Phase shift measurement of the THz wave with laser displacement sensor

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It is an advantage of THz-TDS measurement that we can obtain not only the spectral amplitude of THz wave but the phase information without any assumptions. But, it has a difficulty in the position reproducibility of the reference mirror and sample in THz wave reflection measurement. We introduced a laser displacement sensor in order to get the reproducibility of position and measured the THz-TDS reflection signal under the position reproducibility of several micron meter.

I. Introduction

THE electromagnetic wave between approximately 0.1 THz and 10 THz (T = 10^{12}), lying between visible light and radio waves, has long been recognized as an unexploited field. In the last decades, the terahertz time-domain spectroscopy (THz-TDS) has remarkably developed and various applications have been made[1][2].

From the point of view of solid state spectroscopy, the energy range of the THz band is very attractive because it includes elementally excitations such as phonon, magnon, and plasmon of solids. Short-pulse laser plays an important role in generating broad-band THz radiation and in gating for coherent detection of THz radiation. As the result, measuring the waveform of THz radiation gives not only the spectral amplitude but the phase information and we can get the dielectric constants of materials without complicated calculation, *e.g.* Kramers-Kronig analysis with certain assumptions. THz radiation generated by pulse laser irradiation has a pulse shape, order of picosecond pulse duration, and it is used as a probe pulse in the optical pump-THz probe measurement for ultra-fast phenomena[3].

On the other hand, THz-TDS measurement has an advantage of phase sensitive detection because the THz wave has an order of picosecond period and the optical gating pulse has an order of one hundred femtosecond width. But in THz-TDS reflection measurement it is hard to reproduce the position of sample and reference materials.

In this report, using a laser displacement sensor we got the high position reproducibility less than one micron meter, which is equivalent to about three femtosecond, and measured the reflected THz wave from indium arsenide surface.

II. EXPERIMENTAL SETUP

The schematic experimental setup is shown in Fig. 1. A regenerative amplified Ti:sapphire laser was used as a light source, of which repetition rate is 200kHz, center wavelength is 800 nm, output power is 900 mW and autocorrelation pulse width is 70fs. The output pulse from the laser is split into two parts. The first is loosely focused onto the surface of a semiconductor, indium arsenide crystal as the terahertz wave emitter. It is known that indium arsenide is easy to operate without any special treatment to get THz radiation and known as a strong THz emitter[4][5]. The second is focused onto a photoconductive (PC) antenna fabricated on a low temperature grown GaAs (LT-GaAs) as the detector. The shape of antenna is a 30 μm dipole with a 5 μm gap in the center. The THz waves generated from the semiconductor surface was collimated with an off-axis parabolic mirror and then focused onto the sample with another parabolic mirror. Reflected THz waves from the sample were collimated and focused onto the PC antenna for detection by two off-axis parabolic mirrors. Two high-resistivity silicon wafers were inserted in this system. One reflects the rest of excitation pulse, another reflects the gate pulse in order to merge the optical-gate pulse into the terahertz wave path. The gate pulse and the THz wave were focused from the printed antenna side. The THz radiation path and the merged gating laser path are shown in the figure 1. Incident THz wave was well *p*-polarized beam and PC antenna had a strong sensitivity to the polarization of the incident THz waves because of its configuration. The photocurrent from the PC antenna was pre-amplified and then detected with a lock-in amplifier. The excitation pulse was modulated by optical chopper at a frequency 231Hz. In order to detect the sample position, laser displacement meter was used which is composed of Keyence LE-4000 controller and LE-4010 sensor head. Resolution of the displacement meter is 100 nm, but the reproducibility of our measuring system was less than 900 nm. Undoped (100)-oriented indium arsenide (InAs) crystal was measured in this report. The undoped InAs shows slightly *n*-type at room temperature. Carrier density of it is less than 3 x 10^{16}cm^{-3}. The measurements were done at room temperature.

III. Result and Discussion

THz reflection spectrum of *n*-InAs was measured by the combination of standard far-infrared Fourier transform spectrometer (JASCO corporation, FARIS-1) and InSb hot electron bolometer (QMC Instruments Ltd.). The *n*-InAs sample and reference mirror were kept in vacuum condition at this measurement. Incident angle to the sample is about 10 degree. Based on the result, *n*-InAs has a high reflectivity from 0.2 to 2.0THz. Plasmon frequency, $\omega_p/2\pi$, is estimated less than 2.2THz using parameters, $m^*=0.025m_e$[6], and ε_b= 15.15[7] where m_e is the effective mass of electron. The high reflectivity is explained by plasmon reflection. Figure 2 shows the time domain THz waveform reflected by a reference mirror and by the *n* -InAs sample.

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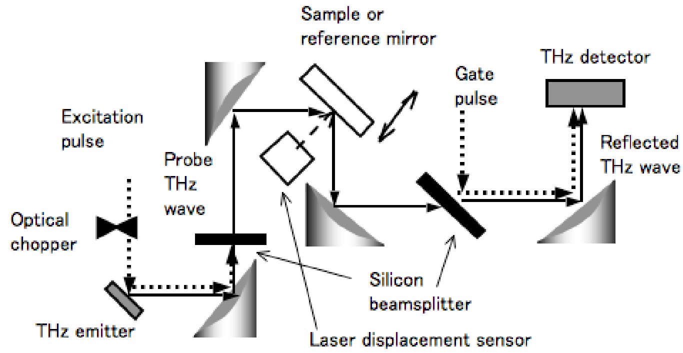

Figure 1: Experimental setup of the time domain THz wave reflection measurements. Excitation and gate pulses come from Ti:sapphire regenerative amplifier laser. Semiconductor surface is used as a THz emitter and photoconductive antenna as a THz detector. Two high-resistivity silicon wafers were inserted in this system to reflect the excitation and gate pulses. The laser displacement meter was used to get the position reproducibility of sample and reference mirror. The resolution of the displacement meter is 100nm, but the reproducibility of our measuring system was less than 900nm.

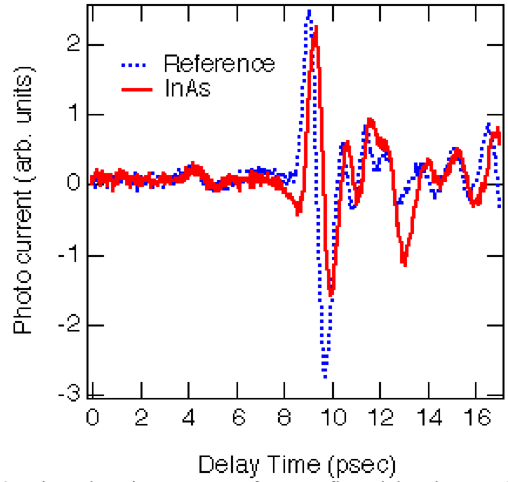

Figure 2: Time domain THz waveforms reflected by the *n*-InAs and the reference mirror . The difference of the peak positions between the reference mirror and InAs sample is about 0.2 picosecond, which is larger than the reproducibility of this measuring system.

The THz signals were measured by photoconductive antenna at room temperature and in the air. The waveforms of reflected THz wave are shown in the figure 2. The difference of peak positions between the reference and InAs is about 0.2 picosecond, which is larger than the reproducibility of this measuring system, three femtosecond, 900nm. In the case of total reflection condition, the peak difference should be zero.

A light beam shift reflected from a plane interface between two media is known as Goos-Hänchen shift[8]. The amount of the shift *S* is expressed as

$$S = \frac{2}{k_1} \frac{tan\alpha_c}{(sin^2\alpha - sin^2\alpha_c)^{\frac{1}{2}}} ,$$

where n_1 is the refractive index of air, α is the inclination to the normal, α_c is the critical angle, $sin\alpha_c = n_2/ n_1$, and k_1 is the wavenumber, $k_1 = 2\pi n_1/\lambda$. Using the dielectric constants from literature[9], we obtain the shift, *S*=0.035mm, 0.12 picosecond time delay. Considering from Snell's law, total time shift should be 0.22 picosecond time delay. The shift was well explained by Goos-Hänchen shift.

In this report, using a laser displacement sensor we got the high position reproducibility less than one micron meter, which is equivalent to about three femtosecond, and made the reflected time domain THz wave measurements.
The phase shift between the reference mirror and indium arsenide surface is observed in the reflected time domain THz waveform measurement and is described by Goos-Hänchen shift.

The laser displacement sensor is effective to the time domain THz reflection measurement.

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REFERENCES

[1] B. Ferguson and X. C. Zhang, Nature Materials **1**, 26 (2002).
[2] K. Sakai (eds.), Terahertz Optoelectronics (Springer, 2005).
[3] R. Huber *et al.*, Nature **414**, 286 (2001)
[4] N. Sarukura, H. Ohtake, S. Izumida, and Z. Liu, J. Appl. Phys. **84**, 654 (1998).
[5] M. Nakajima, Y. Oda, T. Suemoto, and S. Saito, Appl. Phys. Lett. **85**, 4597 (2004).
[6] C. W. Litton, R. B. Dennis, and S. D. Smith, J. Phys. C. **2**, 2146 (1969).
[7] M. Hass and B. W. Hengis, J. Phys. Chem. Solids. **23**, 1099 (1962).
[8] A. W, Snyder, and J. D. Love, App. Optics, **15**, 236 (1976)
[9] H. Hirori, K. Yamashita, M. Nagai, and K. Tanaka, Jpn. J. Appl. Phys. **43**, L1287 (2004).