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Optical Characterisation of Doped Silicon Wafers Using THz Time-Domain Ellipsometry

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Abstract. Terahertz (THz) time-domain spectroscopic ellipsometry (TDSE) is a powerful, self-referenced, and non-destructive technique for characterizing the electrical and optical properties of a wide range of materials including semiconductors such as doped silicon wafers. By analysing the polarization changes of THz pulses reflected off the silicon samples, TDSE provides detailed information on carrier concentration, mobility, complex conductivity, and complex dielectric response. This method leverages the unique sensitivity of THz radiation to free carrier dynamics in semiconductors, enabling precise measurements of doping levels, conductivity, and hence resistivity at once. Here we show the capability of THz TDSE in distinguishing between different doping types (n-type and p-type) and concentration level, providing critical insights for semiconductor research and fast quality control in silicon wafer production.

1 Introduction

The terahertz (THz) region of the electromagnetic spectrum spans frequencies from approximately 0.1 to 10 THz. This region is of great interest due to its potential applications in imaging, spectroscopy, and telecommunication systems. The intersection of semiconductor technology and THz research opens a wide range of possibilities for advanced applications. As research and development continue, these materials will likely play an increasingly vital role in the advancement of THz technologies, impacting a wide range of industries and applications. Silicon and doped silicon wafers, with their tunable electrical properties, play a crucial role in the development and enhancement of THz technologies. The ability to tailor the electrical properties of silicon through doping makes it an ideal material for fabricating THz devices such as emitters [1], detectors [3], modulators [2], and imaging systems [4].

2 Technique and Experimental Setup

Ellipsometry is a well-known characterization technique in the optical region with a power of estimating the thickness and optical properties of thin films in multilayered structures [5].

In THz time-domain ellipsometric measurements, at a given incident angle θ the electric fields for both p-polarized and s-polarized light reflected from the sample surface are recorded. By applying Fast Fourier Transform (FFT) analysis, the frequency-dependent amplitude and phase of these reflected signals are determined. This allows for the direct extraction of the ellipsometric parameters $tan\Psi$ and Δ, which represent the amplitude ratio and the phase difference between the p- and s-polarized light, respectively. These parameters provide insights on the sample's dielectric response via the so-called fundamental equation of ellipsometry:

$$\tilde{\rho} = tan\Psi e^{i\Delta} \tag{1}$$

which contains all the information on the response at the sample interface [5].

For our measurements, we employed an in house-built time-domain ellipsometer (Fig. 1) consisting of a femtosecond laser as the source, fiber-coupled to two photoconductive antennas for coherent emission and detection of the pulsed electric field. Polymeric TPX (polymethylpentene) lenses and conductive wire grid polarizers (WGP) are used to collimate and focus the THz pulse and to control and select the polarization state of the signal, respectively. Compared to previous designs, this configuration offers enhanced precision and improved reliability [6].

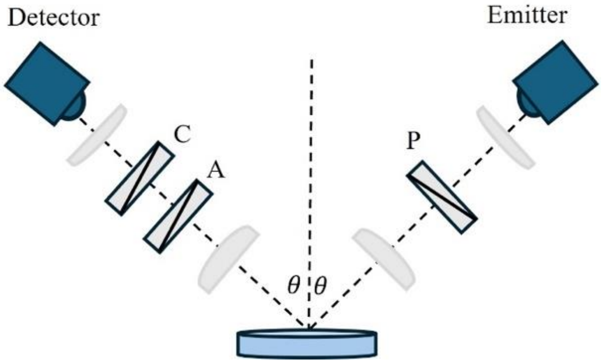

Figure 1. THz-TDSE setup

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3 Results and Discussion

Silicon wafers with different type and doping levels were selected from commercial batches for the measurements. Following precise calibration, each doped silicon wafer was positioned at the focal point of the setup to ensure maximum sensitivity. All measurements were conducted in a closed environment purged with nitrogen gas to eliminate water vapor absorption in the frequency spectrum. The spot size at an angle of $\theta = 65^o$ (close to the Brewster angle for silicon) was maintained at 4 mm. Experimental results were then fitted to a Drude-Smith (DS) model for the dielectric response of samples with carrier densities below $10^{18}\ cm^{-3}$ (#15, #17, #24). For samples #14 and #19, the DS model reduces to the Drude regime due to the absence of the backscattering factor [7]. Figure 2 presents the real and imaginary components of the dielectric response for all samples, alongside the corresponding fit. Given the reported resistivity values of samples #15, #17, and #24 ranging from 1 to 5 Ω·cm, we anticipate relatively low dielectric response values within the investigated frequency window. This expectation aligns with the inherent electrical properties dictated by the resistivity range. For samples #14 and #19, as their reported resistivity was in the range of 0.001-0.005 Ω·cm, we expected higher values for dielectric response. TDSE retrieved dielectric response of these low resistivity samples. Fitting the experimental data retrieved by THz-TDSE to Drude/Drude-Smith model of dielectric response gives us insights about electrical properties of different doped silicon wafers such as carrier density (n), plasma frequency (ω_p), relaxation time of the charge carrier (τ), resistivity (ρ). The effective mass was set to $m^* = 0.29 m_e$ for n-doped samples and $m^* = 0.39 m_e$ for p-doped samples (m_e is the free electron mass). During the fitting process, the high-frequency dielectric constant was held constant to $\epsilon_\infty = 11.5$ for samples #15, #17, and #24, and $\epsilon_\infty = 12$ for samples #14 and #19, whereas all other parameters were treated as free variables. Performing the fit, we retrieved within 10% the same values of d.c. resistivity as reported by a standard 4-probe technique. The results are summarized in table 1.

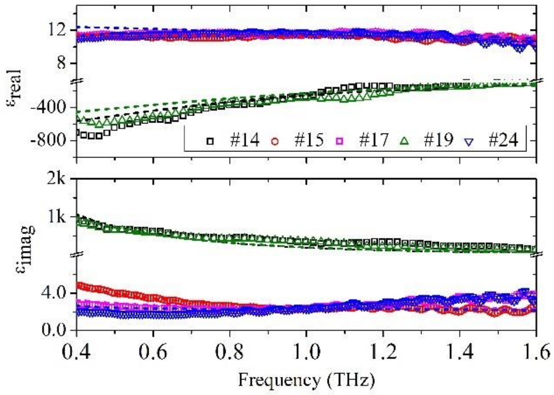

Figure 2. Real and imaginary parts of the dielectric response of samples #14, #15, #17, #19, and #24 retrieved by THz-TDSE (scattered points) along with the respective Drude-Smith or simple Drude fit (solid lines).

Table 1. Electrical properties of doped silicon wafers.

Sample	$\boldsymbol{\omega_p}$ **(2π*THz)**	$\boldsymbol{\omega_\tau}$ **(2π*THz)**	**ρ (Ω·cm)**	**n (cm^{-3})**
#14	127.7	4.7	0.003	$5.13 * 10^{18}$
#15	19.3	13.3	0.90	$1.17 * 10^{17}$
#17	20.2	13.0	1.29	$2.23 * 10^{17}$
#19	128.5	5.4	0.003	$5.21 * 10^{18}$
#24	18.5	12.0	1.57	$2.81 * 10^{16}$

4 Conclusions

This study demonstrates the efficacy of terahertz time-domain spectroscopic ellipsometry in the fast optical characterization of doped silicon wafers. By properly fitting the experimental data to the Drude and Drude-Smith models, we were able to extract critical electrical properties such as carrier density, plasma frequency, relaxation time, and resistivity. The obtained d.c. resistivity values closely match those measured by the four-probe method, validating the reliability of the technique. Our findings confirm that THz-TDSE is a powerful, non-destructive tool for semiconductor research, capable of measuring different impurity levels in semiconductors, from low (10^{16}) to reasonably high doping (10^{18}).

References

1. P.K. Lu, X. Jiang, Y. Zhao, D. Turan, M. Jarrahi, Appl. Phys. Lett. **120**, 261107 (2022)
2. L. Wang, *et al.*, Nanomaterials **9**, 965 (2019)
3. C.Y. Jen, "Silicon doping profile measurement using terahertz time domain spectroscopy", PhD Thesis, Rochester Institute of Technology (2014)
4. J. Wang, M. Naftaly, E. Wasige, Applied Sciences **12**, 3822 (2022)
5. Fujiwara, H., *Spectroscopic Ellipsometry: Principles and Applications*. John Wiley & Sons (2007)
6. Z. Mazaheri, C. Koral, and A. Andreone, Sci. Rep. **12**, 7342 (2022)
7. T. L. Cocker, *et al.*, Phys. Rev. B **96**, 205439 (2017)