Acoustic wave amplification in ion-implanted piezoelectric semiconductor

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An analytical study on excitation of acoustic waves and novel properties introduced by considering that the implanted ions in a group III-V crystal agglomerate to form nanoclusters (NCs) and some of them acquire negative charge in compensated piezoelectric semiconductor plasma has been presented. By using multi-fluid analysis and Maxwell’s equations, a compact dispersion relation for the acoustic wave in a piezoelectric semiconductor has been derived. It is found that the presence of charged NCs not only modifies the wave spectrum but also alters the amplification characteristics even though NCs, on account of their heavy masses, are assumed to be stationary in the background.

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1 Introduction

Recently, there has been much interest on the study of linear and non-linear optical properties of nanoclusters (NCs) of implanted ions in solids. These NCs can be formed by ion-implantation process within the host material. The shape and size of these NCs are determined by various factors such as ion-influence, damage caused to the host material lattice by the ion-implantation etc. The presence of this additional component i.e. NCs inside the material introduces some unique potential structures and alters the properties and dispersion characteristics of various waves produced in it. In the last decade, the NCs formation of metal ions such as Ag⁺, Cu⁺, Fe⁺ etc. by ion-implantation techniques in SiO₂ glasses has been carried out in a number of laboratory experiments. It is found that the implantation of metal ions in the host material would modify its high magnetic coercivity, nonlinear optical properties etc. These metallic NCs buried in glasses are promising bistable materials which make them potentially attractive candidates for device applications in the various fields including photonics, nonlinear optics, optoelectronics etc.

On the other hand, semiconductors are doped with impurities mainly to change its electrical properties. Among doping techniques, ion-implantation has proved to be very promising and is used for almost all kinds of doping in semiconductor integrated circuits. The main advantages of ion-implantation over the other techniques such as diffusion are the large range of doses, extremely accurate dose control, wide choice of masking the target material as well as its processing temperatures. The principle side effect of ion-implantation is that it damages the crystal lattice. An appropriate annealing process such as thermal annealing or laser annealing could repair this damage, which allows the lattice bonds to form again resulting into re-crystallization.

The implanted ions within the semiconductor may also form NCs. Moreover, it may be possible that the NCs present in semiconductors usually acquire negative charge due to high mobility of electrons in comparison to positively charged holes. As a result, the balance of charge is altered by the presence of NCs in otherwise compensated medium and a charge imbalance parameter δ comes into play. The charging of NCs causes depletion of species (electrons in this case) of higher mobility, however, the ratio of number density of electrons to that of holes cannot be, in general, less than the square root of the ratio of their effective masses i.e.

\[ \delta = \frac{n_{be}}{n_{bh}} \geq \left( \frac{m_e}{m_h} \right)^{1/2} \]

This has diverted the attention of researchers in the recent years towards this new medium. This diverted attention aims towards two sub-fields namely Coulomb crystal formation and wave spectrum analysis in these media. Recently, Salimullah10 predicated, first time, the possible Coulomb crystal formation in piezoelectric semiconductors. Later in the same medium, the role of electron-phonon

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coupling in the formation of plasma crystal was also reported\cite{11}. But very few reports are available in the literature on wave spectrum analysis\cite{12,13}. This present status has motivated the researchers in this field. In the present paper, the choice of the acoustic wave stems from the fact that the interaction between electrons and acoustic vibrations is one of the fundamental interaction processes in solids. This interaction gives useful information regarding the band structure of the host medium. The amplification of acoustic waves by the application of $dc$ electric field has been commercially exploited for the fabrications of delay-lines, acousto-electric amplifiers, oscillators etc. The properties of the medium and wave characteristics could be better explained if the dispersive and dissipative properties could be fully understood. To the best of our knowledge, no investigation has been reported on wave propagation and resulted instabilities in ion-implanted semiconductors except two very recent reports of our group concerning excitation of new electro-acoustic mode\cite{12} and modification in electro-kinetic mode characteristics\cite{13}. In both these papers, it was assumed that the negatively charged colloids were participating in the wave propagation phenomena. Hence, the dispersion and absorption characteristics of one of the fundamental waves i.e. acousto-electric wave in the NCs laden piezoelectric semiconductor have been studied.

2 Theoretical Formulation

In the present model, we have considered an ion-implanted semiconductor of group III-V with equal number densities of electrons and holes i.e. $n_{0e} = n_{0h}$. Let the implantation of metal ions in the semiconductor followed by annealing results into formation of NCs which tends to acquire a net negative charge through the different electron sticking processes. These charged NCs act as foreign particles inside the medium, as a result, a charge imbalance is created in the otherwise compensated medium. Hence, the condition for charge neutrality in the medium modifies to

$$-en_{0e} + en_{0h} - nz_d e n_{0a} = 0,$$ \hspace{1cm} \ldots (1)

where $n_{0e,h,d}$ is the concentration of electrons (with charge $-e$), holes and NCs respectively, $z_d$ is the number of electrons residing on to the NCs surface. The charge on NCs i.e. $z_d e$ can vary significantly depending on medium parameters\cite{14-16}. Thus, because of neutrality condition given in Eq. (1), it is possible to have in such medium:

$$n_{0e} \ll n_{0h} \hspace{1cm} \ldots (2)$$

To study the modification and amplification in acoustic mode, let us consider a compensated piezoelectric semiconductor plasma sample of infinite extent in the presence of implanted immobile charged NCs. The medium is subjected to a $dc$ electric field applied along the $z$-axis due to which electrons will acquire drift along $-z$ direction and holes will acquire drift along $+z$ direction. We have considered an acoustic wave propagating along the $z$-axis of the medium. The average size of NCs is assumed to be less than the inter-grain distance, the electron Debye radius as well as the wavelength, so that they can be treated as point masses\cite{17}. Hence, the material can be safely treated as multi-component plasma consisting of electrons, holes and immobile charged NCs, which remains stationary in the background.

By employing the multi-fluid balance and Maxwell’s equations and following the procedure adopted by Steele and Vural\cite{18}, we get the dispersion relation for acousto-electric interaction in NCs laden semiconductor as:

$$\left(\omega^2 - \kappa^2 \delta^2 \right)^2 \left[ 1 - \frac{\delta^2}{m(\omega + \kappa \theta_{0e})} \right] \left[ 1 - \frac{\delta^2}{m(\omega - \kappa \theta_{0h})} \right] = K^2 \kappa^2 \delta^2,$$ \hspace{1cm} \ldots (3)

where $K^2 = \left( \frac{\beta^2}{\varepsilon \varepsilon_o} \right)$ is the dimensionless electromechanical coupling coefficient and $\delta = \frac{n_{0e}}{n_{0h}}$, which measures the charge imbalance in the medium, with the remainder of the negative charge residing on the NCs, so that the total system is charge neutral. All other symbols have their usual meaning as given by Steele and Vural\cite{18} with subscripts $e, h$ stand for electrons and holes, respectively.

In the absence of piezoelectricity ($\beta = 0$), the coupling parameters on RHS of Eq. (3) vanishes and we get two independent modes as:

$$\omega^2 - \kappa^2 \delta^2 = 0 \hspace{1cm} \ldots (4a)$$

and
It can be inferred from Eq. (5) that the acoustic mode is amplified only when gain per radian $\alpha$ is positive. Now, we shall discuss the gain characteristics of acoustic wave for two different velocity regimes as follows:

(a) when $\gamma_e > 0 \text{ and } \gamma_h > 0 \text{ i.e. } \eta_{be} > \eta_e < \eta_{bh}$

In this velocity regime, $\alpha$ will be positive only when the expression within the square bracket in the numerator of Eq. (5) is positive i.e. when

$$\delta < m \left[ \frac{\omega_{bh}}{\omega_{de}} - \frac{v_e}{v_h} \right]$$

and

$$\delta < m \left[ \frac{v_e}{v_h} \right]$$

If the conditions given in Eqs 6 and 7 are fulfilled simultaneously the gain per radian will be

$$\alpha \approx \frac{1}{2} K^2 |\gamma_h| \left[ \frac{\omega_{bh}}{\omega_{de}} \right] \left[ \frac{\omega}{\omega_{de}} + \frac{\omega_{bh}}{v_e} \right] + \frac{1}{2} K^2 |\gamma_h| \left[ \frac{\omega}{\omega_{de}} - \frac{\omega_{bh}}{v_e} \right]$$

$$\left( A^2 + B^2 \right)^{-1}$$

where

$$A = \left[ \frac{\omega^2}{\omega_{de}} + \frac{\omega_{bh}}{\omega_{de}} + \frac{\omega^2_{ph}}{m} + \gamma_e \gamma_h \right]$$

and

$$B = \gamma_h \left[ \frac{\omega}{\omega_{de}} + \frac{\omega^2_{ph}}{m} \right] - \gamma_e \left[ \frac{\omega}{\omega_{de}} + \frac{\omega_{bh}}{v_e} \right]$$

In which $\omega_{de,h} = \frac{\eta_{s,e}}{D_{e,h}}$ is the electron and hole diffusion frequencies,

$$\gamma_{e,h} = \frac{\eta_{bh}}{\eta_e} \pm 1, \quad \omega_{bh} = \frac{\omega_{ph}}{v_h}$$

It may be inferred from above analysis that the amplifying nature of the acoustic wave will be very much decided by the value of charge imbalance parameter $\delta$. Hence, the presence of background stationary charged NCs modifies the wave spectrum effectively in this velocity regime.
(b) when $\gamma_e > 0$ and $\gamma_h < 0$ i.e. $\theta_0e > \theta_s > \theta_0h$

In this velocity regime, one will get decayed mode ($\alpha < 0$) always; hence of no interest here.

3 Results and Discussion

The dispersion relation derived can be employed to study the amplification characteristics of the acoustic mode in the ion implanted group III-V semiconductor. To have some numerical appreciation, we have considered the case of a compensated semiconductor viz. InSb at 77K. The parameters chosen are: $m_e = 0.014 \ m_0$, $m_h = 0.40 \ m_0$; $m_0$ being the free mass, $\varepsilon_L = 17.54$, $\beta = 0.054 \ \text{cm}^{-2}$, $\rho = 5.8 \times 10^3 \ \text{kg.m}^{-3}$, $n_{0e} = n_{0h} = 10^{24} \ \text{m}^{-3}$, $\nu_e = 3.5 \times 10^{11} \ \text{s}^{-1}$ and $\nu_h = 4.4 \times 10^{11} \ \text{s}^{-1}$. We have used Eq. (6) for the numerical appreciation of gain coefficient and its dependence on external parameters.

Figure 1 shows the dependence of gain per radian ($\alpha$) on wave frequency ($\omega$) with charge imbalance as parameter ($\delta$). It is inferred from Fig. 1 that gain per radian ($\alpha$) follows the identical nature of variation with frequency $\omega$ for all values of $\delta$. The gain per radian first increases with increase in frequency, achieves the maximum value and then starts decreasing with increasing frequency. At higher frequencies, the wavelength of acoustic mode becomes smaller than the Debye length, so that the $ac$ electric field produced by the acoustic mode will not be screened by the mobile charged particles. Since the screening is what actually produces the charge bunching, that bunching will be greatly reduced.

In turn, the gain depends on the bunching, so that it too reduced at such high frequency. In the absence of NCs, the medium has equal number densities of electrons and holes ($\delta = 1$); the concerning curve infers that the acoustic mode has the lowest value of gain per radian. For $\delta = 1$, we found that at $\omega \approx 1.5 \times 10^{12} \ \text{s}^{-1}$, the maximum value of $\alpha \approx 1.16 \times 10^9 \ \text{mks units}$ is obtained. When NCs are introduced some of the electrons due to their higher mobility stick onto them and a charge imbalance ($\delta < 1$) is created in the medium. As a result, the value of $\alpha$ becomes significantly modified. It is seen that while nature of variation remains the same, the value of $\alpha$ increases with the decrease in the value of $\delta$. As $\delta$ decreases, the value of $\alpha_{\text{max}}$ increases and the frequency at which one gets maximum value of $\alpha$ is shifted towards lower frequency regime. Thus, the result shows that charge imbalance increases the gain constant as well as band width of the amplifier. This behaviour may be attributed to the partial compensation of the plasma medium characterized by $\delta < 1$ values. Decrement in the value of $\delta$ means decrement in the number of free electrons which are drifting in opposite direction to that of wave whereas the number of holes drifting along the wave propagation direction remains unaffected. Hence, under the condition of charge imbalance in the medium the amplification of the acoustical waves will be more pronounced since the charge carriers of opposite signs (holes) create the favourable effect in the interaction between acoustical and space charge waves.

The variation of acoustic gain per radian $\alpha$ with applied electric field $E_0$ with $\delta$ as parameter is depicted in Fig. 2. The externally applied $dc$ electric field is favourable to achieve gain of the acoustic

![Fig. 1—Variation of gain $\alpha$ with wave frequency $\omega$ with $\delta$ as parameter at $E_0=10^4\ \text{Vm}^{-1}$](image1)

![Fig. 2—Variation of gain $\alpha$ with Electric field $E_0$ with $\delta$ as parameter at $\omega=10^{12}\ \text{s}^{-1}$](image2)
mode in the medium. With the increase in electric field strength the gain per radian also increases. The effect of $\delta$ on gain is obtained similar to that shown in Fig. 1.

4 Conclusions

We have shown that the amplification characteristics of acoustic mode are strongly modified when some of the NCs acquire negative charge in-group III-V semiconductor. The role of NCs becomes increasingly effective as the charge sticking on them increases. The most important inferences that may be drawn from the study are: (1) We get amplification of acoustic mode only when electrons and holes both drift faster than the acoustic wave velocity in a compensated semiconductor; (2) The charge imbalance increases the acoustic gain constant as well as bandwidth of the amplifier; (3) The addition of NCs in heavily doped semiconductor is found to be more influential on amplification of the AW. Hence, authors have found favourable modification in acoustic mode spectrum in presence of electron-hole plasma embedded with NCs. Thus, for the experimental verification of our theoretical idea, we propose to initiate a serious laboratory experimental effort.

References