Indian Journal of Pure & Applied Physics
Vol. 44, February 2006, pp. 188-191

Electro-kinetic wave spectrum in group-IV semiconductors: Effect of streaming carriers

S Ghosh & Preeti Thakur

School of Studies in Physics, Vikram University, Ujjain 456 010 (MP), India
*E-mail: drsanjayghosh@rediffmail.com

Received 25 May 2005; revised 2 September 2005; accepted 19 October 2005

The implanted ions in a group-IV semiconductor agglomerate to form nano-clusters (NCs) and some of them acquire negative charge which change the balance between electron-hole densities in an otherwise compensated semiconductor. An analytical study has been made on wave spectrum of electro-kinetic (EK) waves propagating through such medium. Using multi-fluid analysis and Maxwell's equations, a linear dispersion relation for the EK wave in such medium has been derived. This dispersion relation is used to study slow electro-kinetic wave phenomena and resultant instabilities numerically. The drift velocities of electrons and holes are found to be responsible for converting two aperiodic modes into periodic ones. They are also found helpful in reducing the absorption of all the four possible EK modes. It is found that choosing the proper values of applied electric field and wave number one may optimize the amplification coefficients of propagating modes.

Keywords: Electrostatic waves, Electrostatic oscillations, Plasma effects, Doping, Ion-implantation, Colloids (NCs)

IPC Code: B82B

1 Introduction

During the past few years a number of reports[1-10] have been made regarding the optical properties of nano-clusters (NCs) formed due to the implantation of ions in semiconductors. These NCs are synthesized within the host material by the implantation of various metal ions [such as Ag^+, Cu^+, Fe^+, etc] in solids and have been revealed by a number of laboratory experiments[1-10]. These ions when implanted inside the host material, firstly get neutralized during slowing down process and then somehow agglomerate to form NCs. This process may damage the lattice of the host material; hence an appropriate annealing process[1] should be followed for re-crystallization. In this way, the presence of NCs in addition to mobile charge carriers represents the solid as a multi-component semiconducting medium. The shape and size of these NCs are determined by various factors like ion-fluence, damage caused to the host material lattice by implantation, annealing treatment, etc[11]. Their size can be changed by controlling the ion dose, the implantation energy and annealing temperature. Since an understanding of wave propagation through a medium, can provide a tremendous insight regarding properties of the host material therefore, such ion implanted solids become promising media to be revisited to study wave spectrum phenomena.

As in the case of SiO_2 glasses, we believe that by various electron sticking processes some of the NCs formed within the semiconductor might acquire a net negative charge due to higher mobility of electrons, that would change the balance between electron and hole densities in an otherwise compensated semiconductor. This in turn can give rise to several novel wave phenomena. This concept has changed the direction of research in recent years[12,13]. Sallimullah *et al.*[12] have first time predicted the possible Coulomb lattice formation in piezoelectric semiconductors in the same medium, later on the role of electron-phonon coupling in the formation of wake potential was also reported[13]. Even though the formation of plasma crystal and existence of novel modes are two interesting areas to study in such media in many earlier studies much emphasis has been given on the formation of plasma crystals to study collective properties and physical processes in condensed matter. But to the best of our knowledge, no serious attempt has been made to study the waves and instabilities in implanted semiconductors, except a few very recently reported works of Ghosh *et al.*[14,15] concerning excitations of novel electro-acoustic[14] and modified Alfven modes[15] in an ion-implanted nanosized colloids laden semiconductor medium.

Motivated by the present status and the works of Ghosh *et al.*[14,15], the object of the present paper is to study analytically the wave spectrum of electro-kinetic waves in NCs laden semiconductor and the effect of streaming carriers due to presence of strong dc electric field. We here firmly believe that the interaction of charged NCs with streaming carriers of host materials may become responsible for the modifications of excited modes and thus becomes effectively useful to study wave phenomena. Here our interest in electro-kinetic wave stems from the fact that it is a low frequency propagating wave supported by electrons and holes streams and thus this basic negative energy-carrying mode is a very well suited probe for the study of semiconductor medium. Hence it has much fundamental importance in many laboratory studies made by plasma physicists as well as material scientists.

The basic equations describing electro-kinetic wave in ion-implanted group IV semiconductor using multi-fluid plasma model is outlined and the derived dispersion relation reveals that the presence of charged NCs and streaming carriers modifies the wave spectrum of longitudinal electro-kinetic wave.

2 Theoretical Formulation

In the present model, the uniform plasma present in-group IV semiconductor is considered. Let the implantation of metal ions in the semiconductor be resulted into the formation of NCs. Let the sample be placed in static electric field $\boldsymbol{E_0}$, applied along –z direction so that electrons are drifted towards +z and holes towards –z directions. Due to higher mobility of electrons, some of the NCs tend to acquire a net negative charge. These NCs remain stationary in the background by considering them to be massive enough to respond to the considered perturbations and regarded as just another component of the medium. The quasi-neutrality condition at equilibrium in this medium is given by

$$n_{0h} = n_{0e} + z_d\, n_{0d}\,, \qquad \ldots(1)$$

where $n_{0\alpha}$ (α = e, h, d) is the equilibrium number density of particle species α, and $z_d = q_d/e$ is the charge number on the surface of NCs. It is assumed here that $z_e = -1$ and $z_h = 1$. The carrier concentration $n_{0\alpha}$ satisfies the equation of continuity, which is given by

$$\frac{\partial n_\alpha}{\partial t} + \frac{\partial}{\partial z}\left(n_\alpha \vartheta_\alpha\right) = 0, \qquad \ldots(2)$$

and the momentum balance equation for the given carrier type can be written as

$$\frac{\partial \vartheta_{z1\alpha}}{\partial t} + \vartheta_{0\alpha}\frac{\partial \vartheta_{z1\alpha}}{\partial z} = \frac{z_\alpha q_\alpha}{m_\alpha} E_{z1} - \nu_\alpha \vartheta_{z1\alpha} - \frac{{\vartheta_{t\alpha}}^2}{\rho_{0\alpha}}\frac{\partial \rho_{1\alpha}}{\partial z}\,, \qquad \ldots(3)$$

where subscripts 0 and 1 used in Eqs. 2 and 3, represent zero and first order quantities, respectively. Here m_α, q (= -e for electrons and +e for holes), υ_α, ν_α, ρ_α, and $\upsilon_{t\alpha}$ are the carrier mass, charge, drift, collision frequency, charge density and thermal velocity, respectively. All the remaining symbols have their usual meanings.

Assuming first order quantities varying as $\exp[i(\omega t - kz)]$ (where ω and k are, respectively, angular frequency and wave number of the propagating mode), and following Steele and Vural[16], we obtain the dispersion relation for longitudinal electro-kinetic wave in presence of stationary negatively charged NCs in the background as

$$\varepsilon(\omega,k) = 1 + \frac{\omega_{pe}^2}{\left[(\omega - k\vartheta_{0e})(\omega - k\vartheta_{0e} - i\nu_e) - k^2\vartheta_{te}^2\right]}$$

$$+ \frac{\omega_{ph}^2}{\left[(\omega + k\vartheta_{0h})(\omega + k\vartheta_{0h} - i\nu_h) - k^2\vartheta_{th}^2\right]} + \frac{\omega_{pd}^2}{\omega^2} = 0 \qquad \ldots(4)$$

where

$$\omega_{pe,h}^2 = \frac{e^2 n_{0e,h}}{\varepsilon m_{e,h}}, \quad \omega_{pd}^2 = \frac{z_d^2 e^2 n_{0d}}{\varepsilon m_d}\,, \quad \vartheta_{0e,h} = \frac{eE_0}{m_{e,h}\,\nu_{e,h}}\,,$$

$\varepsilon = \varepsilon_0 \varepsilon_L$; ε_L being the lattice dielectric constant.

On comparing Eq. (4) with Eqs (4-36) of Steele and Vural[16], one finds that the last two additional terms of R.H.S. of above Eq. (4) represent the contributions of holes and the presence of charged NCs in the medium. Hence Eq. (4) is the modified form of dispersion relation for electro-kinetic wave in NCs laden semiconductor plasma.

In collision dominated or low frequency regime [$\nu_{e,h} \gg \left(\omega \mp k\vartheta_{0e,0h}\right)$], the dispersion relation in

Eq. (4) can be written in the form of polynomial in ω as

$$\omega^4-\omega^3\left[i\omega_{\mathrm{Re}}\left(k^2\lambda_{De}^2-1\right)+i\omega_{Rh}\left(k^2\lambda_{Dh}^2-1\right)+k\left(\vartheta_{0e}-\vartheta_{0h}\right)\right]$$

$$-\omega^2\begin{bmatrix}k^2\left(k^2\lambda_{De}^2\lambda_{Dh}^2-\lambda_{De}^2-\lambda_{Dh}^2\right)\omega_{\mathrm{Re}}\omega_{Rh}\\+k^2\left(\vartheta_{0e}\vartheta_{0h}+ik\lambda_{De}^2\omega_{\mathrm{Re}}\vartheta_{0h}-ik\lambda_{Dh}^2\omega_{Rh}\vartheta_{0e}\right)\\+ik\left(\vartheta_{0e}\omega_{Rh}-\vartheta_{0h}\omega_{\mathrm{Re}}\right)-\omega_{pd}^2\end{bmatrix}$$

$$-\omega\left[ik^2\omega_{pd}^2\left(\lambda_{De}^2\omega_{\mathrm{Re}}+\lambda_{Dh}^2\omega_{Rh}\right)+k\left(\vartheta_{0e}-\vartheta_{0h}\right)\omega_{pd}^2\right]$$

$$-k^4\lambda_{De}^2\lambda_{Dh}^2\omega_{pd}^2\omega_{\mathrm{Re}}\omega_{Rh}-ik^3\vartheta_{0h}\lambda_{De}^2\omega_{pd}^2\omega_{\mathrm{Re}}$$

$$-ik^3\vartheta_{0e}\lambda_{Dh}^2\omega_{pd}^2\omega_{Rh}-k^2\vartheta_{0e}\vartheta_{0h}\omega_{pd}^2=0, \qquad \ldots(5)$$

where $\omega_{\mathrm{Re},h}=\dfrac{\omega_{pe,h}^2}{\nu_{e,h}}$, $\lambda_{De,h}^2=\dfrac{\vartheta_{te,h}}{\omega_{pe,h}}$ are the dielectric relaxation frequencies and the square of Debye wavelengths of electrons and holes, respectively.

Equation (5) being polynomial of fourth order in ω with complex coefficients is to be solved numerically to study the dispersion and amplification characteristics of four possible modes of propagation.

3 Results and Discussion

The dispersion relation derived in the preceding section can be employed to study the wave spectrum of longitudinal electro-kinetic wave in ion-implanted group IV semiconductor. This relation is solved numerically for complex frequency $\omega\,(=\omega_r+i\omega_i)$ with real positive values of propagation constant *k*.

The form of perturbations was considered as $\exp[i(\omega t-kz)]$ and so the mode may be growing in time when imaginary part of the wave angular frequency becomes negative for the real values of *k* i.e. $\omega_i < 0$ and decaying when $\omega_i > 0$.

To have some numerical results, we have considered the case of Ge with the following set of parameters: $m_e = 0.0815\,m_0$, m_0 being the free electron mass, $m_h = 4\,m_e$, $m_d = 10^{-27}$ kg, $\varepsilon_L = 15.8$, $n_{0e} = 10^{19}$ m^{-3}, $n_{0h} = 5\times10^{19}$ m^{-3}, $\nu_e = 3.463\times10^{11}$ s^{-1}, $\nu_h = 1.194\times10^{11}$ s^{-1} and $\nu_d = 3.422\times10^{8}$ s^{-1} at 77 K. The dispersion and absorption characteristics of possible modes are displayed in Figs 1 and 2.

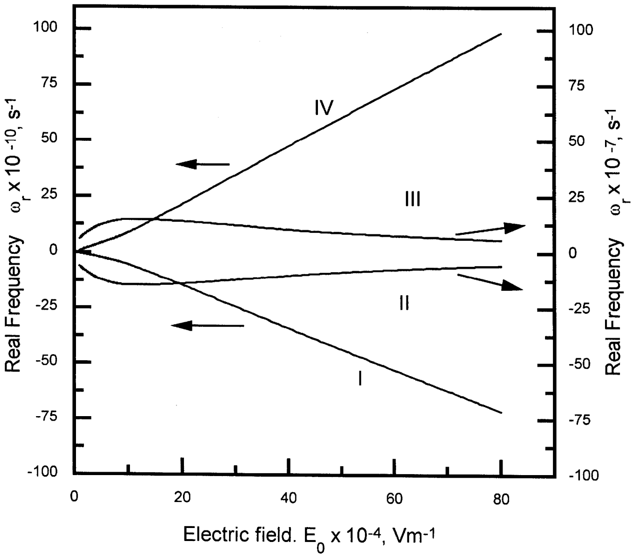

Fig. 1 — Variation of real frequency of all four modes with electric field E_0 at $k = 2\times10^5$m^{-1}

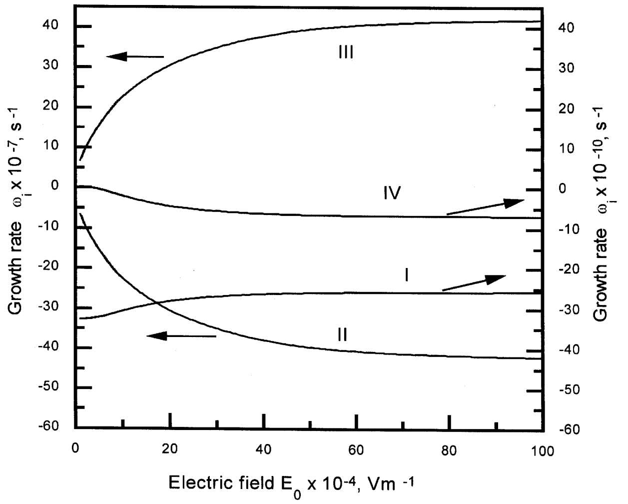

Fig. 2 — Variation of growth rates of all four modes with electric field E_0 at $k = 2\times10^5$m^{-1}

Figure 1 represents the variation of phase constants of all the roots with amplitude of dc electric field $\boldsymbol{E_0}$ at $k = 2\times10^5$ m^{-1}. It is found that first and fourth and second and third modes have exactly opposite nature of variations with $\boldsymbol{E_0}$; i.e. when one mode propagates along negative *z* direction than other one propagates along positive *z* direction. But magnitude wise both the modes of a pair have nearly identical phase constants. It may also be seen from Fig. 1 that the increase in carrier drift increases the magnitude of phase constants of first and fourth mode continuously whereas magnitude of phase constants of second and third modes first increases slightly and than becomes nearly independent of $\boldsymbol{E_0}$. It is also found that all these modes are periodic in nature in the presence of electric field whereas in absence of $\boldsymbol{E_0}$, the second and third modes were reported aperiodic in nature ($\omega_r = 0$).

Figure 2 displays the variation of ω_i with $\boldsymbol{E_0}$ for all the four modes at $k = 2 \times 10^5\ \text{m}^{-1}$. Figure 2 infers that out of the four modes, three (first, second and fourth) are growing in nature whereas the third mode is found to be decaying always. The growth rates of second and fourth modes increase with the increment in $\boldsymbol{E_0}$ but that of the first mode initially decreases slightly and then becomes saturated.

The above discussion reveals that the streaming charge carriers are not only responsible for noticeable modifications in the existing wave spectrum of longitudinal electro-kinetic waves but also responsible for the amplification of three out of four possible modes.

4 Conclusions

The effect of streaming charge carriers on the excitation of low frequency electro-kinetic wave in uniform group IV semiconductor, consisting of charged NCs is investigated in the present work. The presence of participating but stationary negatively charged NCs gives rise to four interesting modes of propagation. The important inferences are:

1. By increasing the strength of electric field, the phase velocities of contra-propagating modes increase.
2. The presence of electric field is responsible to convert the two aperiodic modes (second and third) into periodic ones. Also it is found favourable to achieve maximum amplification for the remaining two modes (first and fourth).
3. The addition of the charged NCs in the two components streaming semiconducting medium is found to be effectively influential for the modifications of wave spectrum of the longitudinal electro-kinetic waves.

Thus, this fundamental study of wave spectrum of the longitudinal electro-kinetic wave in streaming electron-hole semiconductor embedded with NCs is important for understanding the waves and instability phenomena.

Acknowledgement

One of the authors (PT) thanks Ms. Pragati Khare for the help rendered by her during the course of this work. We would like to thank the referee for valuable suggestions to improve the manuscript.

References

1 Ila D, Wu Z, Smith C C, Poker D B, Hensley D K, Klatt C & Kalbitzer S, *J Nucl Instr Meth B*, 127 (1997) 570.

2 Ila D, Williams E K, Sarkisov S, Smith C C, Poker D B & Hensley D K, *J Nucl Instr Meth B*, 141 (1998) 289.

3 Magruder III R H, Zuhr R A & Osborne D H, *J Nucl Instr Meth B*, 99 (1995) 590.

4 Takeda Y, Hioki T, Motohiro T, Noda S & Kurauchi T, *J Nucl Instr Meth B*, 91 (1994) 515.

5 Haugland Jr. R F, Yang L, Magrunder III R H, Witting J E, Becker K & Zuhr R A, *Opt Lett*, 18 (1993) 373.

6 Cheang-Wong J C, Oliver A, Crespo A, Hernandez J M, Munoz E & Espejel-Morales R, *J Nucl Instr Meth B*, 161 (2000) 1058.

7 Sarkisov S S, Williams E, Curley M, Ila D, Venkateshwarlu P, Poker D B & Hensley D K, *J Nucl Instr Meth B*, 141 (1998) 294.

8 Haus J W, Kalyaniwalla N, Inguva R, Blomer M & Bowden C M, *J Opt Soc Am B*, 6 (1992) 797.

9 Tarasov K A, Isupov V P, Bokhonov B B, Gaponov Yu A, Tollochko B P, Sharafutdinov M R & Shatskaya S S, *J Mater Synth Proc*, 8 (2000) 21.

10 White C W, Budal J D, Zhu J G & Withrow S P, *Appl Phys Lett*, 68 (1996) 2389.

11 Sze S M, *Semiconductor devices: Physics and Technology*, (John Wiley, India) 2002.

12 Salimullah M, Ghosh S & Amin M R, *Pramana*, 54 (2000) 185.

13 Salimullah M, Shukla P K, Ghosh S, Nitta H & Hayashi Y, *J Phys D: Appl Phys*, 36 (2003) 958.

14 Ghosh S, Sharma G R, Khare Pragati & Salimullah M, *Physica B*, 351 (2004) 163.

15 Ghosh S, Sharma G R & Salimullah M, *Physica B*, 355 (2005) 37.

16 Steele M C & Vural B, *Wave Interactions in Solid State Plasmas* (Mc-Graw Hill, New York) 1969, p. 45.