PHASE-SHIFT OF LIGHT CONTROLLED BY CURRENT ACROSS A MAGNETIC FIELD IN SEMICONDUCTORS IN THE VOIGT CONFIGURATION

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ABSTRACT

It is shown that a large phase-shift is expected for light (of wavelengths in the infrared) propagating through narrow-gap semiconductors, such as InSb, along the direction of $J \times H$ force from the notable effect of the electromagnetic excitation, especially at high currents and high magnetic fields, which enables us to control the phase-shift by the current even at room temperature. Discussions are also made on the inverted population which plays essential role on this phenomenon, besides the amplifying action.

1. INTRODUCTION

In these years we have been studying a pumping action of the electromagnetic force for photons of wavelength $\lambda \approx ch/E_g$, corresponding to the energy gap E_g of narrow-gap semiconductors, such as InSb ($E_g \approx 0.23$ eV), through which a current density J is passing across a magnetic field H [1-5]. In the course of the investigation of the inverted population caused by the electromagnetic excitation, we have conceived that the electromagnetic force ($J \times H$ force) should cause a notable phase-shift and enhance the Voigt ellipticity of a light propagating along the direction of $J \times H$ force, as illustrated in Fig. 1, besides the pronounced pumping (amplifying) action. This can be regarded as a natural extension of the concept of Voigt effect [6]. In particular, it must have a useful application that the plane of polarization of light propagating through a semiconductor can be controlled by the conduction current in the non-linear region of the voltage-current characteristics disclosed recently under high magnetic fields [7].

FIG. 1. Schematic drawing of rotation of polarization plane of light propagating through semiconductors along the direction of $J \times H$ in the Voigt configuration ($k \perp H$).

2. THEORY OF PHASE-SHIFT IN TWO-BAND MODEL

Let us first consider the Voigt phase-shift, in the case of $J = 0$, for a propagating light with wave vector k and angular frequency ω incident upon an intrinsic semiconductor having n_1 electrons and n_2 holes per cm^3 in the Voigt configuration ($k \perp H$) as shown in Fig. 1. Suppose that $k \parallel \hat{y}$, $H \parallel \hat{z}$, and the polarization of the E_{rf} vector of light makes an angle φ ($\neq 0, \pi/2$) with respect to H and assume $\omega\tau \gg 1$, τ being the relaxation times of electrons and holes. For the propagating light with angular frequency ω , which satisfies the relation $E_g > \hbar\omega > \hbar\omega_p$, ω_p being the plasma frequency, the dispersion relation can be written as follows in terms of the dielectric tensor ϵ_{ij} ; the wave vector, k_o , of the ordinary mode ($E_{rf,o} \parallel H$) is expressed as

$$k_o^2 = (\omega/c)^2 \epsilon_{zz} = (\omega/c)^2 \epsilon_{\infty} [1 - (\omega_{p1}/\omega)^2 - (\omega_{p2}/\omega)^2], \quad (1)$$

and the wave vector, k_e , of the extraordinary mode ($E_{rf,e} \perp H$) is expressed as

$$\begin{aligned} k_e^2 &= (\omega/c)^2 (\epsilon_{xx} + \epsilon_{xy}^2 / \epsilon_{yy}) \approx (\omega/c)^2 \epsilon_{xx} \\ &= (\omega/c)^2 \epsilon_{\infty} [1 + \omega_{p1}^2 / (\omega_{c1}^2 - \omega^2) + \omega_{p2}^2 / (\omega_{c2}^2 - \omega^2)], \end{aligned} \quad (2)$$

where the dielectric tensor ϵ_{ij} is connected with the conductivity tensor σ_{ij} by the relation [6]

$$\epsilon_{ij} = \epsilon_{\infty} \delta_{ij} - i(4\pi/\omega) \sigma_{ij}, \quad (3)$$

and $\epsilon_{yy} \gg \epsilon_{xy}$ is utilized since $n_1 \approx n_2$. Here, δ_{ij} is the Kronecker's delta, ϵ_{∞} is the high frequency dielectric constant of the medium, ω_{pi} is the plasma angular frequency, and ω_{ci} is the cyclotron angular frequency given, respectively, by

$$\omega_{pi}^2 = 4\pi n_i e^2 / m_i \epsilon_{\infty}, \quad \omega_{ci} = eH / m_i c, \quad (i = 1, 2) \quad (4)$$

for electrons ($i = 1$) and holes ($i = 2$), where e is the electronic charge, c the light velocity, n_i the carrier concentration, and m_i the effective mass of electrons or holes. Expanding the roots of eqs.(1) and (2), by use of $\omega \gg \omega_{pi}$, ω_{ci} , to get k_o and k_e , we have a useful expression for the Voigt phase-shift, δ , per unit path, between the ordinary and extraordinary modes as follows [8];

$$\delta = k_o - k_e = \frac{\sqrt{\epsilon_{\infty}}}{2c\omega^3} (\omega_{p1}^2 \omega_{c1}^2 + \omega_{p2}^2 \omega_{c2}^2). \quad (5)$$

This is the general expression of the Voigt ellipticity for the 2-band model of electrons and holes. For compensated electron-hole plasmas, putting $n_1 = n_2 = n_o$ in eq.(5), we have

$$\delta = \frac{2\pi n_o e^4 H^2}{\sqrt{\epsilon_{\infty}} c^3 \omega^3} \left[\left(\frac{1}{m_1}\right)^3 + \left(\frac{1}{m_2}\right)^3 \right], \quad (6)$$

where n_o is the electron concentration in thermal equilibrium. Equation (5) indicates that the Voigt effect is additive with respect to electrons and holes, whereas the Faraday rotation vanishes when $n_1 = n_2$.

Next we consider the effect of the $J \times H$ force on the Voigt ellipticity when $J \neq 0$. Let $J // \hat{x}$, and $H // \hat{z}$, then electrons and holes are driven by the $J \times H$ force to the $-y$ direction with the same drift velocity v_d ($// -\hat{y}$), since the Hall electric field E must vanish at high magnetic fields when $n_1 = n_2$. Then, the angular frequency of light, ω , sensed by the drifting electrons and holes with drift velocity v_d should be Doppler shifted to $\omega' = \omega \pm kv_d$. However, this shift can be neglected, since $\omega \gg kv_d$ when $\omega \gg \omega_p$ [9]. Thus, the most important effect of the $J \times H$ force emerges as the increase in the carrier number due to the excitation, especially through the valence to conduction bands breakthrough [7,10], as long as the parabolic band model is assumed. Although having the analytical expression for the effective carrier concentration n^* is difficult when the interband breakthrough takes place, the value could be evaluated from the voltage-current characteristics as will be discussed in the following section. Therefore, in the present case we can merely replace the electron concentration n_o by the effective concentration n^* in eq.(6), and then we have the expression for the Voigt phase-shift per unit path [8];

$$\delta = \frac{2\pi n^* e^4 H^2}{\sqrt{\epsilon_{\infty}} c^3 \omega^3} \left[\left(\frac{1}{m_1}\right)^3 + \left(\frac{1}{m_2}\right)^3 \right]. \quad (7)$$

3. POPULATION INVERSION AND VOLTAGE-CURRENT CHARACTERISTICS

Now, let us consider the population inversion caused by the electromagnetic excitation at high magnetic fields. Figure 2 shows the voltage-current characteristics of n-InSb at 80 K for given transverse magnetic fields, which were first disclosed by us [7,10]. The dimension of the sample were 4 mm long, 0.55 mm wide, and 0.2 mm thick. The carrier concentration n_o and the Hall mobility μ at 77 K were $1 \times 10^{15} \text{ cm}^{-3}$ and $3 \times 10^5 \text{ cm}^2/\text{Vs}$, respectively. The values of n_o and μ at 293 K were $2.1 \times 10^{16} \text{ cm}^{-3}$ and $6.1 \times 10^4 \text{ cm}^2/\text{Vs}$, respectively. As can be seen in the figure, an S-type negative resistance arises under the application of high magnetic fields. The value of the critical current density J for occurrence of the negative resistance becomes considerably smaller as the strength of the magnetic field increases. In the case of $H = 0$, the V-I curve shows merely Zener-type breakthrough, but no indication of negative resistance was observed. After some computations, it has been confirmed that the negative resistance is caused by the

FIG. 2. V-I characteristics of InSb at 80 K. $J \perp H$.

valence to conduction bands breakthrough, which takes place when the condition,

$$(J_c H / n^* c) l^*(H) \approx E_I, \quad (8)$$

is satisfied at high currents and high magnetic fields [7,10], indicating the significant role of the $J \times H$ force in compensated electron-hole plasmas under high magnetic fields. Here, $E_I \approx (3/2)E_g$ is the ionization energy of electron-hole pairs [11], J_c is the critical current density at which $dE/dJ = 0$, n^* is the effective carrier concentration, $l^*(H)$ is an effective ambipolar diffusion length, being interpreted as the distance by which the excess carriers excited by the $J \times H$ force can move along the lines of force ($\parallel \hat{y}$) until they are annihilated by the recombination. In the present case, the value of $l^*(H)$ are reasonably estimated to be 2.0 μm , 1.2 μm and 0.8 μm , respectively, for magnetic fields of 5, 10 and 20 kG, in accordance with the order of the ambipolar diffusion length expected from the life time [12], and so the left-hand side of eq.(8) can be regarded as the acquired energy of an electron accelerated by the $J \times H$ force while the electron can move freely in advance the recombination. Thus, we can understand that eq.(8) is the condition for initiation of the multiplication of electron-hole pairs (avalanche) through the interband breakthrough by the action of $J \times H$ force. If the kinetic energy gained in the acceleration exceeds the value E_I , the avalanche will follow, decreasing drastically in the resistivity at higher currents.

In fact, by application of high magnetic fields, H , along the z -direction, the effective (induced) electric field, E^* , equivalent to the $J \times H$ force acting along the $-y$ -direction, becomes stronger than the longitudinal electric field, E , along the x -direction ($J \parallel \hat{x}$), which might cause impact ionization [13] at current as high as $I \approx 15$ A if there were no application of transverse magnetic fields; for $H = 20$ kG and $J = 4.5$ kA/cm², the value of E^* defined by $E^* = (JH/n^*c)$ becomes as high as 4.9 kV/cm. Thus, we can see that such a high value of E^* could easily cause the interband breakthrough in narrow-gap semiconductors, such as InSb, which gives rise to drastic increase of carrier concentration and leads to a highly inverted population resulting in lasing for light of wavelength, $\lambda \approx hc/E_g$, [10]. The value of the effective carrier concentration, n^* , for the case of $H = 20$ kG and $J = 30$ kA/cm², is estimated to be 1.8×10^{16} cm⁻³ at 80 K from the steady state V-I characteristics of Fig. 2, although this value of n^* is never the peak value at the excitation but the considerably smaller mean value during the excitation and the recombination relaxation [10].

At room temperature, a similar interband breakthrough has been observed, as shown in Fig. 3, at high currents and high magnetic fields, indicating a notable increase in the effective carrier concentration n^* , and hence suggesting a remarkable increase of the Voigt phase-shift at high currents.

4. EVALUATION OF ENHANCEMENT OF THE VOIGT PHASE-SHIFT BY CONDUCTION CURRENT

In Figs. 4 and 5, the Voigt phase-shift per unit path, δ , calculated from eq.(7) by using the value of n^* estimated from the V-I characteristics

FIG. 3. V-I characteristics of InSb at 293 K. $J \perp H$.

FIG. 4. Current dependence of the Voigt phase-shift per unit path, δ , estimated for 10.6 μm light propagating in InSb in the configuration $k \parallel J \times H$ at 293 K.

at 293 and 80 K, are shown for incident light of wavelength $10.6 \mu\text{m}$. Here appropriate values of the parameters, $\epsilon_\infty = 15.7$, $m_1 = 0.0133 m_0$ and $m_2 = 0.18 m_0$, m_0 being the electron rest mass, are assumed. The calculated value at 80 K for $J = 0$, of course, agrees well with the experimental value by Teitler et al. [14], if the difference in the value of carrier number and wavelength is taken into account. The relatively large value of δ at room temperature comes from the large value of n^* owing to the large value of the intrinsic carrier concentration ($n_i = 2.1 \times 10^{16} \text{ cm}^{-3}$ at 293 K). Anyway, it is interesting to see that the value of the Voigt phase-shift δ is much enhanced by the conduction current and increases rapidly with increasing current in the nonlinear region of the V-I curve even at room temperature, whereas the Faraday rotation vanishes because of $n_1 = n_2$. This outstanding result must have useful applications in controlling the phase-shift and hence modulating the intensity of the incident light by current flow in combination with a suitable polarizer.

In the case of $E_{F1} - E_{F2} > \hbar\omega > E_g$, where E_{F1} and E_{F2} are the quasi Fermi levels for electrons and holes, respectively, the incident light is to be amplified by means of the stimulated emission [3,4,10], besides the phase-shift discussed so far. In this case, the multiplication of photons takes place, consequently the quantum mechanical treatment is needed in a strict sense. Nevertheless, the classical expression (7), using effective carrier concentration n^* , seems to be still valid at least formally, when it is taken into account that the polarization of photons has to be conserved at the stimulated emission. In the simple estimate, the value of δ for this amplifying frequency range ($\lambda \approx 5.3 \mu\text{m}$ for InSb) becomes $\sim 1/8$ because of the λ dependence. However, the value might be much larger than that, when the multiple reflection of light by the surfaces of the sample has to be taken into account for the lasing mode.

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FIG. 5. Current dependence of the Voigt phase-shift per unit path, δ , estimated for $10.6 \mu\text{m}$ light propagating in InSb in the configuration $k \parallel J \times H$ at 80 K.