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Carrier wave instability in the presence of electric and magnetic fields

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Using hydrodynamic model of plasmas the general dispersion relation has been derived incorporating the effects of diffusion, Hall field and hot carrier under the collision dominated regime when the d.c. magnetic field is applied along Z-axis parallel to the propagation vector and the d.c. electric field is inclined by an arbitrary angle θ with the Z-axis in the X-Z plane. The dispersion relation has been solved for the typical cases of n-InSb and nearly intrinsic InSb separately to study the possibility of wave instability. In n-InSb, a nearly stable carrier wave is obtained for $0° \leq \theta \leq 90°$. In intrinsic InSb nonoscillatory forward mode with considerable growth rate is obtained for $10^3 \leq k \leq 3 \times 10^4 m^{-1}$, $0.1 \leq B_0 \leq 1.0$ Tesla and $14.4 \leq E_0 \leq 18.0$ kVm^{-1}. At $k = 10m^{-1}$, $0.5 \leq B_0 \leq 1.0$ Tesla, $30° \leq \theta < 90°$ backward carrier wave oscillation with a large growth rate is observed.

1. Introduction

Bok and Nozieres (1963) first investigated the possibility of instability of the TEM waves in two component semiconductor-plasmas when the dc electric field $\mathbf{E}_0$, magnetic field $\mathbf{B}_0$ and the wave vector $\mathbf{k}$ are all in the same direction and obtained the threshold condition for the onset of the instability. It was shown by Misawa (1963) that a small arbitrary angle θ between $\mathbf{E}_0$ and $\mathbf{B}_0$ causes the coupling of the quasilongitudinal mode with the quasitransverse mode and leads to the instability in one component plasma in contrast to the result of Bok and Nozieres (1963). Hasegawa (1965) and Akai (1966) have studied instability for special conditions like $\theta = 0°$ and $90°$ under several assumptions. Freire (1970) analysed the active propagation of the slow cyclotron and slow helicon modes on the basis of kinetic power theorem neglecting the effect of Hall drift and diffusion when the drift velocity $\mathbf{V}_0$ makes an angle θ with both $\mathbf{B}_0$ and $\mathbf{k}$. Using kinetic theory, Brauer (1973) obtained the dispersion relation for $\theta = 90°$. Pic and Ligeon (1974) have studied the helicon wave propagation in InSb for the special case of $\theta = 90°$. Morisaki and Inuishi (1967) have observed experimentally the angular dependence of microwave emission from InSb on the applied magnetic field direction. Thus it can be seen that no systematic and detailed analysis of the effect of orientation of the electric field with the magnetic field on the instability of the carrier wave has been made. In contrast to earlier work, we have set up the general dispersion relation for the mixed mode (E_{1x}, E_{1y}, E_{1z}) and solved it numerically for a wide range of system parameters for extrinsic and intrinsic semiconductors. The analysis takes into account the effects of Hall drift and diffusion. A couple of interesting results have been obtained. As a typical case, calculations have been made for InSb at 77°K taking into account the appropriate scattering mechanisms and hot carrier effect which becomes important in the carrier wave propagation (Kobayashi and Fujisawa 1972). The result shows that in n-type semiconductor, the unstable mode propagates with a phase velocity (v_ϕ) of the order of the drift velocity of the electrons v_{oze} along the direction of propagation (such waves are known as carrier waves (Kobayashi and Fujisawa, 1972)). v_ϕ decreases with the increase of θ but increases with E_0 and is independent of B_0. The growth rate $|\omega_i|$ is very small for all values of θ and thus leads to nearly stable propagation. On the other hand, in the intrinsic semiconductor the growth rate of the unstable mode is such that it leads to nonoscillatory propagation since $|\omega_i| >> \omega_r$. This is in conformity with the result of Gueret (1968) in the absence of magnetic field and diffusion. Also when $0.5 \leq B_0 \leq 1.0$ Tesla, $k \approx 10\text{m}^{-1}$ and $\theta < 90°$, the backward carrier wave oscillation (with ω_r negative and $|\omega_i| > |\omega_r|$) is observed.

2. Theoretical Formulations

2.1. Dispersion Relation

Using hydrodynamic model of the plasmas, the general dispersion relation has been derived. The propagation of an electromagnetic wave and dc magnetic field $\mathbf{B}_0$ are taken along the Z-axis, the dc electric field $\mathbf{E}_0$ being in the X-Z plane making an arbitrary angle θ with the Z-axis. The ac part of the momentum transfer equation of the carriers, under the collision dominated regime ($\nu_j >> \omega, \omega_j$) including the effect of diffusion is given as

$$\nu_j v_{1j} = -\frac{e}{m_j}\left(\mathbf{E}_1 + v_{1j} \times \mathbf{B}_0 + \mathbf{v}_{0j} \times \mathbf{B}_1\right) + \frac{v^2_{thj}}{\rho_{0j}} \nabla \rho_{1j} \qquad (1)$$

where the suffix j is replaced by e and h for the electrons and holes respectively.

In writing eqn. (1), it is assumed that the variation of wave disturbances are slow in time and space compared with the microscopic variations due to collisions with lattice.

We have assumed that each of the variables $\mathbf{E}$, $\mathbf{B}$, $\mathbf{v}_j$ and ρ is the sum of a time invariant part (Subscript 0) and a small first order a.c. perturbation

(Subscript 1) which is proportional to [exp i $(\omega t-kz)$], e.g., $\mathbf{E} = \mathbf{E}_0 + \mathbf{E}_1 \times$ [exp i $(\omega t - kz)$] where ω and k represent the wave angular frequency and the wave number respectively. v_{thj} represents the thermal velocity of the j th species of the carrier given by $v_{thj} = (k_B T_j / m_j)^{\frac{1}{2}}$ where T_j is the carrier temperature.

Under the chosen configuration, eqn. (1) yields

$$v_{1xj} = -\frac{e}{m_j}\frac{\nu_j}{a_j^2}\frac{\bar{\omega}_j}{\omega}\left[E_{1x} + \frac{\omega_{cj}}{\nu_j}E_{1y}\right],$$

$$v_{1yj} = -\frac{e}{m_j}\frac{\nu_j}{a_j^2}\frac{\bar{\omega}_j}{\omega}\left[-\frac{\omega_{cj}}{\nu_j}E_{1x} + E_{1y}\right]$$

and

$$v_{1zj} = -\frac{e}{m_j\,\nu_j}\left[\frac{kv_{0xj}}{\omega}E_{1x} + \frac{kv_{0yj}}{\omega}E_{1y} + b_j E_{1z}\right]. \qquad (2)$$

where $a_j^2 = \nu_j^2 + \omega_{cj}^2$, $b_j = 1 + (kv_{thj}/\bar{\omega}_j)^2$ and $\bar{\omega}_j = \omega - \mathbf{k}\cdot\mathbf{v}_{0j}$ $= \omega - kv_{0zj}$, $\omega_{pj}^2 = n_{0j}\,e^2/m_j\,\epsilon_0\,\epsilon_l$ and $\omega_{cj} = eB_0/m_j$ and is negative for electrons and positive for the holes, ϵ_l is the lattice dielectric constant and ϵ_0 is the absolute permitivity.

The ac current density $\mathbf{J}_{1j}$ is given by

$$\mathbf{J}_{1j} = \rho_{0j}\,\mathbf{v}_{1j} + \rho_{1j}\cdot\mathbf{v}_{0j} \qquad (3)$$

where $\rho_{1j} = \rho_{0j}\,(k\,v_{1zj}/\bar{w}_j)$

Using equations (2) and (3) we obtain

$$J_{1xj} = \epsilon_0\,\epsilon_l\,w_{pj}^2\left[\left(-\frac{\nu_j}{a_j^2}\frac{\bar{w}_j}{w} + \frac{k^2 v_{0xj}^2}{\nu_j\,w\,\bar{w}_j}\right)E_{1x} + \left(\frac{w_{cj}}{a_j^2}\frac{\bar{w}_j}{w} + \frac{k^2 v_{0xj}\,v_{0yj}}{\nu_j\,w\,\bar{w}_j}\right)E_{1y} + \frac{kv_{0xj}}{\nu_j\,\bar{w}_j}\,b_j\,E_{1z}\right],$$

$$J_{1yj} = \epsilon_0\,\epsilon_l\,w_{pj}^2\left[\left(-\frac{\omega_{cj}}{a_j^2}\frac{\bar{w}_j}{\omega} + \frac{k^2 v_{0xj}\,v_{0yj}}{\nu_j\,w\,\bar{w}_j}\right)E_{1x} + \left(-\frac{\nu_j}{a_j^2}\frac{\bar{w}_j}{w} + \frac{k^2 v_{0yj}^2}{\nu_j\,w\,\bar{w}_j}\right)E_{1y} + \frac{kv_{0yj}}{\nu_j\,\bar{w}_j}\,b_j\,E_{1z}\right]$$

and

$$J_{1zj} = \epsilon_0\,\epsilon_l\,w_{pj}^2\,\frac{w}{v_j\,\bar{w}_j}\left[\frac{kv_{0xj}}{w}E_{1x} + \frac{kv_{0yj}}{w}E_{1y} + b_j\,E_{1z}\right]. \qquad (4)$$

The wave equation is given as

$$\mathbf{k} \times \mathbf{k} \times \mathbf{E}_1 = \mathrm{L}w\mu_0 \mathbf{J}_1 - \frac{w^2}{c_1^2} \mathbf{E}_1 \tag{5}$$

where μ_0 is the absolute permeability and c_1 is the velocity of electromagnetic wave in the lattice given by $c_1 = (1/\mu_0\varepsilon_0\varepsilon_1)^{\frac{1}{2}}$.

From equations (4) and (5) one gets

$$\begin{vmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{vmatrix} \begin{vmatrix} E_{1x} \\ E_{1y} \\ E_{1z} \end{vmatrix} = 0 \tag{6}$$

Thus the general dispersion relation is obtained as

$$\begin{vmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{vmatrix} = 0 \tag{7}$$

where

$$G_{xx} = k^2c_1^2 - w^2 + i \sum_{j=e,h} w_{dj}\, w_j \left(\frac{\nu_j^2}{a_j^2} + \frac{k^2 v_{oxj}^2}{w_j^2} \right),$$

$$G_{xy} = i \sum_{j=e,h} w_{pj}^2 \left(\frac{w_{cj}}{a_j^2}\, w_j + \frac{k^2 v_{oxj}\, v_{oyj}}{\nu_j\, w_j} \right),$$

$$G_{xz} = i \sum_{j=e,h} w_{dj}\, b_j\, w \frac{k v_{oxj}}{w_j},$$

$$G_{yx} = i \sum_{j=e,h} w_{pj}^2 \left(- \frac{w_{cj}}{a_j^2}\, w_j + \frac{k^2 v_{oyj}\, v_{oxj}}{\nu_j\, w_j} \right),$$

$$G_{yy} = k^2c^2_l - w^2 + i \sum_{j=e,h} w_{dj}\, \bar{w}_j \left(\frac{\nu^2_j}{a^2_j} + \frac{k^2 v^2_{oyj}}{\bar{w}^2_j} \right),$$

$$G_{yz} = i \sum_{j=e,h} w_{dj}\, b_j\, w \frac{kv_{oyj}}{\bar{w}_j}, \quad G_{zx} = i \sum_{j=e,h} w_{dj}\, w \frac{kv_{oxj}}{w_j},$$

and

$$G_{zy} = i \sum_{j=e,h} w_{dj}\, w \frac{kv_{oyj}}{\bar{w}_j}, \quad G_{zz} = - w^2 \left[1 - i \sum_{j=e,h} w_{dj}\, b_j \Big/ \bar{w}_j \right].$$

$\omega_{dj} = \omega_{pj}{}^2/\nu_j$ is the dielectric relaxation frequency of jthe species carrier.

2.2. Carrier Temperature

In the homogeneous semiconductor, dc part of the momentum transfer equation becomes

$$\nu_j\, \mathbf{v}_{oj} = -\frac{e}{m_j} \left(\mathbf{E}_o + \mathbf{v}_{oj} \times \mathbf{B}_o \right) \tag{8}$$

Under the present configuration we get the components of the drift velocity $\mathbf{v}_{oj}$ of the carrier as

$$\left.\begin{aligned} v_{oxj} &= -\frac{e}{m_j}\frac{\nu_j}{a^2_j} E_{ox}, \quad v_{oyj} = -\frac{\omega_{cj}}{\nu_j} v_{oxz} \\ \text{and} \quad v_{ozj} &= -\frac{e}{m_j\, \nu_j} E_{oz}. \end{aligned}\right\} \tag{9}$$

The carrier temperature T_j is obtained from the energy balance eqution in the steady state

$$(\mathbf{J}_{oj} \cdot \mathbf{E}_o / n_{oj}) = \langle \delta\varepsilon/\delta t \rangle_{po} \tag{10}$$

where $\langle \delta\varepsilon/\delta t \rangle_{po}$ represents the average rate of loss of energy of a carrier due to polar optical phonon scattering.

Using equation (9) we obtain

$$\left(\mathbf{J}_{oj}\, \mathbf{E}_o / n_{oj} \right) = \frac{e^2}{m_j\, \nu_j} \left[\frac{\nu_j{}^2}{a_j{}^2} \operatorname{Sin}^2\theta + \operatorname{Cos}^2\theta \right] E_o{}^2 \tag{11}$$

where $E_{ox} = E_o \operatorname{Sin}\theta$ and $E_{oz} = E_o \operatorname{Cos}\theta$.

Following Stratton (1958) we have

$$< \delta\, \varepsilon/\delta t >_{po} = \left(\frac{2k_B \Theta_D}{\pi\, m_j}\right)^{\frac{1}{2}} e\, E_{oj}\, \frac{\exp(x_o - x_j) - 1}{\exp(x_o) - 1}$$

$$\times\; x_j^{\frac{1}{2}}\; e^{x_j/2}\, K^o (x_j/2) \tag{12}$$

Using equations (10), (11) and (12) one can obtain the carrier temperature T_j as a function of the electric field for different values of B_0 and θ.

The momentum transfer collision frequency ν_j of the carriers is taken to be due to acoustic phonon scattering and is given as (Conwell 1967)

$$\nu_j = \nu_{oj}(T_j / T_0)^{\frac{1}{2}} \tag{13}$$

ν_{oj} is the collision frequency of the carrier at $T_j = T_0$.

3. Result and Discussion

3.1. Extrinsic Semiconductor

Equation (7) represents the dispersion relation for the mixed mode (E_{1x}, E_{1y} and E_{1z}). At $\theta = 90°$, the formation of mixed mode due to the coupling between the quasilongitudinal and quasitransverse has been mentioned by Hasegawa (1965) and Brauer (1973) which can also be obtained from our dispersion relation. When $\theta = 0°$ and $90°$, our configuration becomes identical to the case I and case II of Hasegawa who has solved the dispersion relation under various assumptions. To obtain meaningful solutions of the dispersion relation for a wide range of system parameters, we have solved it numerically with the help of the computer IBM 360/44. As a typical case, we have taken n-InSb at 77°K with the following physical constants:

Debye Temperature	Θ_D	$= 278°K$,
Lattice dielectric constant	ϵ_l	$= 17.88$,
Optical dielectric constant	ϵ_∞	$= 15.58$,
Electron effective mass	m_e	$= 0.014\ m_0$,
Electron collision frequency at 77°K,	ν_{oe}	$= 3.5 \times 10^{11} sec^{-1}$,
Electron concentratration	n_{oe}	$= 4.0 \times 10^{20} m^{-3}$.

Equation (7) reduces to the following from under quasistatic approximation ($k^2 c_l^{\,2} >> \omega^2$):

$$A_1\omega^3 + A_2\omega^2 + A_3\omega + A_4 = 0 \tag{14}$$

where
$$A_1 = \rho_1$$
$$A_2 = -3\rho_1 kv_{0z} - i\rho_2$$
$$A_3 = 3\rho_1 k^2 v_{0z}^2 + \rho_4 + i2\rho_2 kv_{0z},$$
$$A_4 = -kv_{0z}(\rho_2 k^2 v_{0z}^2 + \rho_4) + i(\rho_3 - \rho_2 k^2 v_{0z}^2),$$
$$\rho_1 = (\omega_{pe}^2 \omega_{ce}/a_e^2)^2 + (\omega_{de} \nu_e^2/a_e^2)^2,$$
$$\rho_2 = \omega_{de}[b_e(\omega_{pe}^2 \omega_{ce}/a_e^2)^2 + b_e(\omega_{de} \nu_e^2/a_e^2)^2 + 2k^2 c_1^2 \nu_e^2/a_e^2],$$
$$\rho_3 = \omega_{de} k^4 c_1^2 (b_e c_1^2 - v_{0x}^2 - v_{0y}^2)$$
and
$$\rho_4 = (k\omega_{de} \nu_e/a_e)^2 (v_{0x}^2 + v_{0y}^2 - 2b_e c_1^2 - k^4 c_1^4).$$

The wave will grow temporally in the forward direction when ω_r is positive and $\omega_i < 0$ (Hsieh 1974, Hasegawa 1975). The numerical analysis shows

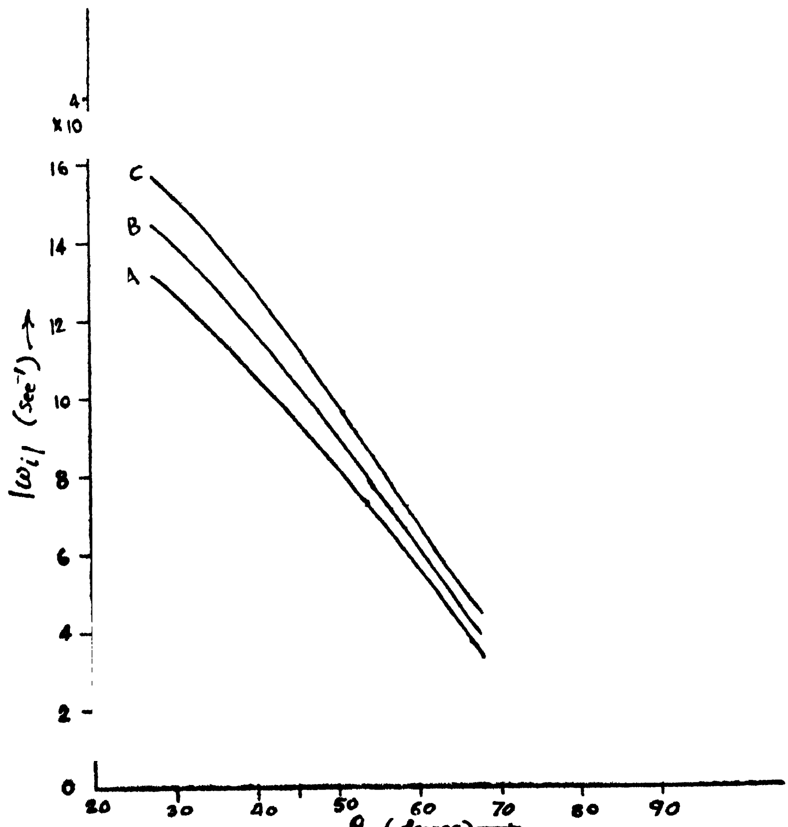

Fig. 1. Variation of the phase velocity $v\phi$ with the angle θ in n-InSb. A, $E_0 = 14.4$ kVm^{-1}; B, $E_0 = 16.2$ kVm^{-1}; C, $E_0 = 18.0$ kVm^{-1}.

that for single stream the growth rate $|\omega_i|$ is very small in comparison with the phase constant for $0 \leq \theta < 90°$. Thus it leads to nearly stable propagating mode. Fig. 1 shows the variation of the phase velocity $v_\phi (= \omega_r/k)$ with θ and E_0. v_ϕ decreases with the increase of θ but increases with E_0 and is independent of both B_0 and k. When $\theta = 90°$, no instability is seen to be present which is in agreement with Akai's result (1966) for configuration D and is due to the fact that at $\theta = 90°$, $v_{0ze} = 0$.

3.2. Intrinsic Semiconductor

For two types of carriers (viz., electrons and holes), the dispersion relation (7) reduces to the following form under quasistatic approximation :

$$B_1\omega^4 + B_2\omega^3 + B_3\omega^2 + B_4\omega + B_5 = 0 \tag{15}$$

where

$$B_1 = y_2 + y_3 + y_5 + Z_6,$$

$$B_2 = -kv_{0ze}(4y_2 + 3y_3 + y_5 + 2Z_6) - iZ_3,$$

$$B_3 = k^2v^2_{0ze}(6y_2 + 3y_3 + Z_6) + kv_{0ze}(Z_1 - y_1) - (y_4 + Z_5) + i(2Z_3kv_{0ze} - Z_4),$$

$$B_4 = -k^3v^3_{0ze}(4y_2 + y_3) + kv_{0ze}(Z_1 - y_1 + 2Z_5) + i[kv_{0ze}(Z_4 - Z_3kv_{0ze}) + Z_2],$$

$$B_6 = k^2v^2_{0ze}(y_2k^2v^2_{0ze} - Z_5) + iZ_2kv_{0ze},$$

$$Y_1 = \omega_{de}^3k^3v_{0xe}v_{0ye}\omega_{ce}\nu_e/a_e^2,$$

$$Y_2 = \omega_{dh}(\omega_{de}\omega_{ce}\nu_e/a_e^2)^2,$$

$$Y_3 = \left(\omega_{de}\omega_{ce}\nu_e/a_e^2\right)\left(\frac{\omega_{de}^2\omega_{ce}\nu_e}{a_e^2} + 2\frac{\omega_{dh}^2\omega_{ch}\nu_h}{a_h^2}\right),$$

$$Y_4 = k^2\omega_{de}^2v_{0xe}^2\omega_{dh}\nu_h^2/a_h^2,$$

$$Y_5 = \omega_{de}(\omega_{dh}\omega_{ch}\nu_h/a_h^2)^2,$$

$$Z_1 = k^2\omega_{de}[k^2c_1^4 - v^2_{0xe}(\omega_{de} + \omega_{dh})\omega_{dh}\nu_h^2/a_h^2 - (\omega_{dh}\nu_hv_{0ye}/a_h)^2],$$

$$Z_2 = k^4c_1^2\omega_{de}\omega_{dh}(v_{0xe}^2 + v_{0ye}^2),$$

$$Z_3 = (k^2c_1^2\omega_{dh}\nu_h^2/a_h^2)(\omega_{de} + 2\omega_{dh}),$$

$$Z_4 = k^2 c^2\, ^2\omega_{\mathrm{I}}\ \omega_{\mathrm{de}}\ \omega_{\mathrm{dh}}\ \nu_{\mathrm{h}}\ ^2/a_{\mathrm{h}}\ ^2, \quad Z_5 = k^4 c^4\ ^4\omega_{\mathrm{I}}\ _{\mathrm{dh}}$$

and
$$Z_6 = \omega_{\mathrm{dh}}\ (\omega_{\mathrm{dh}}\ \omega_{\mathrm{ch}}\ \nu_{\mathrm{h}}\ /a_{\mathrm{h}}\ ^2)^2 + (\omega_{\mathrm{d}} + \omega_{\mathrm{dh}})\ (\omega_{\mathrm{dh}}\ \nu_{\mathrm{h}}\ ^2/a_{\mathrm{h}}\ ^2)^2$$

$$+2\omega_{\mathrm{de}}\ ^2\omega_{\mathrm{ce}}\ \nu_{\mathrm{e}}\ \omega_{\mathrm{dh}}\ \omega_{\mathrm{ch}}\ \nu_{\mathrm{h}}\ /a_{\mathrm{e}}\ ^2 a_{\mathrm{h}}\ ^2 .$$

We have neglected the effect of diffusion in the longwavelngth region and assumed $v_{oe} >> v_{oh}$ along all the three directions. Equation (15) has been solved for nearly intrinsic InSb at 77°K with the additional physical cons'ants :

Hole effective mass	$m_e = 0.4\ m_0$,
Hole collision frequency at 77°K,	$\nu_{oh} = 4.4 \times 10^{11}$ sec^{-1},
Hole concentration	$n_{oh} = 1.6 \times 10^{21}$m^{-3}.

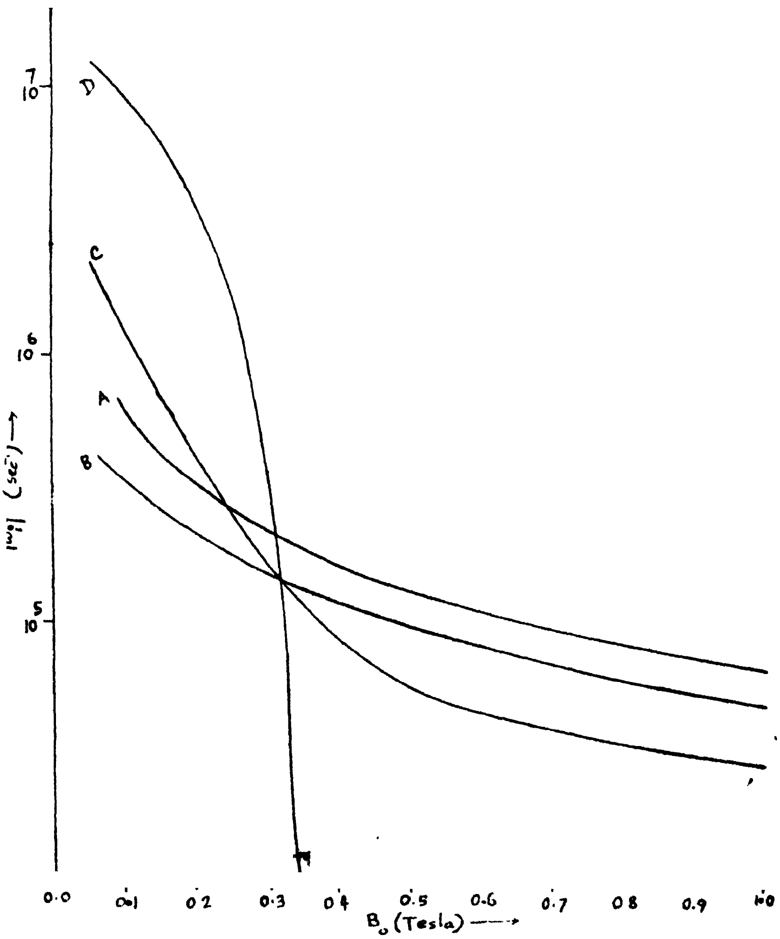

Fig. 2. Variation of the growth rate $|\omega_i|$ with the magnetic field in nearly intrinsic InSb at $k=5000$ m^{-1}, $E_0=16.2$ kVm^{-1}. A, $\theta=30°$; B, $\theta=45°$; C, $\theta=60°$; D, $\theta=90°$.

The numerical analysis has been made for $30° \leq \theta \leq 90°$, $0.1 \leq B_0 \leq 1.0$ Tesla, $14.4 \leq E_0 \leq 18$ kVm^{-1} and $10^3 \leq k \leq 3\times10^4 m^{-1}$. It is always seen that for the unstable forward mode, $\omega_r \leq |\omega_i|$ and hence, the mode is nonoscillatory in nature. Figures 2 to 4 show the variation of growth rate $|\omega_i|$ with system parameters. From Fig. 2, we notice that for $\theta = 90°$, the instability is seen only for $B_0 \leq 0.20$ Tesla. Fig. 3 shows that the growth rate

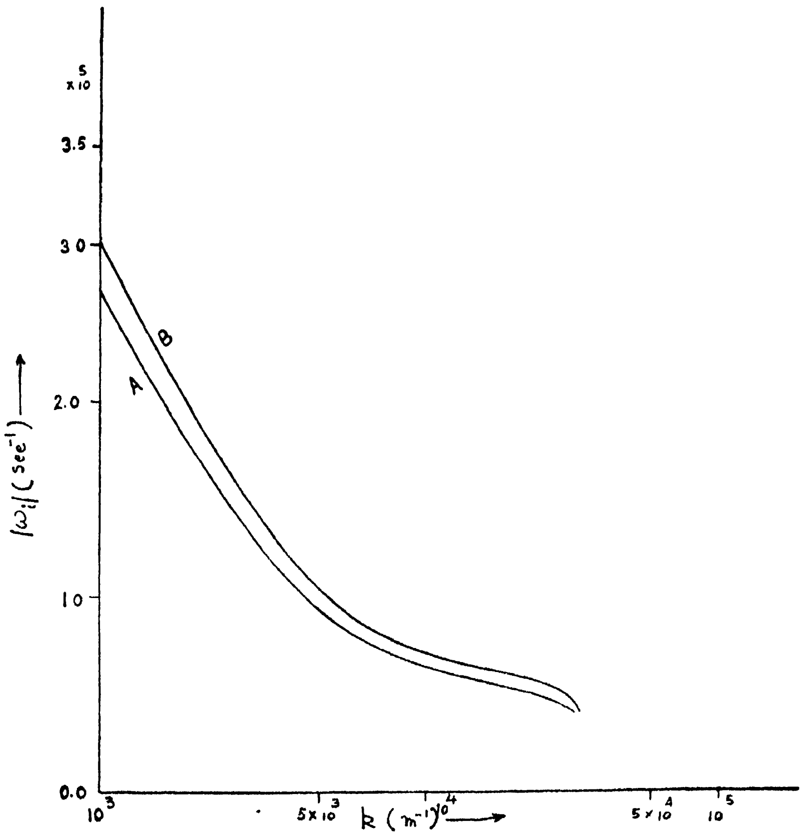

Fig. 3. Variation of $|\omega_i|$ with the wave number k for nearly intrinsic InSb at $\theta=45°$, $B_0=0.5$ Tesla A, $E_0=14.4$ kVm^{-1}; B. $E_0=16.2$ kVm^{-1}.

decreases fast with the increase of the wave number k. For $k >> 3\times10^4 m^{-1}$, $|\omega_i|$ becomes so small that the mode becomes almost stable. With the electric field, $|\omega_i|$ increases slowly but at higher values of k, it becomes almost independent of E_0. From fig. 4 one can see that the growth rate decreases very fast with the increase of θ and for $\theta \sim 90°$, there is no growth ($|\omega_i| \approx 0$).

Johnson (1955) has experimentally realised the backward wave oscillator and has shown that when the beam current is low it leads to regenerative amplification and for high beam current, the tube oscillates. We also observe background unstable mode ($\omega_r<0$) when k is small. When the growth rate of the forward mode decreases, the backward mode increases. Fig. 5 illustrates

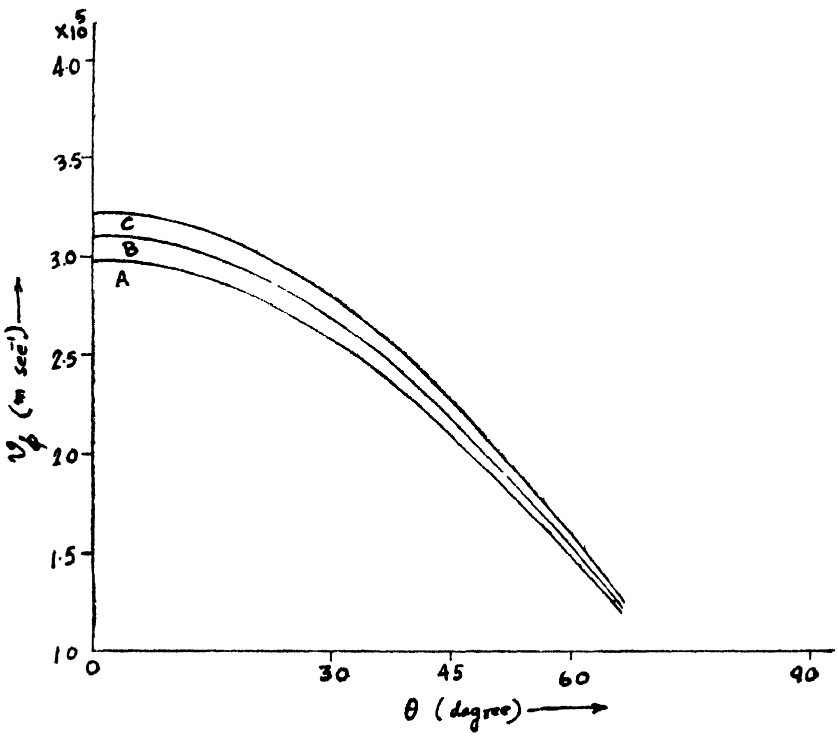

Fig. 4. Variation of $|\omega_i|$ with θ for nearly intrinsic InSb at $k=5000$ m^{-1}. $B_0=0.5$ Tesla. A, $E_0=14.4$ kVm^{-1}; B, $E_0=16.2$ kVm^{-1}; C, $E_0=18.0$ kVm^{-1}.

the variation of the growth rate and the phase velocity of this mode. The phase velocity of this mode is of the order of the drift velocity of the electron (v_{oze}) along the direction of propagation. The growth rate is found always greater than $|\omega_r|$ ($|\omega_r|$ being in the MHz region). Its variation with θ is similar to that of the forward mode but its dependence on the magnetic field is opposite. The phase velocity decreases with the magnetic field and the angle θ. As $\theta\rightarrow 90°$, v_ϕ becomes very large and instability vanishes.

Conclusion

Carrier wave instability of the mixed mode (E_{1x}, E_{1y} and E_{1z}) has been analysed. In an extrinsic semiconductor, the wave propagates as a stable one. In intrinsic semiconductor, two types of modes viz. forward and backward are unstable. The forward mode is a nonoscillatory one whereas the backward mode is a carrier mode with a large growth rate. The possibility of the backward wave oscillator is analysed.

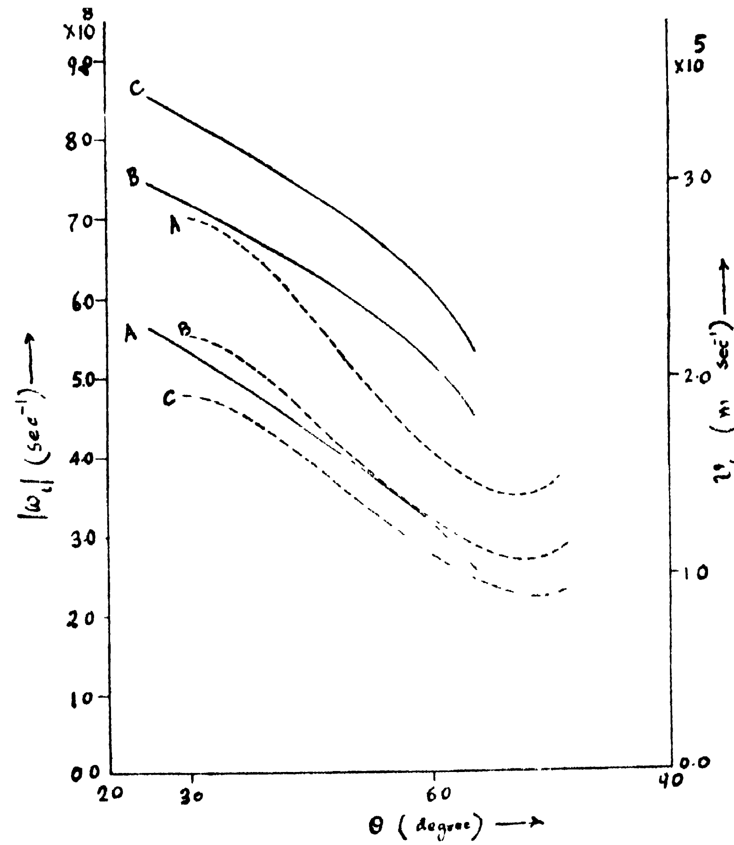

Fig. 5. Variation of $|\omega_i|$ and $|v_\phi|$ of the backward mode in nearly intrinsic InSb at $k=10\ m^{-1}$, $E_0=14.4\ kVm^{-1}$. A, $B_0=0.5$ Tesla; B. $B_0=0.8$ Tesla C, $B_0=1.0$ Tesla. Continuous curve for $|\omega_i|$ and broken curve for $|v_\phi|$

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