Stimulated Brillouin Scattering in ion implanted semiconductor plasmas having SDDC

N.Yadav*, P.S. Malviya**, and S.Ghosh*

School of Studies in Physics, Vikram University, Ujjain 465010, India*
Department of Physics, Govt. J.N.S. Post Graduate College, Shujalpur 465333, India**
Corresponding author E-mail address: psm.sehore@rediffmail.com **

Abstract: A high power laser propagating through ion implanted semiconductor plasma undergoes stimulated Brillouin scattering (SBS) arises due to nonlinear current density and acousto-optical strain of the medium in third-order optical polarization. We have considered that the negatively charged colloidal grains (CGs) are embedded in semiconductor plasma by means of ion implantation. By considering net negative charge of the CGs, we present an analytical study of the effects of CGs on threshold intensity, effective susceptibility and Brillouin gain characteristics. It is found that as the charge on the CGs builds up, the Brillouin gain and threshold are significantly modifies the characteristics for the onset of SBS processes.

Index terms-stimulated Brillouin scattering (SBS), colloidal grains (CGs), strain dependent dielectric constant (SDDC)

1. Introduction:
Stimulated Brillouin scattering (SBS) has numerous applications in diverse areas ranging from optical phase conjugation, real-time holography, optical storing and pulse compression for laser-induced fusion. In laser induced fusion experiments, the SBS is of great concern because it significantly redirects the pump energy away from the target and adversely affects the energy absorption. It is therefore, desirable to minimize SBS process in these experiments [1-5].

The origin of SBS lies in the effective third-order optical susceptibility of the medium. In SBS phenomenon, the maximum scattering occurs in the backward direction [6]. Semiconductors are particularly the most promising materials with highest probability of large third-order nonlinear optical phenomena to occur and are used for fabrication of sophisticated optical devices [7].

Ion implantation a process in which use of ions is made to dope and modify semiconductor materials. The colloids that act as third species or foreign particles are the result of the implantation of any metal ion inside the medium. Colloidal plasmas are a new and fascinating field of plasma physics. These colloids acquire a negative charge through the sticking of high mobility free electrons on them. The negatively charged colloidal grains (CGs) are assumed to be of uniform size and smaller than both the wavelength under study and the carrier Debye length [8-9].

In the present paper, we investigate the effects of negatively charged CGs on the SBS through third order optical susceptibility, originating from induced current density and acousto-optical polarization, in a transversely magnetized n-type ion implanted semiconductor plasmas. The presence of charged CGs in semiconductor plasma medium add new dimensions to the analysis presented in n-doped magneto-active semiconductors with strain dependent dielectric constants (SDDC). It is found that ion implantation modifies the properties of material.

2. Theoretical Formulation:
We have considered the well-known hydrodynamic description of a homogeneous, ion-implanted n-type semiconductor plasma having SDDC (for which $k_a l \ll 1$, $k_a$ and $l$ being the acoustic wave number and mean free path of an electron, respectively). In order to make an analytical study of the threshold pump field,
threshold intensity and effective gain constant of Brillouin cell made of a homogeneous, ion-implanted n-type crystal. The theoretical formulation starts with the derivation of the total current density $\tilde{J}$ for the resonant Stoke’s component arises due to nonlinear interaction of the waves, followed by deduction of the effective Brillouin susceptibility through nonlinear polarization arising due to nonlinear induced current and acousto-optical strain. We apply the pump electric field $\tilde{E}_0 \exp\left[i(k_0 x - \omega_0 t)\right]$ parallel to the acoustic wave $\tilde{k}_a$ (along the x-axis), and dc magnetic field $\tilde{B}_o$ normal to $\tilde{k}_1$ (along the z-axis).

The basic equations are employed for analysis:

$$\frac{\partial v_0}{\partial t} + \nu v_0 = -\frac{eE_{\text{eff}}}{m}$$

(1)

$$\frac{\partial v_1}{\partial t} + \nu v_1 + \left(v_0 \frac{\partial}{\partial x}\right)v_1 = -\frac{e}{m} \left(E_1 + v_1 \times B_0\right) - \frac{k_BT}{mn_{\text{oe}}} \nabla n_1$$

(2)

$$\frac{\partial}{\partial t} + \delta_d n_0 \frac{\partial}{\partial x} + v_0 \frac{\partial}{\partial x} = 0$$

(3)

$$\frac{\partial^2 u}{\partial t^2} = \frac{c}{\rho} \frac{\partial^2 u}{\partial x^2} - \frac{(\varepsilon g E_{\text{eff}}^\ast)}{\rho} \frac{\partial E_1^\ast}{\partial x}$$

(4)

$$\frac{\partial E_1}{\partial x} = -\frac{n_1 e}{\varepsilon} + gE_{\text{eff}} \frac{\partial^2 u^\ast}{\partial x^2}$$

(5)

and

$$P_{\text{ao}} = -\varepsilon g E_{\text{eff}} \nabla u^\ast$$

(6)

where $\tilde{E}_{\text{eff}} = \tilde{E}_0 + \tilde{v}_0 \times \tilde{B}_0$.

Equations (1) and (2) represent the zeroth and first order oscillatory fluid velocities of electrons with effective mass $m$ and charge $e$; $\nu$ is the collision frequency. In equation (1), $\tilde{E}_{\text{eff}}$ represent the effective electric field which includes the Lorentz force $(\tilde{v}_0 \times \tilde{B}_0)$ in presence of external magnetic field $\tilde{B}_0$.

Equation (3) is the continuity equation, where $n_0$ and $n_1$ are the equilibrium and perturbed carrier densities. In III-V semiconductor plasmas (i.e. $n_{0e} \approx n_{0h} \approx n_0$) embedded with CGs, the electrons and holes from all directions colloidal with CGs and get stick onto them. However, greater number of electrons sticks onto the CGs as compared to holes in given time interval. The charge imbalance parameter is defined as $\delta_d = \frac{Z_d e n_{0d}}{n_{0h}}$.

The plasma is quasi neutral and the conservation of particle number density must always holds. Thus charged should be hold: $n_{0e} e = n_{0h} e - Z_d e n_{0d}$

Where $n_{0d}$ is concentration of CGs and $Z_d$ is charge state of colloids. [10-12].
The equation (4) describes the lattice vibration in ion implanted semiconductor plasma in which \( \rho, u \) and \( c \) being mass density of the crystal, lattice displacement and crystal elastic stiffness, respectively. The space charge field \( \vec{E} \) is determined by the Poisson’s equation (5) in which \( \vec{D} = \varepsilon \vec{E}(1 + gS) \) and \( \varepsilon = \varepsilon_0 \varepsilon_s \) where \( \vec{D} \) is the electric displacement, \( \varepsilon_s \) is dielectric constant in absence of any strain, \( S = \frac{du}{dx} \) and \( g = \frac{\varepsilon_s}{3} \) is coupling constant due to SDDC. Equation (6) shows that the acoustic wave generated due to acousto-optic strain. The interaction of the pump with the generated acoustic wave produces an electron density perturbation, which in turn drives an electron plasma wave and induces current density in the Brillouin active medium. In an n-type semiconductor, this density perturbation can be obtained by using the standard approach [13].

Differentiating equation (3) and using Equations (1) and (5), we obtain.

\[
\frac{\partial^2 n_1}{\partial t^2} + \nu \frac{\partial n_1}{\partial t} + \omega_p^2 n_1 + \frac{\partial \omega_p^2 k^2 \varepsilon g E_{\text{eff}} u^*}{e} = i k n_1 \bar{E} \tag{7}
\]

Where, \( \omega_p^2 = \left[ \delta_d \left( \omega_p^2 + \frac{k^2 k_B T}{m} \right) \right] \), \( \omega_p^2 = \left( \frac{n_0 e^2}{m} \right) \), \( \omega_c = \left( \frac{eB_0^2}{m} \right) \) and \( \bar{E} = \frac{e \bar{E}_{\text{eff}}}{m} \).

Here, \( \omega_c \) is cyclotron frequency and \( \omega_p \) is the plasma frequency of the medium. We neglect the Doppler shift under the assumption that \( \omega_0 \gg \nu \gg k_0 v_0 \).

The perturbed electron concentration \( n_1 \) will have slow and fast components, such that \( n_1 = n_s + n_f \). The slow component is associate with the low frequency acoustic wave \( \omega_a \), while the fast component with high frequency electromagnetic wave \( \omega_0 \pm \omega_a \). Considering only the Stoke’s component of the scattered electromagnetic wave into account we shall have \( \omega_i = \omega_0 - \omega_a \) and \( k_1 = k_0 - k_a \). For spatially uniform laser irradiation \( |k_0| \approx 0 \) yields \( k_1 = k_a = k \), (say) we obtain the following coupled equations from equation (7) under rotating wave approximation (RWA),

\[
\frac{\partial^2 n_s}{\partial t^2} + \nu \frac{\partial n_s}{\partial t} + \omega_p^2 n_s = i k n_f^* \bar{E} \tag{8a}
\]

\[
\frac{\partial^2 n_f}{\partial t^2} + \nu \frac{\partial n_f}{\partial t} + \omega_p n_f + \frac{k^2 \delta_d \omega_p^2 \varepsilon g E_{\text{eff}} u^*}{e} = i k n_s^* \bar{E} \tag{8b}
\]
Equations (8a) and (8b) indicate that the slow and fast components of the density perturbations are coupled to each other via the pump field. Thus, it is obvious that the presence of the pump field is the fundamental necessity for SBS to occur.

The slow component $n_s^*$ may be obtained from Equations (4) and (8) as

$$n_s^* = \frac{m k^2 \delta_d \omega_x^2 e^2 g^2 E_{eff} E_1}{e^2 \rho (\omega_x^2 - k^2 v_a^2)} \left[ 1 - \frac{(\Delta_x^2 + i \omega_a \nu)(\Delta_x^2 - i \omega_a \nu)}{k^2 E^2} \right]^{-1}$$  \hspace{1cm} (9)

where $\Delta_a = \frac{\nu}{\rho} \omega_a^2 - \omega_a^2$ and $\Delta_x^2 = \frac{\nu}{\rho} \omega_x^2 - \omega_x^2$.

It is evident from the above expression that $n_s^*$ strongly depends upon magnitude of the input pump intensity. The density perturbation thus produced subsequently affects the propagation characteristics of the generated waves.

The Stoke’s component of the induced current density may be obtained from the relation

$$J(\omega_1) = \delta_d n_0 e v_{1x} + n_s^* e v_{0x}$$  \hspace{1cm} (10)

The preceding analysis under RWA yields

$$J(\omega_1) = -\frac{i \delta_d n_0 e^2 E_1}{m(\omega_0^2 - \omega_1^2)} + \frac{i k^2 \delta_d \omega_x^2 e^2 g^2 \omega_0^3 |E_0|^2 E_1}{\rho(\omega_a^2 - k^2 v_a^2)(\omega_0^2 - \omega_1^2)} A$$  \hspace{1cm} (11)

where $A = \left[ \frac{k^2 E^2 - (\Delta_x^2 + i \omega_a \nu)(\Delta_x^2 - i \omega_a \nu)}{k^2 E^2} \right]^{-1}$ and $F_{0x} = \frac{e}{m} (E_{eff})_x = \frac{e E_x \omega_0^2}{m(\omega_0^2 - \omega_x^2)}$

Thus $(E_{eff})_x = \frac{E_x \omega_0^2}{(\omega_0^2 - \omega_x^2)}$ (12)

The first term of the equation (11) represents the linear component of the induced current density and the second term represents nonlinear coupling amongst the three interacting waves via total nonlinear current density. The induced polarizations as the time integral current density can be written as

$$P_{ed}(\omega_1) = \int J(\omega_1)\, dt = -\frac{k^2 \delta_d \omega_x^2 e^2 g^2 \omega_0^3 |E_0|^2 E_1}{\rho \omega_a^2 (\omega_a^2 - k^2 v_a^2)(\omega_0^2 - \omega_1^2)} A$$  \hspace{1cm} (13)

www.ijsrp.org
The origin of the SBS process lies in that component of $P_{ao}(\omega_i)$ which depends on $|E_0|^2E_i$. The third-order susceptibility corresponding to $P_{ao}(\omega_i)$ is known as Brillouin susceptibility ($\chi_{B_{ao}}$). Now, the threshold pump amplitude for the onset of SBS may be obtained by setting $P_{ao}(\omega_i)=0$ (i.e $A=0$) in equation (13), this condition yields,

$$|E_{0th}| = \frac{m}{e\kappa} \left[ 1 - \frac{\omega_e^2}{\omega_0^2} \right] \left[ (\Delta_a^2 + i\omega_a\nu)^{1/2} (\Delta_i^2 - i\omega_i\nu)^{1/2} \right]$$  \hspace{1cm} (14)

Therefore, the interaction between the pump and the centro-symmetric crystal will be dominated by the SBS phenomena at a pump power level well above the threshold field $E_{0th}$. The corresponding pump intensity can be obtained by using the relation

$$I_{th} = \frac{1}{2} \eta E_0 c |E_{0th}|^2$$  \hspace{1cm} (15)

The Brillouin susceptibility due to induced current density is

$$(\chi_B)_{cd} = -\frac{\epsilon k^2 \delta_d \omega_p^2 g^2 \omega_0^3}{\rho \omega_i (\omega_a^2 - k_v^2 \nu_a^2)(\omega_0^2 - \omega_i^2)} A$$  \hspace{1cm} (16)

It is clear from above expression that $(\chi_B)_{cd}$ is a function of material parameters such as carrier concentration $n_0$ via plasma frequency $\omega_p$, charge imbalance parameter $\delta_d$, and $B_0$ via cyclotron frequency $\omega_c$. Besides the Brillouin susceptibility $(\chi_B)_{cd}$, the system also possesses an acousto-optical polarization $P_{ao}(\omega_i)$ due to the interaction of the pump with acoustic wave generated in the medium. The acousto optical polarization is obtained from equations (4) and (6) as

$$P_{ao} = -\frac{k^2 \epsilon^2 g^2 \omega_p^3 |E_0|^2 E_i}{\rho (\omega_a^2 - k_v^2 \nu_a^2)(\omega_0^2 - \omega_i^2)}$$  \hspace{1cm} (17)

The induced polarization due to acousto-optic interaction, is given by

$$P_{ao}(\omega_i) = \varepsilon (\chi_B)_{ao} |E_0|^2 E_i$$  \hspace{1cm} (18)

Where $(\chi_B)_{ao}$ is Brillouin susceptibility due to acousto-optic polarization.

Again by keeping the pump intensity well above the threshold, the Brillouin susceptibility for acousto optic process is obtained from equations (17) and (18) as,

$$(\chi_B)_{ao} = -\frac{\epsilon k^2 \omega_p^4}{\rho (\omega_a^2 - k_v^2 \nu_a^2)(\omega_0^2 - \omega_i^2)}$$  \hspace{1cm} (19)

From equations (15) and (17) we obtain the effective Brillouin susceptibility as,

$$(\chi_B)^{eff.} = (\chi_B)_{cd} + (\chi_B)_{ao}$$  \hspace{1cm} (20)

$$= -\frac{\epsilon k^2 \omega_p^4}{\rho (\omega_a^2 - k_v^2 \nu_a^2)(\omega_0^2 - \omega_i^2)} \left[ 1 + \frac{\delta \omega_p^2}{\omega_i \omega_0} A \right]$$  \hspace{1cm} (21)

Equation (21) may be separated into real and imaginary parts $(\chi_B)^{eff.} = (\chi_B)^{eff.} + i(\chi_B)^{eff.}$ as,
It is found that initially $I_{th}$ decreases abruptly as the $k$ increases in ion implanted semiconductors with chosen values of charge imbalance parameter $\delta_d$. It can be seen that at $k \approx 1 \times 10^7 m^{-1}$ the intensity is $I_{th} \approx 5.1 \times 10^{13} Wm^{-2}$. The $I_{th}$ decreases abruptly with wave number $k$ up to $k >> 4 \times 10^7 m^{-1}$ and then afterwards decreases slowly. It is evident from the figure that as the fraction of negative charge stick on to the CGs $\delta_d$, decreases (i.e. $\delta_d \approx 1 > 0.90 > 0.80$), the $I_{th}$ gets lowered.

Figure 2 depicts the variation of threshold pump fields $E_{0th}$ with the function of cyclotron frequency $\omega_c$. The value of theratio $\frac{\omega_c}{\omega_0}$ can be changed for various value of the cyclotron frequency $\omega_c$. It is found that initially at the ratio $\left(\frac{\omega_c}{\omega_0} \approx 0.477\right)$, the threshold pump field is $E_{0th} \approx 1.48 \times 10^6 Vm^{-1}$. As we increase the $\omega_c$, the $E_{0th}$ decreases slowly. When $\omega_c$ become nearly equal to $\omega_0$ (i.e. $\omega_c \approx \omega_0$), the threshold pump field gets the minimum value at $E_{0th} \approx 8.84 \times 10^4 Vm^{-1}$for the chosen value of $\delta_d$. The increase in cyclotron frequency (i.e.
\( \omega_c > \omega_0 \), the \( E_{0th} \) also increases gradually for all value of \( \delta_d \). The decrease in fraction \( \delta_d \) negative charge stick on to the CGs, the \( E_{0th} \) values gets reduced as shown in figure.

The dependence of effective real susceptibility \( [\chi_{eff}]_{real} \) on magnetic field [via cyclotron frequency \( \omega_c \)] is shown in figure 3. The magnitude of \( [\chi_{eff}]_{real} \) decreases abruptly with increases in the value of ratio \( \omega_c/\omega_0 \).

It is found that when \( \omega_c \approx \omega_0 \) [i.e.at the ratio \( \omega_c/\omega_0 \approx 1 \)] the \( [\chi_{eff}]_{real} \) attains minimum value \( [\chi_{eff}]_{real} \approx -1.65 \times 10^{-10} \text{V}^2\text{m}^{-2} \). On increase in ratio \( \omega_c/\omega_0 > 1 \) there is increase in \( [\chi_{eff}]_{real} \).

Afterward for further value of \( \omega_c/\omega_0 \approx 1.3 > 1 \), saturates the \( [\chi_{eff}]_{real} \). The decrease in charge imbalance
parameter $\delta_d << 1$ the minimum value of susceptibility also shifts toward higher. Figure 4 represents the variation of the effective susceptibility with respect wave number $k_0$. It can be seen that the effective susceptibility $[\chi_{\text{eff, real}}]$ usually decreases with increase wave number $k_0$.

Figure 3 Effective susceptibility $[\chi_{\text{eff, real}}]$ Vs cyclotron frequency $\omega_c$ at $E_0 = 1 \times 10^8 V m^{-1}$ and $n_0 = 10^{25} m^{-1}$.

Figure 4 Variation of effective susceptibility real $[\chi_{\text{eff, real}}]$ Vs wave number $k_0$ at $E_0 = 1 \times 10^8 V m^{-1}$
The dependence of effective Brillouin gain via $\omega_p/\omega_0$, on carrier concentration ($n_0$) is shown in figure 5. It is seen that gain is nearly independent of $n_0$, but on the higher value ($>10^{25} \text{m}^{-3}$) of $n_0$, when $\omega_p^2 > \omega_0 \omega_1$, the gain increases rapidly with small increase in $n_0$. The role of charge imbalance parameter $\delta_d$ shows unusual characteristics initially when ($>5 \times 10^{25} \text{m}^{-3}$) the gain is high for $\delta_d = 1$ but at $<5 \times 10^{25} \text{m}^{-3}$ gain is high for $\delta_d = 0.80$.

![Figure 5 Variation of effective Brillouin gain $g_B^{\text{eff}}$ with carrier concentration [ in terms of $\omega_p/\omega_0$] when $E_0 = 5 \times 10^7 \text{Vm}^{-1}$.

> Figure 5 Variation of effective Brillouin gain $g_B^{\text{eff}}$ with carrier concentration $n_0$, when $E_0 = 5 \times 10^7 \text{Vm}^{-1}$.

4. Conclusion: In present analysis, we have analytically studied the influence of CGs on the threshold intensity, effective susceptibility and Brillouin gain of the Stokes component. It is observed from the study that significant change in threshold and gain characteristics when the charge imbalance parameter is slightly changed. The presence of CGs plays a strong catalyzing effect in changing the Brillouin gain and the threshold value.

5. References
   doi: 10.1063/1.4926710
   doi: 10.1063/1.2163817

AUTHORS

First Author – P. S. Malviya, Govt. J.N.S. P.G. College, Shujalpur (M.P.)-465333,
   Email: psm_sehore@rediffmail.com
Second Author – N. Yadav, School of Studies in Physics, Vikram University, Ujjain (M.P.)-456010
Third Author – S. Ghosh, School of Studies in Physics, Vikram University, Ujjain (M.P.)-456010