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Terahertz Wave Oscillations in a Solid State Plasma without an Irradiation of the Laser Beams

Katsutoshi Kamakura*

Department of Electrical and Electronics Engineering, Kokushikan University,
4-28-1 Setagaya, Setagaya-ku, Tokyo, Japan
Email: kamakura@kokushikan.ac.jp

Abstract— We present a theoretical analysis on terahertz wave oscillations in a solid state plasma in InSb without an irradiation of the laser beams. It is found by computer analysis of the dispersion equation for longitudinal waves in the solid state plasma that the maximum frequency of the terahertz waves is 3.54 THz at an electron-hole density of 5×10^{18} cm^{-3} and a transverse magnetic field of 20 kG . In this case the wavelength of terahertz waves in the solid state plasma is 22.4 nm and the phase velocity is 0.79×10^{7} cm / sec.

1. Introduction

In recent years, there have been many reports on terahertz wave radiations. The frequencies of the terahertz waves are in the range about from 100 GHz to 10 THz. It has been reported that the terahertz wave radiations occur from semiconductors using an irradiation of the laser beams. Many of the compound semiconductors such as GaAs, InAs, InP and InSb have been used to cause the terahertz radiations [1-4]. In all of previous works the laser beams were necessary to radiate the terahertz waves from those semiconductors.

Recently, we found by a computer analysis of the dispersion equation for longitudinal waves in the solid state plasma in InSb that the absolute instability corresponding to the oscillations occurred in the region of terahertz waves. In the theoretical study the terahertz wave oscillations occur 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 θ. (θ is an angle between the carrier drift velocity and the external magnetic field)

In this paper we describe the terahertz wave oscillations for longitudinal waves in the solid state plasma in InSb under the external magnetic field. We also discuss the properties of the terahertz wave oscillations when the electron-hole plasma density, the external magnetic field and the angle θ vary.

Furthermore, we will propose the structure of the terahertz oscillation device in order to obtain a coherent wave.

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 ***Bo*** [5] is

$$\sum_{i=e,h} \Big[\ \omega_{pi}^2\left\{(\omega-k\upsilon_{oi}-j\nu_{ci})^2-\omega_{ci}^2\cos^2\theta\right\}\Big] \Big/ \Big[(\omega-k\upsilon_{oi})\,(\omega-k\upsilon_{oi}-j\nu_{ci})\left\{(\omega-k\upsilon_{oi}-j\nu_{ci})^2-\omega_{ci}^2\right\} - k^2\upsilon_{Ti\perp}^2(\omega-k\upsilon_{oi}-j\nu_{ci})^2\sin^2\theta - k^2\upsilon_{Ti//}^2\left\{(\omega-k\upsilon_{oi}-j\nu_{ci})^2-\omega_{ci}^2\right\}\cos^2\theta\ \Big]=1\,, \qquad (1)$$

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. See the reference 5 on notations for those physical quantities in Eq. (1). On the computer analysis of the dispersion equation we used the mapping operation for determining a nature of the absolute instability in the plasmas as previously presented by Bers and McWhorter [6] and Briggs [7].

The numerical computations of the dispersion equation were performed in the case of various electron-hole plasma densities, external magnetic fields and angles θ. The electron drift velocity of $\upsilon_{oe} = 8\times10^{7}$cm/sec was used in the numerical computations. Under the avalanche breakdown condition, the density of the electrons n_{oe} is equal to that of the holes n_{oh} ($n_{oe}=n_{oh}=n_o$).

3. Result and Discussion

We have analyzed the dispersion equation (1) by the

* **Present Address :** Institute for Solid State Physics, Darmstadt University of Technology, Hochschulstrasse 6 , D-64289 Darmstadt, Germany

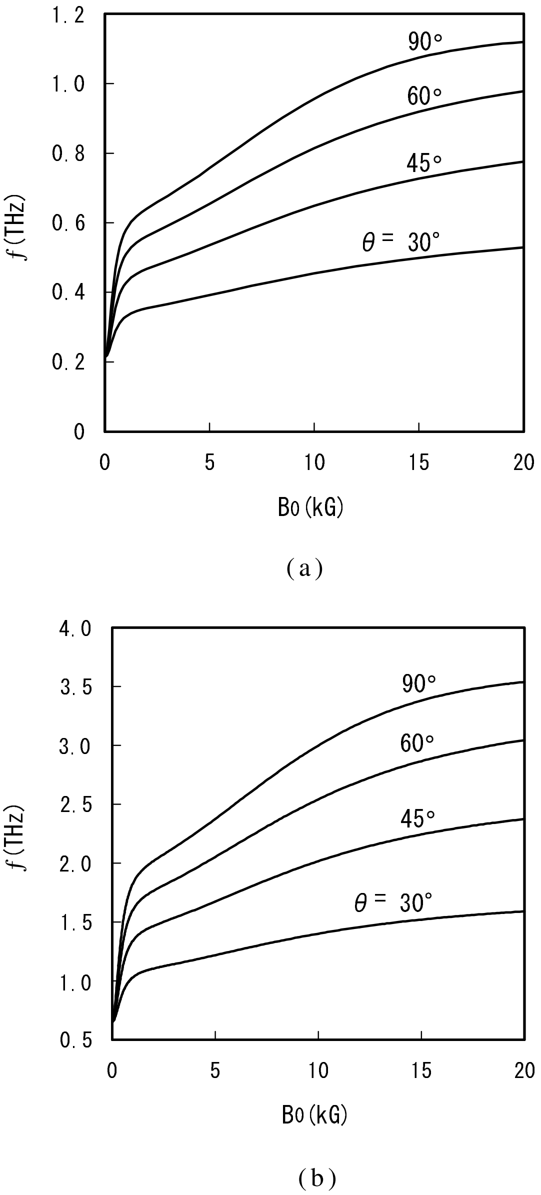


Figure 1. Relation between the oscillation frequency f of terahertz waves and the external magnetic field $\boldsymbol{B_0}$.
(a) $n_0 = 5\times10^{17}$ cm^{-3}, (b) $n_0 = 5\times10^{18}$ cm^{-3}.

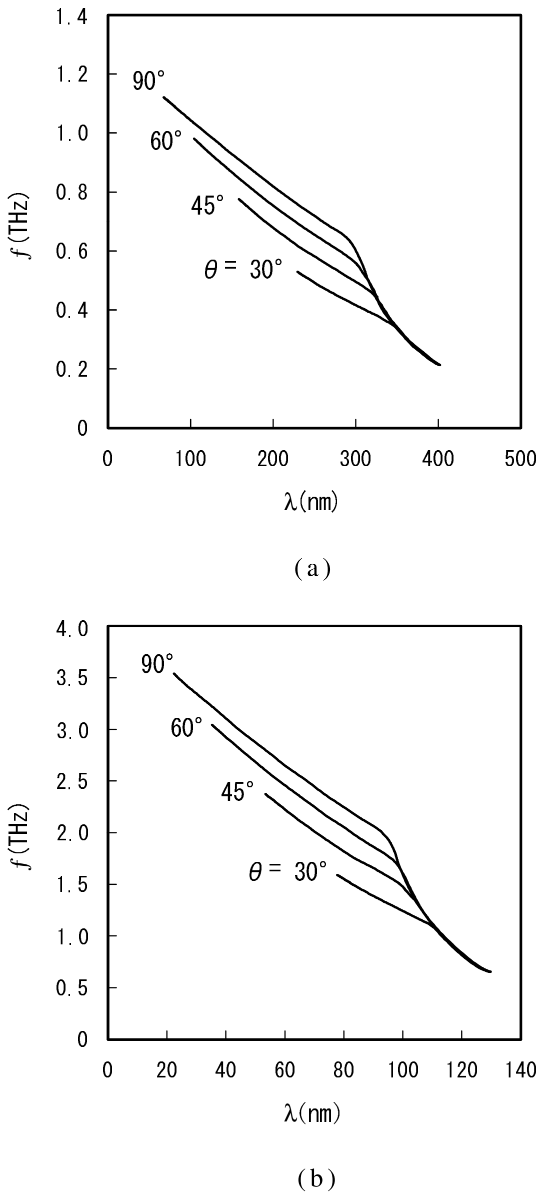


Figure 2. Relation between the oscillation frequency f and the wavelength λ of terahertz waves.
(a) $n_0 = 5\times10^{17}$ cm^{-3}, (b) $n_0 = 5\times10^{18}$ cm^{-3}.

numerical computations and clarified the properties of the terahertz wave oscillations in the solid state plasma in InSb.

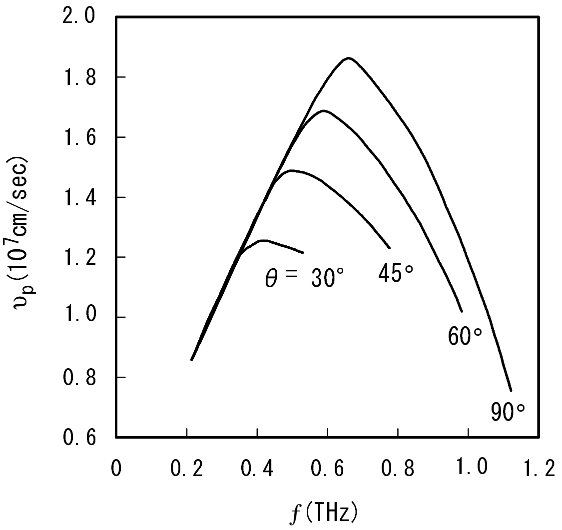
Figure 1 shows the relation between the oscillation frequency f of terahertz waves and the external magnetic field $\boldsymbol{B_0}$ as a parameter of the angle θ. The relations in Fig.1 (a) and (b) are shown at the typical values of the electron-hole densities of $n_0 = 5\times10^{17}$ cm^{-3} and 5×10^{18} cm^{-3}, respectively. The frequency increases with the magnetic field and the angle θ in the region of terahertz waves and it takes a maximum value under the transverse magnetic field as shown in Fig. 1. The frequency at the density of 5×10^{18} cm^{-3} is larger than the frequency at the density of 5×10^{17} cm^{-3} at a given magnetic field and an angle θ. In the present numerical computations the maximum frequency is 3.54 THz at the density of 5×10^{18} cm^{-3} under the transverse magnetic field of 20 kG .

We have calculated the wavelength λ and phase velocity υ_p of terahertz waves by use of the wave number k and angler frequency ω in Eq. (1).

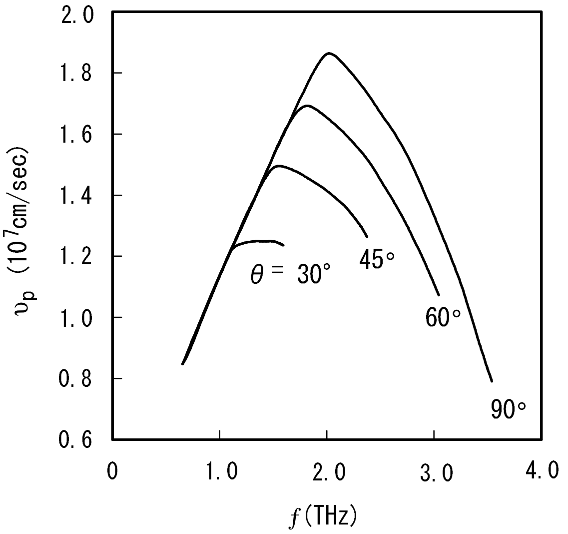
Figure 2 shows the relation between the oscillation frequency f and the wavelength λ of terahertz waves. It is found that the frequency increases with decreasing the wavelength. In Fig. 2 (a) the wavelength varies from about 70 nm to 400 nm in the case of the density of 5×10^{17} cm^{-3}. In the case of density of 5×10^{18} cm^{-3} in Fig. 2 (b) the wavelength varies from about 20 nm to 130 nm.

Figure 3 shows the relation between the oscillation frequency f and the phase velocity υ_p 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 ($\times10^7$ cm/sec) in the case of the density of 5×10^{17} cm^{-3} in Fig. 3 (a) and it varies from 0.79 to 1.86 ($\times10^7$ cm/sec) in the case of the density of 5×10^{18} cm^{-3} in Fig. 3 (b). Thus, when the density varies from 5×10^{17} cm^{-3} to 5×10^{18} cm^{-3}, the phase velocity dose not almost change, however, the frequency corresponding to the maximum velocity has a different value. In the case of the density of 5×10^{17} cm^{-3} the frequency corresponding to the maximum velocity is 0.66 THz and in the case of the density of 5×10^{18} cm^{-3} it is 2.02 THz. The maximum phase velocity is on the order of 10^7 cm/sec when the electron-hole density, the external magnetic field and the angle θ vary and it is always smaller than the electron drift velocity ($\upsilon_{oe} = 8\times10^7$ cm/sec) . When the electron drift velocity υ_{oe} is larger than the phase velocity υ_p , the waves grow in amplitude at the expense of energy of the electron drift velocity so that the oscillations can occur. This mechanism is based on the two-stream instability.

There have been reports on the observations of coherent microwave oscillations in InSb [8], InAs [9] and the millimeter wave radiation in InSb [10] at the frequency up to 102 GHz under the transverse magnetic field. In the case of high frequency above the millimeter waves the broadband frequency spectrum of the radiation was observed.

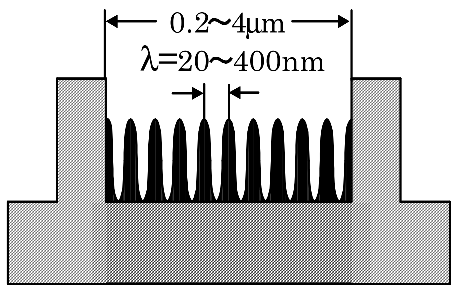


(a)

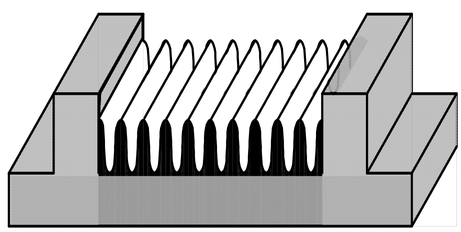


(b)

Figure 3. Relation between the oscillation frequency f and the phase velocity υ_p of terahertz waves.
(a) $n_0 = 5\times10^{17}$ cm^{-3}, (b) $n_0 = 5\times10^{18}$ cm^{-3}.



(a)



(b)

Figure 4. Structure of the terahertz oscillation device.
(a) Side view of the device,
(b) General view of the device.

Some frequency selective mechanisms such as Fabry-Perot cavity would be necessary in order to obtain the coherent terahertz oscillations. We propose the structure of the terahertz oscillation device as shown in Fig.4. In this device a slot of width play important role for the frequency selective mechanism. The oscillation frequency would be determined by the wavelength λ as indicated in Fig. 4 (a)

As mentioned previously the wavelengths in the region of terahertz waves are from about 20 nm to 400 nm. By use of recent advanced nano-technologies it would be possible to produce the terahertz oscillation device of InSb as shown in Fig. 4.

If this device is produced, the terahertz wave oscillator may be simple structure because the oscillations occur without the irradiation of the laser beams to the semiconductor.

4. Conclusion

We have clarified by the computer analysis of the dispersion equation that the terahertz oscillations occur in the solid state plasma in InSb. The frequency of terahertz oscillations increases with the electron-hole density, the external magnetic field and the angle θ. 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 oscillations is 3.54 THz at the density of $n_0 = 5\times10^{18}$ cm^{-3} and the transverse magnetic field of B_0 = 20kG . In this case the wavelength λ of terahertz waves is 22.4 nm and the phase velocity υ_p is 0.79×10^7 cm/sec.

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

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