Terahertz-Time Domain Spectroscopic (THz-TDS) Measurement of Moderately-Doped Silicon Using InAs Emitter Under Magnetic Field

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ABSTRACT

The complex refractive index of silicon using terahertz-time domain spectrocscopy (THz-TDS), with an InAs wafer under the influence of a magnetic field as emitter, has been studied. By applying a magnetic field on the InAs emitter, the detected temporal waveform broadens and the spectral weight of its Fourier spectrum shifts toward the low frequency region. Calculating the real (n) and imaginary (κ) parts of the complex refractive index of silicon, it is found that with the application of a magnetic field the plots of these quantities in the low frequency region (sub-terahertz region) are smoother than those without magnetic field. These features indicate that a significant enhancement of the signal-to-noise *(S/N)* ratio in the low frequency can be obtained by applying a magnetic field on the InAs emitter.

INTRODUCTION

Irradiating the surface of bulk semiconductors with femtosecond laser pulses produces the emission of electromagnetic (EM) radiation into free space with frequencies that extend into the terahertz (THz) region. The mechanism of such radiation was considered to be due to the acceleration of photocarriers in the surface depletion field (Zhang, 1990). It has been reported that the component of the temporal spectrum in the low frequency region is enhanced with the increase of the magnetic field strength (Migita et al., 1999). The low frequency region is important in the study of semiconductors since the dispersion of the complex refractive index in such region is dependent on two essential parameters of semiconductors, namely, carrier density (N) and mobility (μ). The quality and electrical properties of semiconductors are mostly characterized by these parameters. A powerful tool in determining these parameters is a technique known as terahertz-time domain spectroscopy (THz-TDS) (Grischkowsky et al., 1990). However, in the calculation of the complex refractive index of semiconductors, scattering of data points due to noise in the low frequency region is relatively high for THz-TDS measurements. It is therefore vital that in this region, in particular the sub-terahertz region, the signal-to-noise (*S/N*) ratio of THz-TDS measurement be enhanced. In this report, an InAs wafer immersed in a relatively weak magnetic field is used as a THz-TDS emitter in characterizing a moderately-doped silicon sample.

EXPERIMENTAL

A conventional THz-TDS set-up was used wherein the laser beam was derived from a mode-locked Ti:sapphire laser which produces optical pulses with a width of 120fs and a wavelength of 810nm at a repetition rate of 82 MHz. The THz emitter used in this experiment was an n-type (111) InAs wafer with carrier density $N < 3 \times 10^{16}$ cm^{-3} and mobility $\mu > 2 \times 10^4$ cm^2/V-s while the detector used was a bow-tie type photoconductive antenna made of Au/Ge/Ni alloy on low temperature grown GaAs (LT-GaAs). Using a beam splitter, the laser optical pulses were separated into pump and probe pulses. Pump pulses with an average power of about 400mW illuminated the InAs wafer, immersed in a magnetic field of 0.2T, at an incidence angle of 45° w.r.t. the surface normal. Electromagnetic pulses generated by the InAs wafer were focused onto the detector using a pair of off-axis paraboloidal mirrors and a Si hemispherical lens. An optical chopper was used to chop the pump pulses at 2 kHz and the signal was locked-in detected after amplification by a current amplifier. Probe pulses with an average power of about 15 mW gated the detector. An n-type silicon wafer with resistivity of 1.1(± 0.2) Ω-cm and thickness of 400 μm was used as sample and was inserted between the off-axis paraboloidal mirrors. The THz radiation waveforms were monitored by changing the time delay between the pump and probe pulses.

RESULTS AND DISCUSSIONS

Fig. 1 shows the reference (without the sample) temporal THz waveforms of the primary pulse with and without magnetic field. A sharp and narrow waveform is observed without magnetic field while broad waveforms are observed with the application of the magnetic field. The sharp waveform is attributed to the radiation due to the acceleration of photocarriers by the built-in surface electric field $\boldsymbol{E}_{\mathrm{surf}}$. On the other hand, the waveform broadening observed upon the application of the magnetic field is ascribed to the superposition of the surface electric field $\boldsymbol{E}_{\mathrm{surf}}$ and the Lorentz force $\mathbf{v} \times \boldsymbol{B}$. The waveform associated with $\mathbf{v} \times \boldsymbol{B}$ is expected to be broad compared to that of the surface electric field $\boldsymbol{E}_{\mathrm{surf}}$ since the former requires a certain delay time to attain sufficient velocity for radiation to occur. It is also observed that by reversing the direction of the magnetic field, the broad component of the temporal waveform is inverted, i.e., the phase of the field oscillation between $+\boldsymbol{B}$ and $-\boldsymbol{B}$ are opposite. This waveform inversion is due to the reversal of the acceleration direction of the photoexcited carriers by the magnetic field.

The Fourier transform of these waveforms is shown in Fig. 2. The Fourier spectra of $\boldsymbol{B} = 0$ and of $+\boldsymbol{B}$ are found to be almost similar over the whole spectrum range. On the other hand, when $-\boldsymbol{B}$ is utilized the spectral density shifted towards the low frequency region. The amplification of the spectrum amplitude by $-\boldsymbol{B}$ in the low frequency region can be attributed to the increase of the broad components by the Lorentz force. From the amplitude and phase information of the Fourier

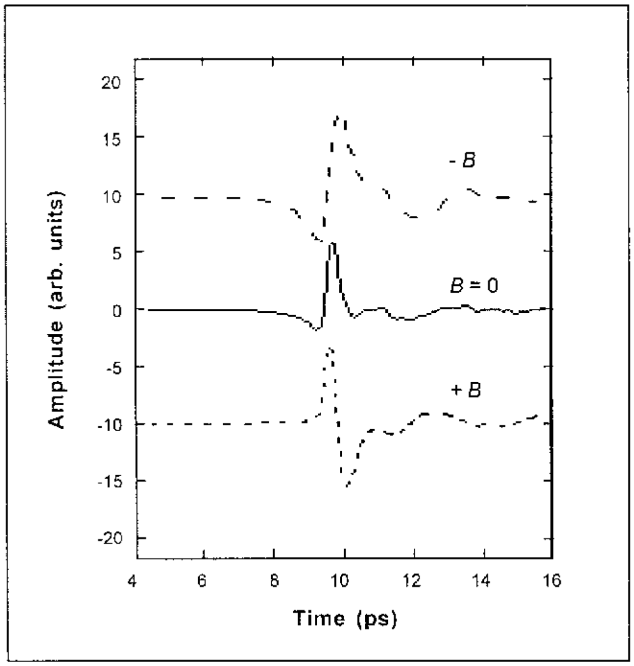

Fig. 1. THz temporal waveforms

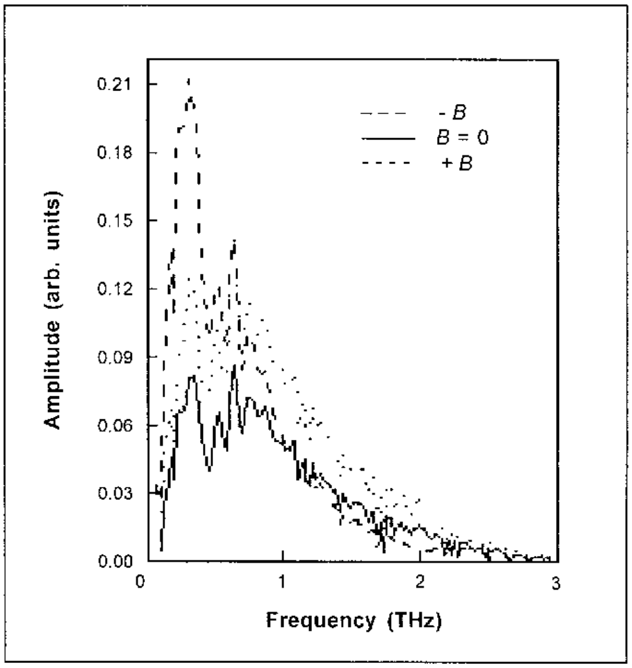

Fig. 2. Fourier spectra of waveforms

spectra, the transmittance T(ν) and phase shift $\phi(\nu)$ are determined. Because T(ν) and $\phi(\nu)$ can be expressed as functions of the complex index of refraction ($\tilde{n} = n + i\kappa$) (Collin, 1960) the real (n) and imaginary (κ) parts of the $\tilde{n}$ are then numerically calculated from the experimentally obtained T(ν) and $\phi(\nu)$. Using the carrier density (N) and scattering time of free carriers (τ) of Si as fitting parameters, the numerically calculated values of n and κ are compared via curve fitting to the Drude model (van Exter & Grischkowsky, 1990) since the optical response of Si is well explained by such model.

Figs. 3 and 4 show the plots in the low frequency region of n and κ of the silicon sample. When $\boldsymbol{B} = 0$, a somewhat large deviation from the curve calculated using the Drude model is observed for both n and κ. This is due to the noise factor, which is relatively large in the low frequency region. Such deviation is noticeably minimized when a magnetic field is applied on the InAs wafer, which indicates a reduction in the noise level, i.e., an enhancement of the signal-to-noise (*S/N*) ratio. In particular, when $-\boldsymbol{B}$ is applied the data points in the low frequency region are well-fitted to the Drude curve. This indicates an improvement of the THz-time domain spectroscopic (THz-TDS) measurement.

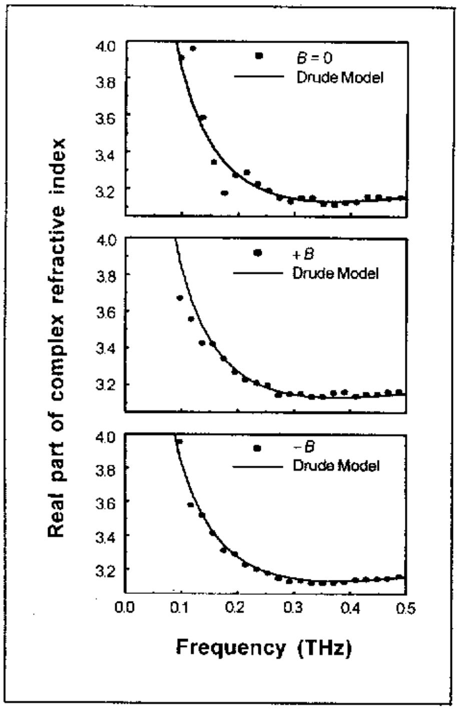

Fig. 3. Real part vs. Frequency plot

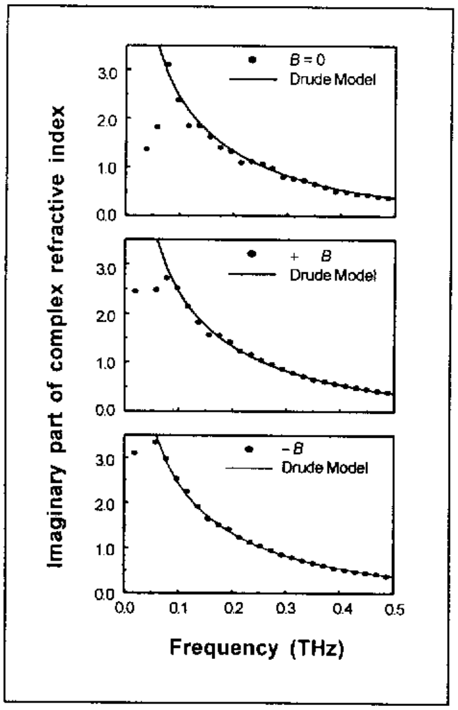

Fig. 4. Imaginary part vs. Frequency plot

SUMMARY

The complex refractive indices of a silicon wafer are measured using a THz-time domain spectroscopy (THz-TDS) with an InAs emitter. By applying a weak magnetic field (0.2T), the spectral density in the low frequency region is greatly enhanced, which improves the *S/N* ratio of the complex refractive indices in this region. The InAs wafer under a magnetic field proved to be a good sub-THz emission source for characterizing the electrical properties of semiconductors.

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