

# Terahertz Oscillation of Longitudinal Waves in a Solid State Plasma

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**Abstract:** We have clarified by the computer analysis of the dispersion equation for longitudinal waves that the terahertz oscillation occurs in a solid state plasma in InSb under an external dc magnetic field. It has been reported that the terahertz radiations occur from various semiconductors using the irradiation of the laser beams to the semiconductors. In all of the previous studies the laser beams were necessary to radiate the terahertz waves. We propose the first report on the terahertz oscillation in a semiconductor without the irradiation of the laser beams. The computer analysis to calculate the dispersion equation for longitudinal waves in the solid state plasma in InSb is performed for arbitrary orientations of the carrier drift velocity relative to the external magnetic field. It is found that the absolute instability corresponding to the terahertz oscillation occurs at the high electron-hole plasma density. The oscillation frequencies of terahertz waves are varied by the electron-hole density, the external magnetic field and the angle  $\theta$ , where  $\theta$  is an angle between the carrier drift velocity and the external magnetic field. It is found by the computer analysis that the maximum frequency is 3.54 THz at the electron-hole density of  $n_0 = 5 \times 10^{18} \text{ cm}^{-3}$  and the transverse magnetic field of  $B_0 = 20 \text{ kG}$ . In this case the wavelength  $\lambda$  of terahertz waves is 22.4 nm and the phase velocity  $v_p$  is  $0.79 \times 10^7 \text{ cm/sec}$ .

**Keywords:** Terahertz oscillation, Solid state plasma, InSb, Absolute instability, Longitudinal waves

## 1. INTRODUCTION

In recent years, there have been many reports on the terahertz radiations [1–7]. The frequencies of the terahertz waves are in the range about from 100 GHz to 10 THz. It has been reported that the terahertz radiations occur from semiconductors using the irradiation of the laser beams. Many of the compound semiconductors such as GaAs, InP, InAs and InSb have been used to occur the terahertz radiations. In all of the previous studies the laser beams were necessary to radiate the terahertz waves from those semiconductors.

There are two types of instabilities in the solid state plasma, that is, the convective instability corresponding to spatial amplification and the absolute instability corresponding to the oscillation. We have presented a theoretical analysis of the instabilities for longitudinal waves (density waves) in the solid state plasmas and clarified by a computer analysis of the dispersion equation for longitudinal waves that the convective and absolute instabilities occur in an electron-hole plasma in InSb. The frequencies of the instabilities are in the region of microwaves and millimeter waves [8–10].

Recently, it is found by further detailed computer analysis that the absolute instability occurs in the region of terahertz waves in InSb by increasing the electron-hole plasma density. In this study the terahertz oscillation occurs

without the irradiation of the laser beams to the semiconductor. The oscillation frequencies are varied by the electron-hole plasma density, the external magnetic field and the angle  $\theta$ .

In this paper, we describe the terahertz oscillation with the computer analysis of the dispersion equation for longitudinal waves in the solid state plasma in InSb under the external magnetic field. We also discuss the properties of the terahertz oscillation when the electron-hole plasma density, the external magnetic field and the angle  $\theta$  vary.

## 2. DISPERSION EQUATION AND A METHOD OF ANALYSIS

The dispersion equation for longitudinal waves in solid state plasmas for arbitrary orientations of a carrier drift velocity relative to an external magnetic field  $B_0$  [11] is

$$\sum_{i=e,h} [\omega_{pi}^2 \{(\omega - kv_{oi} - jv_{ci})^2 - \omega_{ci}^2 \cos^2 \theta\}] / [(\omega - kv_{oi})(\omega - kv_{oi} - jv_{ci}) \{(\omega - kv_{oi} - jv_{ci})^2 - \omega_{ci}^2\} - k^2 v_{Ti\perp}^2 (\omega - kv_{oi} - jv_{ci})^2 \sin^2 \theta - k^2 v_{Ti\parallel}^2 \{(\omega - kv_{oi} - jv_{ci})^2 - \omega_{ci}^2\} \cos^2 \theta] = 1, \quad (1)$$

where the summation in Eq. (1) is over the electrons and the holes, the symbols  $e$  and  $h$  denote the electrons and the holes, respectively. The additional subscript  $0$  refers to the dc value of the respective quantities, and

$\omega_{pi}$  plasma frequency of carriers.  
 $\omega_{ci}$  cyclotron frequency of carriers.  
 $v_{ci}$  collision frequency of carriers.

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- $v_{oi}$  dc carrier drift velocity.
- $v_{Ti\perp}$  transverse thermal velocity of carriers.
- $v_{Ti\parallel}$  longitudinal thermal velocity of carriers.
- $\theta$  angle between the carrier drift velocity and the external magnetic field.

The values of physical quantities and equations used in the numerical computations of the dispersion equation in the solid state plasma in InSb at 77 K are as follows.

$$\begin{aligned}
 m_e &= 0.013m_o \text{ (} m_o \text{; the mass of free electrons),} \\
 m_h &= 0.55m_o, \mu_e = 200,000 \text{ cm}^2/\text{Vsec}, \\
 \mu_h &= 10,000 \text{ cm}^2/\text{Vsec}, v_{oe} = 8 \times 10^7 \text{ cm/sec}, \\
 v_{oh} &= v_{oe} (\mu_h/\mu_e), \epsilon = 17.5\epsilon_o \text{ (} \epsilon_o \text{; dielectric constant in} \\
 &\text{free space),} \\
 T_{e\parallel} &= T_{h\parallel} = 260 \text{ K}, T_{e\perp} = T_{e\parallel} / \{1 + (\mu_e B_o)^2\}, \\
 T_{h\perp} &= T_{h\parallel} / \{1 + (\mu_h B_o)^2\}, n_{oe} = n_{oh} = n_o.
 \end{aligned}$$

(See the reference No. 11 on further detailed notations for those physical quantities)

On the computer analysis of the dispersion equation we used the mapping operation for determining the nature of absolute instability in the plasmas as previously presented by Bers *et al.* [12] and Briggs [13]. An absolute instability is obtained whenever there is a double root of wave number  $\kappa$  for some complex angular frequency  $\omega$  in the lower-half  $\omega$ -plane, that is, the absolute instability occur when the saddle point is formed in the upper-half  $\kappa$ -plane.

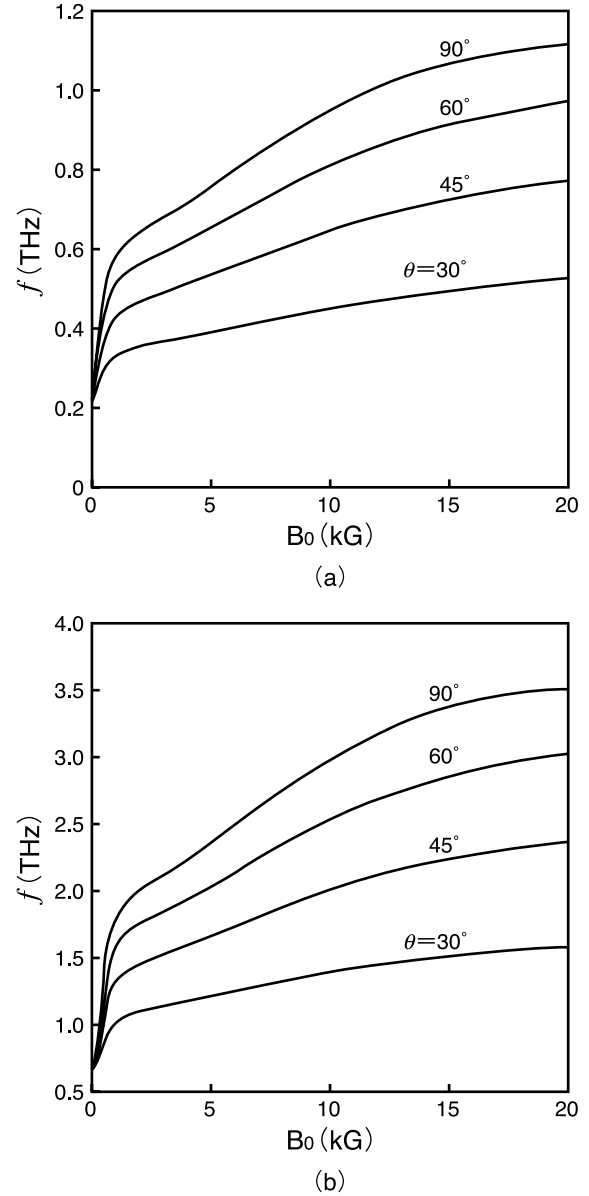
The numerical computations of the dispersion equation were performed in the case of various electron-hole plasma densities, angles  $\theta$  and external magnetic fields. The electron drift velocity of  $v_{oe} = 8 \times 10^7 \text{ cm/sec}$  was used in the numerical computations. Under the avalanche breakdown condition, the density of the electrons is equal to that of the holes ( $n_{oe} = n_{oh} = n_o$ ).

### 3. RESULT AND DISCUSSION

We have analyzed the dispersion equation (1) by the numerical computations and clarified the properties of the terahertz wave oscillation in InSb.

Figure 1 shows the relation between the oscillation frequency of terahertz waves and the external magnetic field as a parameter of the angle  $\theta$ . The relation in Fig. 1(a) and (b) is shown at the typical values of the electron-hole densities of  $n_o = 5 \times 10^{17} \text{ cm}^{-3}$  and  $5 \times 10^{18} \text{ cm}^{-3}$ , respectively. The frequency increases with the magnetic field and the angle  $\theta$  in the region of terahertz waves and it takes a maximum value under the transverse magnetic field, that is, the angle  $\theta = 90^\circ$  as shown in Fig. 1. The frequency at the density of  $5 \times 10^{18} \text{ cm}^{-3}$  is larger than the frequency at the density of  $5 \times 10^{17} \text{ cm}^{-3}$  at a given magnetic field and an angle  $\theta$ . In the numerical computations the maximum frequency is 3.54 THz at the density of  $5 \times 10^{18} \text{ cm}^{-3}$  under the transverse magnetic field of 20 kG.

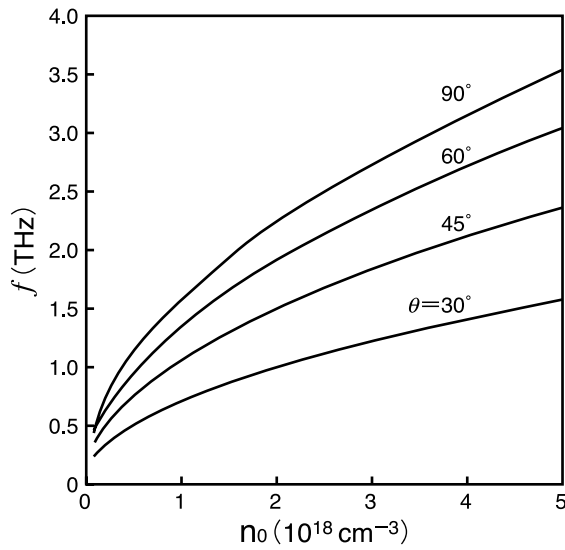
We have analyzed the dependence of the oscillation frequency on the electron-hole density as a parameter of the angle  $\theta$ . Figure 2 shows the relation between the frequency and the density at the magnetic field of 20 kG. The frequency increases with the density and the angle  $\theta$ . For instance, at the angle  $\theta = 90^\circ$ , the frequency is 1.58 THz at



**Fig. 1** Relation between the oscillation frequency  $f$  of terahertz waves and the external magnetic field  $B_o$ .  
(a)  $n_o = 5 \times 10^{17} \text{ cm}^{-3}$ , (b)  $n_o = 5 \times 10^{18} \text{ cm}^{-3}$ .

the density of  $1 \times 10^{18} \text{ cm}^{-3}$  and when the density increases up to  $5 \times 10^{18} \text{ cm}^{-3}$  the frequency increases to 3.54 THz.

We have already reported the computer analysis on the absolute instability in the region of microwaves and millimeter waves. It has been clarified that two modes of absolute instabilities (mode I and mode II) for longitudinal waves in the solid state plasma [8–10]. The absolute instability for mode I occurs in the presence of the external magnetic field while the absolute instability for mode II occurs even when no magnetic field is present. When the electron-hole density is increased up to the density of  $5 \times 10^{18} \text{ cm}^{-3}$  and up to the transverse magnetic field of 20 kG, the frequency for mode I is less than about 0.6 THz. The frequency for mode II is higher than that for mode I in the



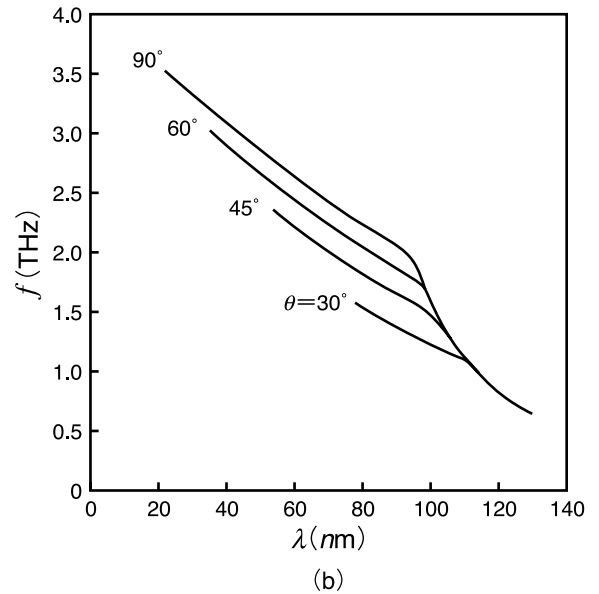
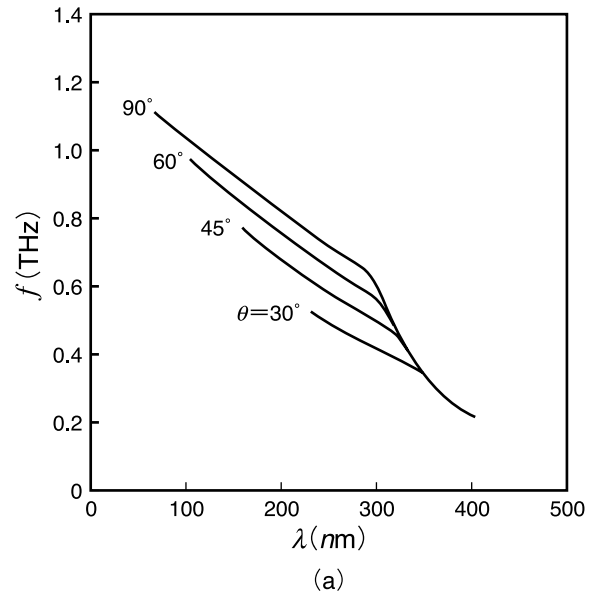
**Fig. 2** Relation between the frequency  $f$  and the electron-hole density  $n_0$ . ( $B_0 = 20$  kG)

high electron-hole density and the high magnetic field. Therefore, we have presented further detailed analysis of the absolute instability for mode II. The properties of the terahertz wave oscillation in Fig. 1 and 2 correspond those of the absolute instability for mode II.

We have calculated the wavelength and phase velocity of terahertz waves by the analysis of dispersion equation on the angular frequency and wave number.

Figure 3 shows the relation between the frequency and the wavelength of terahertz waves. It is found that the frequency increases with decreasing the wavelength. In Fig. 3(a) the wavelength varies from about 70 nm to 400 nm in the case of the density of  $5 \times 10^{17} \text{ cm}^{-3}$ . In the case of the density of  $5 \times 10^{18} \text{ cm}^{-3}$  in Fig. 3(b) the wavelength varies from about 20 nm to 130 nm. It is noted that the relation between the frequency and the wavelength is almost same property regardless of different values of the angle  $\theta$  in the region of low frequency corresponding to the region of low magnetic field as shown in Fig. 3.

Figure 4 shows the relation between the frequency and the phase velocity of terahertz waves. The phase velocity increases with the frequency and by further increase of the frequency, it takes a maximum value and then decreases. The phase velocity varies from  $0.76$  to  $1.86 \times 10^7 \text{ cm/sec}$  in the case of the density of  $5 \times 10^{17} \text{ cm}^{-3}$  in Fig. 4(a) and it varies from  $0.79$  to  $1.86 \times 10^7 \text{ cm/sec}$  in the case of the density of  $5 \times 10^{18} \text{ cm}^{-3}$  in Fig. 4(b). Thus, when the density varies from  $5 \times 10^{17} \text{ cm}^{-3}$  to  $5 \times 10^{18} \text{ cm}^{-3}$ , the phase velocity does not almost change, however, the frequency corresponding to the maximum velocity has different value. In the case of the density of  $5 \times 10^{17} \text{ cm}^{-3}$  the frequency corresponding to the maximum velocity is  $0.66 \text{ THz}$  and in the case of the density of  $5 \times 10^{18} \text{ cm}^{-3}$  it is  $2.02 \text{ THz}$ . The relation between the frequency and the phase velocity is almost same property regardless of differ-



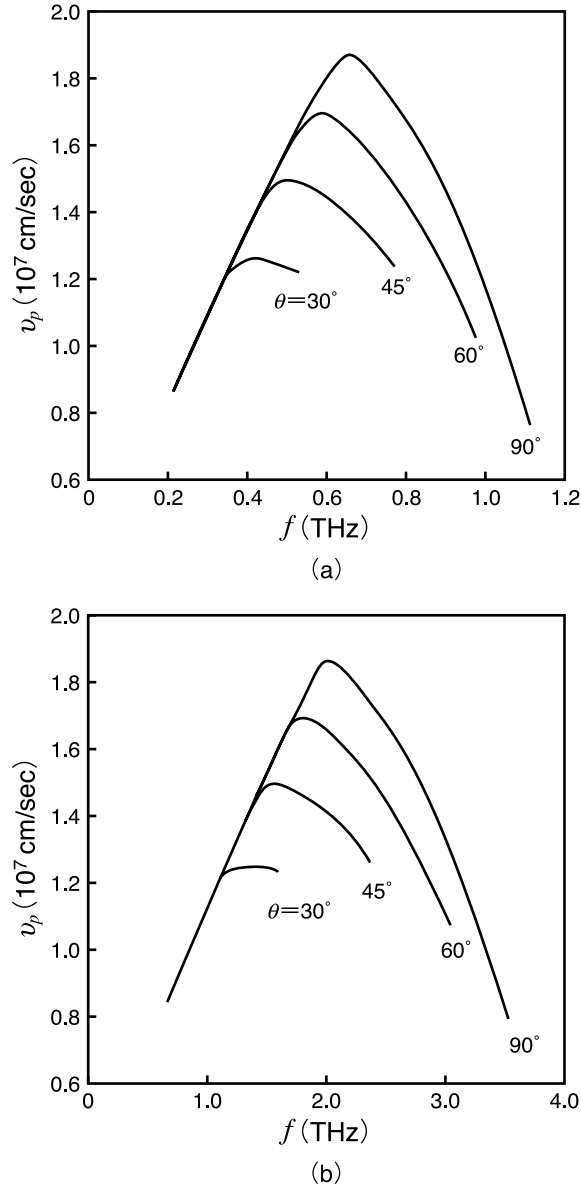
**Fig. 3** Relation between the frequency  $f$  and the wavelength  $\lambda$  of terahertz waves.

(a)  $n_0 = 5 \times 10^{17} \text{ cm}^{-3}$ , (b)  $n_0 = 5 \times 10^{18} \text{ cm}^{-3}$ .

ent values of the angle  $\theta$  in the region of low frequency. This tendency corresponds to the property of the wavelength  $\lambda$  showed in Fig. 3.

The maximum phase velocity is on the order of  $10^7 \text{ cm/sec}$  when the electron-hole density, the external magnetic field and the angle  $\theta$  vary and it is always smaller than the electron drift velocity. In the case of the electron drift velocity  $v_{oe}$  is larger than the phase velocity  $v_p$ , the waves grow in amplitude at the expense of energy of the electron drift velocity so that the oscillation can occur. This mechanism is based on the two-stream instability.

There has been report on the observation of millimeter wave radiation at the frequency up to  $102 \text{ GHz}$  from InSb under transverse magnetic field [14]. In this case the radia-

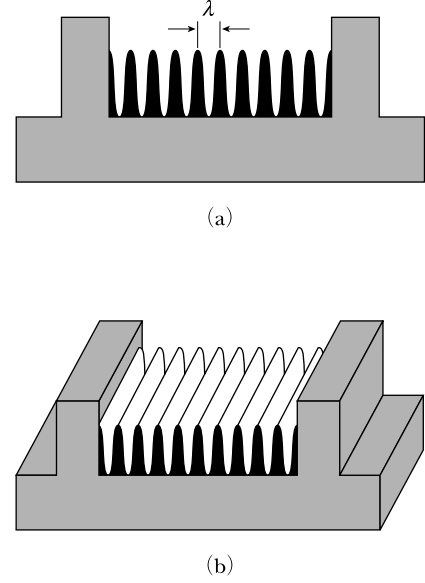


**Fig. 4** Relation between the frequency  $f$  and the phase velocity  $v_p$  of terahertz waves.  
(a)  $n_0 = 5 \times 10^{17} \text{ cm}^{-3}$ , (b)  $n_0 = 5 \times 10^{18} \text{ cm}^{-3}$ .

tion is of a broad-band character. Some frequency selective mechanisms such as Fabry-Perot cavity would be necessary to obtain coherent terahertz oscillation.

We propose the structure of the terahertz oscillation device as shown in Fig. 5. In this device a slot of width play important role for the frequency selective mechanism. The oscillation frequency would be determined by the wavelength  $\lambda$  as indicated in Fig. 5(a).

As mentioned previously in section 3 the wavelengths in the region of terahertz waves are from about 20 nm to 400 nm. By use of recent advanced nano-technology it would be possible to produce the terahertz oscillation device of InSb as shown in Fig. 5. If this device is produced, the device of the terahertz wave oscillator may be simple struc-



**Fig. 5** Structure of the terahertz oscillation device.  
(a) A side view of the device, (b) A general view of the device.

ture because this device oscillates without the irradiation of the laser beams to the semiconductor.

#### 4. CONCLUSION

We have clarified that the terahertz oscillation occurs in the solid state plasma in InSb by the computer analysis of the dispersion equation. The numerical computations of the equation are performed for arbitrary orientation of the carrier drift velocity relative to the external magnetic field. The frequency of terahertz oscillation increases with the electron-hole density, the external magnetic field and the angle  $\theta$ . The wavelength and phase velocity of terahertz waves have been calculated. It is found that the wavelength decreases with increasing of the frequency and the phase velocity takes a maximum value at the certain frequency when the frequency increases. In the present computer analysis the maximum frequency of the terahertz oscillation is 3.54 THz at the density of  $n_0 = 5 \times 10^{18} \text{ cm}^{-3}$  and the transverse magnetic field of  $B_0 = 20 \text{ kG}$ . In this case the wavelength  $\lambda$  of terahertz waves is 22.4 nm and the phase velocity  $v_p$  is  $0.79 \times 10^7 \text{ cm/sec}$ .

We have also proposed the structure of the terahertz oscillation device to obtain a coherent oscillation.

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