Continuous-Wave Terahertz Spectroscopy as a Non-Contact Non-Destructive Method for Characterising Semiconductors

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Using the technique of terahertz photomixing, a continuous-wave terahertz source is used to characterise various semiconductors in the frequency range from 0.06 to 1.0 THz. By directly analysing the interference pattern of the transmission through semiconductor wafers using Fabry-Pérot theory, information regarding the carrier concentration, sample thickness and refractive index is obtained without physically altering the sample. The continuous-wave technique enables measurements to be made at much lower frequencies than achievable with traditional pulsed-wave terahertz techniques.

1. Introduction

Semiconductors are often characterised by their resistivity at room temperature [1] however standard dc measurement techniques require the attachment of electrodes to the sample. Optical characterisation of semiconductors offers a solution to this problem. Terahertz (THz) frequency radiation features absorptions associated with excitations of phonons and free carriers in semiconductors [2]. Early measurements in the THz frequency regime relied on specialised measurements using synchrotron radiation [2]. The advent of THz time domain spectroscopy (TDS) allowed for a cheap and effective way of characterising semiconductors using THz radiation. The results shown in this paper demonstrate the ability of an alternative THz source known as a two-colour THz source to characterise semiconductor wafers. The two-colour system is generally much cheaper and simpler to operate than a TDS system and also has the benefit of higher resolution and sensitivity at lower frequencies.

2. Methodology

2.1. Two-colour continuous-wave THz system

The transmission spectra of the semiconductor samples are taken using a two-colour continuous-wave THz spectrometer. Two tuneable near infrared laser diodes (lasers 1 & 2 of Fig. 1) operating at wavelengths around 853 nm are used to pump a low-temperature-grown gallium arsenide (LTG GaAs) photomixer. The laser diodes are tuned to have a frequency difference within 1 THz. The mixed signal incident on the photomixer has a beat frequency equal to this frequency difference. The desirable properties of LTG GaAs allows the beat frequency to oscillate charge carriers within the chip [3]. A log-periodic antenna built into the chip couples this oscillation to free space producing the continuous-wave THz radiation.

A spectrum is taken with the sample positioned at the THz beam focus shown in Figure 1. The transmitted signal is refocused onto a Schottky diode detector. A reference spectrum is then taken with no sample in the beam path. A simple ratio of the two spectra gives the transmittance, T.

2.2. Theory

Applying the Drude model, the relative permittivity of the sample is given as $\varepsilon = \varepsilon_1 - i\varepsilon_2$, where:

$$\varepsilon_1 = \varepsilon_\infty - \frac{ne^2\tau^2}{m_e\varepsilon_0(1+\omega^2\tau^2)}, \qquad \varepsilon_2 = \frac{ne^2\tau}{m_e\varepsilon_0\omega(1+\omega^2\tau^2)},$$

n is carrier concentration, m_e is the effective electron mass and τ is the collision time. Using Fabry-Pérot theory the transmittance of the sample for *s*-polarisation can be expressed as:

$$T = \left|\frac{(1+\Gamma)(1-\Gamma)}{e^{i\theta}-\Gamma^2 e^{-i\theta}}\right|^2,$$

where:

$$\theta = \left(\frac{2\pi d}{\lambda_0}\right)\left(\varepsilon - \sin^2\theta_i\right)^{1/2}, \qquad \Gamma = \frac{(Z-1)}{(Z+1)} \quad \text{and} \quad Z = \frac{\cos^2\theta_i}{\left(\varepsilon-\sin^2\theta_i\right)^{1/2}}$$

Here θ_i is the angle of incidence, d the thickness of the sample, and λ_0 is the free-space wavelength of the incident radiation [2]. Often $\varepsilon^{1/2}$ is referred to as the complex refractive index, where $\varepsilon^{1/2} = \eta + i\kappa$ [4]. Here η is the real refractive index and κ is the extinction coefficient. If absorption effects are ignored the complex and real refractive indices are equivalent.

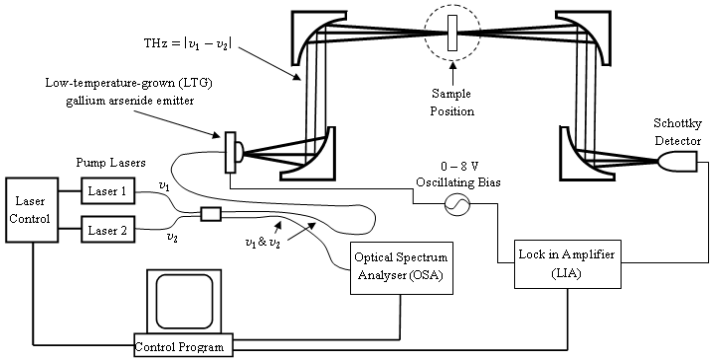

Fig. 1. Diagram of two-colour THz spectrometer setup for measuring semiconductor transmittance.

3. Results and discussion

3.1. Silicon wafer carrier concentrations

Figure 2 shows the spectrum of the transmitted radiation through a silicon sample and the reference spectrum with no sample in the beam path. The Fabry-Pérot oscillations in the silicon spectrum are clearly evident. The sharp absorption dips seen at 0.55 THz and 0.78 THz are part of the well-known H2O molecule rotational series and occur as a result of water vapour in the laboratory air.

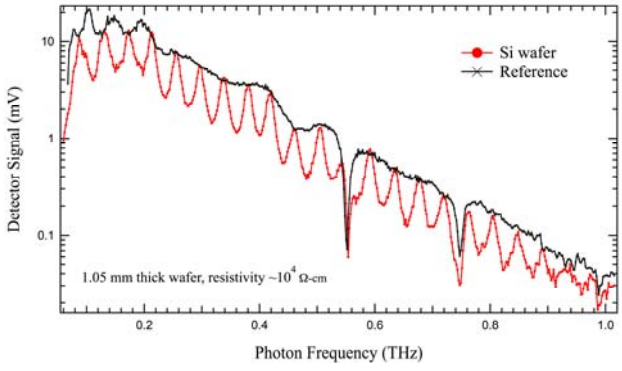

Fig 2. Spectrum of silicon wafer and background reference from 0.06 to 1.0 THz.

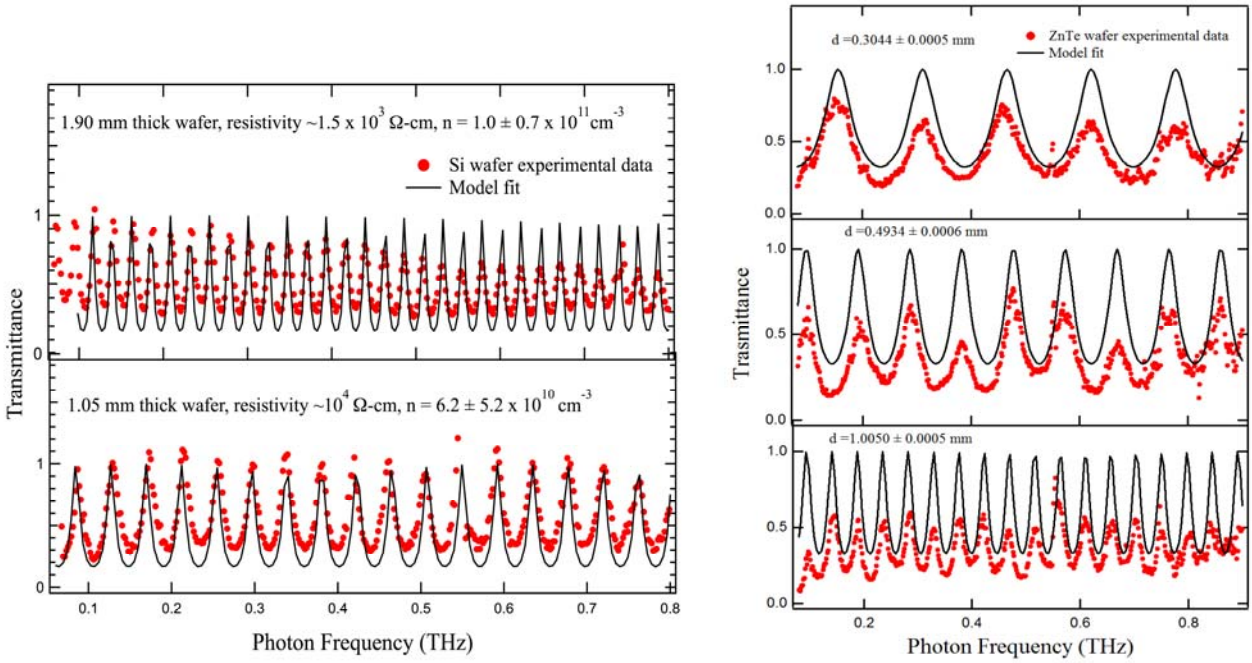

Fig 3. Experimental transmittance fitted using the Drude model for two silicon samples of varying resistivity (left) and a series of ZnTe samples of varying thickness (right).

The transmittance of two high-resistivity silicon wafers is shown in Figure 3. The experimental transmittance is fitted from 0.06 to 0.8 THz using a least squares method with the carrier density as the fitting parameter. The electron mobility can be considered, to a good approximation, independent of the carrier density. We then take a constant value of $\tau = 0.2$ ps calculated from the known electron mobility of 1350 cm^2/Vs, a permittivity of $\varepsilon_\infty = 11.7$ and an effective mass of $m_e = 0.26m_0$ in the fit [1]. As can be seen in Figure 3, the model shows good agreement with the experimental data indicating carrier concentrations of $n = (6.2 \pm 5.2)\times10^{10}$ cm^{-3} and $n = (1.0 \pm 0.7)\times10^{11}$ cm^{-3} for the 1.0×10^4 Ω-cm and 1.5×10^3 Ω-cm samples respectively. These values agree with expected concentrations for samples of high resistivity [1, 2, 5]. The high level of uncertainty in the results can be explained by the lack of sensitivity the transmittance has to changes in the carrier concentration at the low concentration levels found in the high resistivity samples used. For a given thickness a wide range of concentrations could easily fit the data. It is expected that for samples of lower resistivity the carrier concentration will play a more significant role in the absorption and therefore would be able to be determined more accurately from a model fit of the transmittance [5]. It should be noted that the period of the oscillations in the transmittance is dependent to first order on the sample thickness. Therefore, the accuracy of this method is strictly limited by the accuracy to which the sample thickness is known.

3.2. Zinc telluride wafer thicknesses

By ignoring absorption effects the fitting function is simplified by fixing $\varepsilon^{1/2}$ equal to the refractive index. Then, for a known refractive index, the characterisation method may be used for high accuracy measurement of a sample's thickness by fitting for d. Figure 3 shows the experimental and fitted transmittance for a series of zinc telluride (ZnTe) samples of varying thickness. A constant refractive index of 3.188 is used [6]. The poor fit for the amplitudes of the oscillations is a result of neglecting the absorption effects. As d is only dependent on the period of oscillation this method is acceptable when determining d. The

thickness of each ZnTe sample is determined to within 95% confidence and agrees closely with the nominal thicknesses given by the manufacturer.

3.3. Zinc selenide refractive index

Alternatively, if the sample thickness is known to a high accuracy the refractive index can be determined directly from the transmittance by fixing d and fitting for $\varepsilon^{1/2}$. Figure 4 demonstrates this with the refractive index of a 0.76 mm thick zinc selenide (ZnSe) wafer determined to be 3.008 ± 0.002.

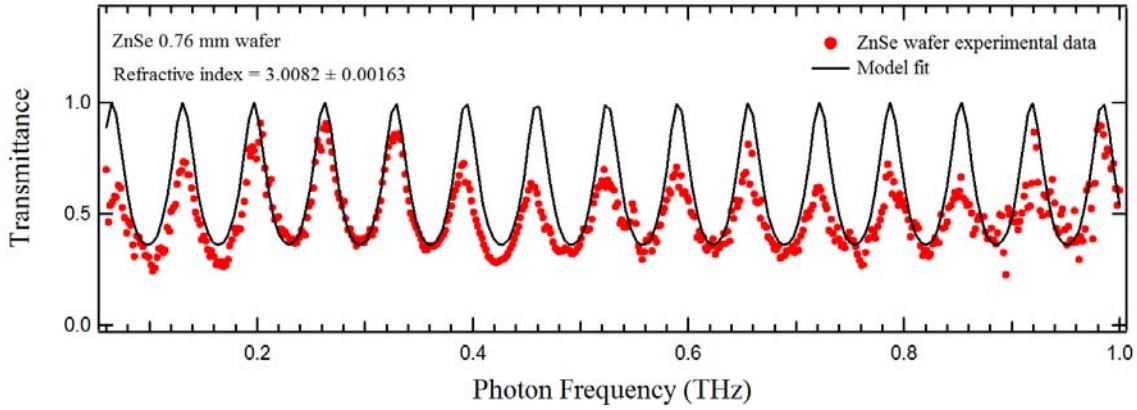

Fig. 4. Experimental transmittance of ZnSe sample fitted with Drude model for determining refractive index.

4. Conclusion

In summary we have shown that a two-colour THz spectrometer may be used to measure the transmittance of high-resistivity semiconductors allowing a non-contact and non-destructive method of determining their carrier concentrations, thicknesses and refractive indices. However determining accurate values of carrier concentrations using this method is limited to samples of a lower resistivity with known sample thicknesses. Therefore, this method is likely to be most useful in industry quality control where less accurate measurements are sufficient for the nominal parameters given with a product. The two-colour THz spectrometer is a top candidate for this type of application due to its low start-up and running costs when compared to other THz spectrometer setups, such as time domain spectroscopy.

Acknowledgments

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References

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