k)}{\omega - k\vartheta_0(1 - \mathrm{i}\delta/k)} \\ \cdot\left(\frac{1}{F_1(\omega, k)} + \frac{\omega}{\omega^2 - \omega_{pn}^2/3}\right)\Bigg] = K^2k^2\vartheta_s^2. \end{aligned} \tag{6}$$

The R.H.S. contains $K^2 = \beta^2/C\varepsilon$, which is a dimensionless electro-mechanical coupling coefficient. If the medium is non-piezoelectric (i.e., $\beta = 0$), the coupling in equation (6) vanishes resulting in two independent modes, those are

$$\omega^2 - k^2\vartheta_s^2 = 0, \tag{7a}$$

$$\begin{aligned} \Bigg[1 - \frac{\omega_{pe}^2(1 + \mathrm{i}\delta/k)}{\omega - k\vartheta_0(1 - \mathrm{i}\delta/k)} \\ \cdot\left(\frac{1}{F_1(\omega, k)} + \frac{\omega}{\omega^2 - \omega_{pn}^2/3}\right)\Bigg] = 0. \end{aligned} \tag{7b}$$

Equation (7a) represents a usual sound mode propagating through an elastic medium and equation (7b) represents the electrokinetic mode modified due to the presence of a NP within the host material via electron cloud plasma frequency (ω_{pn}) and density gradient via term δ. Following the procedure adopted by Steele and Vural [9], we have

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solved the dispersion relation (Equation 6) under collision dominated limit as

$$\omega^2\left(1-\frac{k^2\vartheta_s^2}{\omega^2}\right)\left[1-\frac{\omega_{pe}^2(1+\mathrm{i}\delta/k)}{\omega-k\vartheta_0(1-\mathrm{i}\delta/k)}\cdot\left(\frac{\omega-k\vartheta_0(1-\mathrm{i}\delta/k)}{-\mathrm{i}\nu[\omega-k\vartheta_0(1-\mathrm{i}\delta/k)]-D\nu k^2(1+\mathrm{i}\delta/k)}+\frac{\omega}{\omega^2-\omega_{pn}^2/3}\right)\right]=K^2k^2\vartheta_s^2.$$

Using the standard approximation $k\vartheta_s/\omega = 1+\mathrm{i}\alpha$, where α ($\ll 1$) is gain per radian we obtain from above equation,

$$\omega^2\left(1-(1+\mathrm{i}\alpha)^2\right)\left[1-\frac{\omega_{pe}^2(1+\mathrm{i}\delta/k)}{\omega-k\vartheta_0(1-\mathrm{i}\delta/k)}\cdot\left(\frac{\omega-k\vartheta_0(1-\mathrm{i}\delta/k)}{-\mathrm{i}\nu[\omega-k\vartheta_0(1-\mathrm{i}\delta/k)]-D\nu k^2(1+\mathrm{i}\delta/k)}+\frac{\omega}{\omega^2-\omega_{pn}^2/3}\right)\right]=K^2k^2\vartheta_s^2.$$

Since $\alpha \ll 1$, the above relation reduces to

$$-2\mathrm{i}\alpha\left[1-\frac{\omega_{pe}^2(1+\mathrm{i}\delta/k)}{\omega-k\vartheta_0(1-\mathrm{i}\delta/k)}\cdot\left(\frac{\omega-k\vartheta_0(1-\mathrm{i}\delta/k)}{-\mathrm{i}\nu[\omega-k\vartheta_0(1-\mathrm{i}\delta/k)]-D\nu k^2(1+\mathrm{i}\delta/k)}+\frac{\omega}{\omega^2-\omega_{pn}^2/3}\right)\right]=K^2.$$

After rationalization and some mathematical simplifications, we obtain the expression for gain per radian as

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

where $\omega_R = \omega_{pe}^2/\nu$, $\gamma = \vartheta_0/\vartheta_s - 1$, $X = \omega^2 - \omega_{pn}^2/3$.

The term X in the above equation stands for the effect of NP on the acoustic gain α, as it contains the plasma frequency ω_{pn} of the electron cloud of the NP, whereas δ corresponds to the effect of inhomogeneity of the medium.

3. Results and discussion

In order to have numerical appreciation of the acoustic gain characteristic in an inhomogeneous piezoelectric semiconductor medium, doped with a NP, we have considered n-CdS at 300 K with the following set of physical parameters:

$$m_e = 0.17m_0, \quad \varepsilon_l = 9.35, \quad \beta = 0.21\,\mathrm{C/m^2},$$
$$\mu = 0.035\,\mathrm{m^2/V/s}, \quad \rho = 4820\,\mathrm{kg/m^3}.$$

Using the physical parameters listed above in the expression given by equation (8); the velocity ratio ϑ_0/ϑ_s, wave frequency ω and carrier density n_{0e} dependency of the acoustic gain α for the piezoelectric inhomogeneous n-CdS semiconductor at room temperature have been estimated numerically and are presented graphically in Figures 1 to 6.

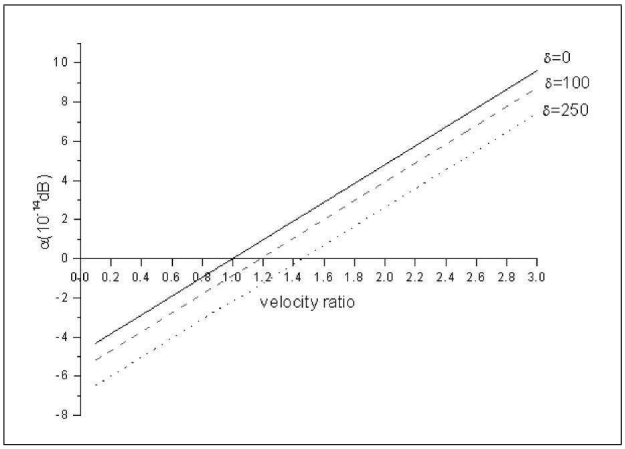


Figure 1. Variation of gain with velocity ratio ϑ_0/ϑ_s, in presence of NP at $\omega = 5\cdot 10^7$ /s and $n_{0e} = 10^{18}$ /m^3.

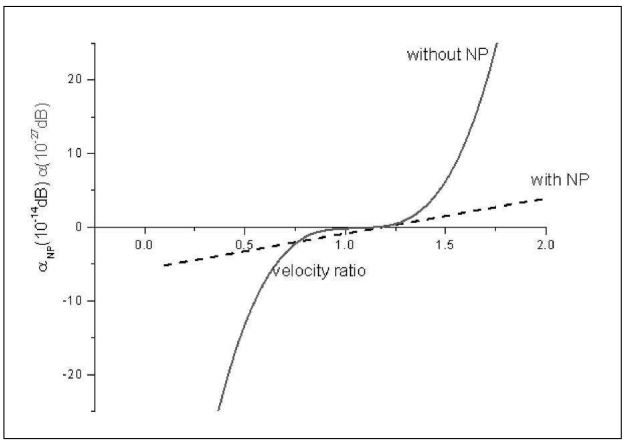


Figure 2. Variation of gain with velocity ratio ϑ_0/ϑ_s, at $\delta = 100$, $\omega = 5\cdot 10^7$ /s and $n_{0e} = 10^{18}$ /m^3.

Figure 1 displays the variation of acoustic gain with velocity ratio ϑ_0/ϑ_s in the presence of a NP at different values of the density gradient δ. It may be inferred from the curves that at $\delta = 0$ (for homogeneous medium), the crossover value for acoustic wave amplification is equal to unity, which is in agreement with the experimentally obtained necessary condition for gain. Similar qualitative observation has also been obtained from Figure 1 of paper I. Thus, in this case also, the acoustic wave will suffer attenuation at a velocity ratio less than unity. But, since we have introduced an inhomogeneity in the medium, the cross over value for the acoustic gain becomes greater than unity. Figure also reflects that the increase in inhomogeneity within the medium results in a decreasing magnitude of the acoustic gain and increasing value of the cross over point for gain.

Figure 2 shows the dependence of gain per radian α on the velocity ratio at ϑ_0/ϑ_s in the presence as well as ab-

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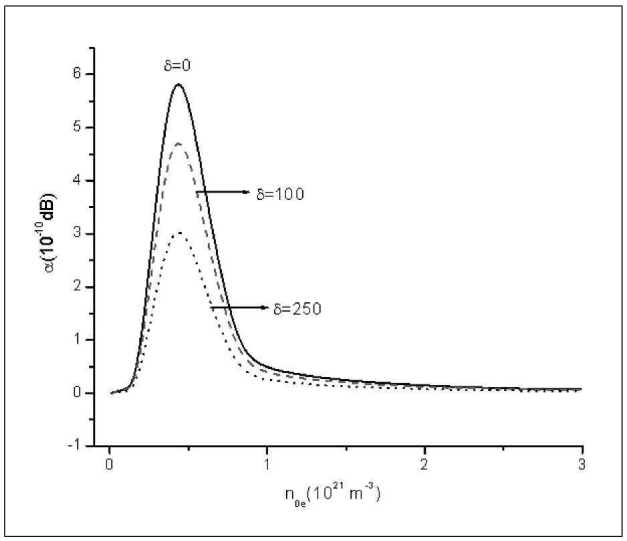


Figure 3. Variation of gain with carrier density n_{0e}, in presence of NP at $\omega = 5 \cdot 10^7$ /s and $\vartheta_0/\vartheta_s = 1.944$.

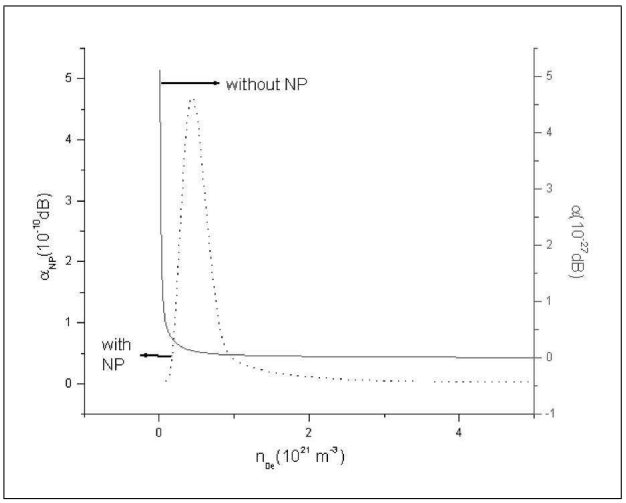


Figure 4. Variation of gain with carrier density n_{0e}, at $\delta = 100$, $\omega = 5 \cdot 10^7$ /s and $\vartheta_0/\vartheta_s = 1.944$.

sence of the NP at $\delta = 100$. The presence of a NP is found to increase the acoustic gain. The cross over point for acoustic gain exceeds from unity ($\vartheta_0/\vartheta_s = 1.2$) in both the physical conditions, that is, medium electrons will require higher drift velocity to generate acoustic wave amplification. The presence of a NP within the medium is found to reduce the rate of increment of acoustic gain with the velocity ratio ϑ_0/ϑ_s.

Figure 3 shows the variation of acoustic gain α with the free electron density n_{0e} in the presence of a NP at different values of density gradient δ. As observed, the acoustic gain suffers a rapid increase in the low density regime and has a maximum at $n_{0e} \approx 0.43 \cdot 10^{21}$ /m^3. With further increase in the free electron density, the acoustic gain reduces sharply and vanishes at higher values of the electron density. This establishes that, at higher electron densities, the plasma wave becomes more stable. Curves also reveal that, the maximum gain is found to be lower for higher values of δ, that is, an increase in inhomogeneity decreases the magnitude of achievable maximum gain. Figure 4, shows the dependence of gain per radian α on n_{0e} at $\delta = 100$ in presence and absence of the NP. It is observed that the presence of a NP enhances the acoustic gain. When a NP is present within the medium, the gain shows the same variation as that of Figure 3 at $\delta = 100$. While, in the absence of the NP the acoustic gain acquires a maximum at lower values of n_{0e}, it falls down abruptly and reaches zero value at higher electron densities.

The nature of the variation of the acoustic gain (in the presence of a NP) against wave frequency ω at different values of δ, is shown in Figure 5. In all three curves, the acoustic gain is found to be a linearly increasing function of the wave frequency ω. It is found that, when the medium is homogenous ($\delta = 0$), the acoustic mode is amplified throughout the frequency range under consideration. As inhomogeneity in the medium increases, the wave frequency at which acoustic mode starts amplifying, also

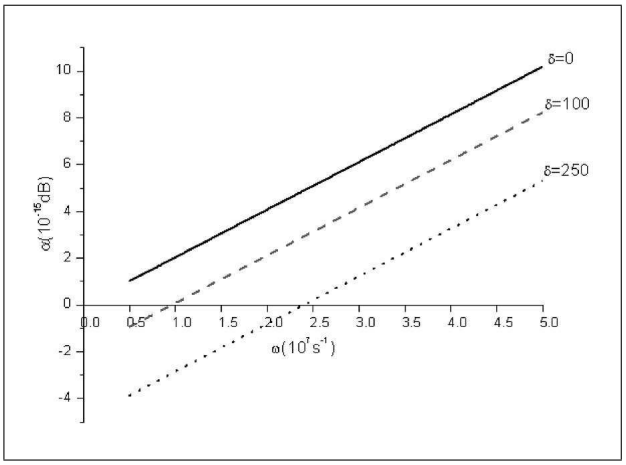


Figure 5. Variation of gain with wave frequency ω, in presence of NP at $n_{0e} = 10^{24}$ /m^3 and $\vartheta_0/\vartheta_s = 1.944$.

increases. At $\delta = 100$, acoustic mode becomes amplified when $\omega > 9.5 \cdot 10^6$/s whereas at $\delta = 250$ acoustic wave amplification occurs at $\omega > 2.39 \cdot 10^7$/s. The figure also reveals that, for higher inhomogeneity in the medium, lesser is the magnitude of acoustic mode amplification. Thus, the inhomogeneity induces a stability effect on the propagating acoustic wave.

Figure 6 shows a comparative plot of the acoustic gain in presence and absence of a NP at $\delta = 100$. In the absence of a NP, the acoustic mode is found to be attenuating for $\omega \leq 9.4 \cdot 10^6$/s. Its attenuation coefficient increases with angular frequency upto $\omega \approx 7.5 \cdot 10^6$/s. For $\omega > 7.5 \cdot 10^6$/s the attenuation coefficient starts decreasing to achieve zero value at $\omega \approx 9.4 \cdot 10^6$/s. Beyond $\omega \approx 9.4 \cdot 10^6$/s, the acoustic mode starts amplifying and its amplification coefficient increases with wave frequency ω. However, in the presence of a NP within the medium, the acoustic mode suffers attenuation with linearly decreasing attenuation coefficient throughout the frequency range considered here.

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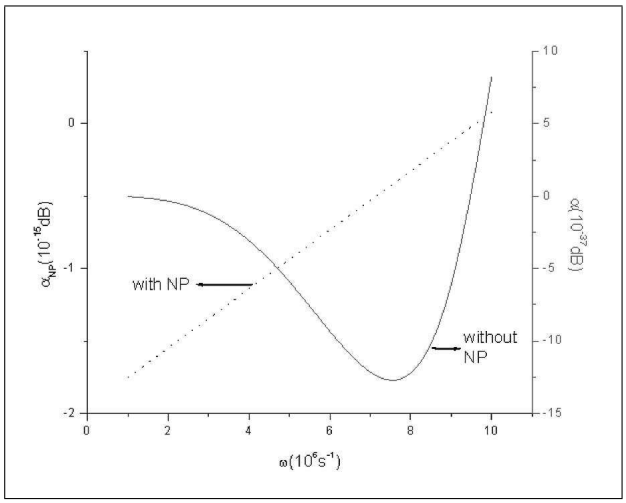


Figure 6. Variation of gain with wave frequency ω, at $\delta = 100$, $n_{0e} = 10^{24}/\mathrm{m}^3$ and $\vartheta_0/\vartheta_s = 1.944$.

4. Conclusion

The present report dealt with the phonon-plasmon interaction in inhomogeneous semiconductor medium embedded with a NP. Hence, the influence of the presence of a NP in the medium and an inhomogeneity through the density gradient on the acoustic gain characteristics was the main aim of this report. The dependencies of the acoustic gain characteristics are studied on the velocity ratio ϑ_0/ϑ_s, wave frequency ω and free electron density n_{0e} of the semiconductor medium. In the case of the velocity ratio, we found that, the NP shifts the attenuation to amplification cross-over point from $\vartheta_0/\vartheta_s = 1$ to a higher value (> 1). The width of the gain spectrum in terms of the electron density n_{0e} is extended by the presence of a NP. The NP is also found to be responsible for enhancement of the acoustic gain magnitude. The density gradient parameter has a remarkable and a favourable influence on the acoustic gain spectrum. With the inhomogeneity, the cross-over point shifts towards higher velocity ratio and the gain shifts to a lower value. The characteristic in terms of carrier density reveals that the maximum gain point remains unaffected but the gain magnitude at this point is reduced by the presence of the density gradient.

The frequency dependency reveals that the presence of an inhomogeneity imposes a restriction on the frequency range in which one may get acoustic amplification. This investigation establishes the fact that the presence of a NP and density gradient in the semiconductor medium are responsible for strong resonant interaction between acoustic phonon and modified plasmon mode. We hope that these results would be helpful in understanding the basic phonon- plasmon interaction phenomena in inhomogeneous media.

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