IB-17

THz time-domain spectroscopic ellipsometry with simultaneous measurements of orthogonal polarizations

Q. Guo[1], Y. Zhang[2], Zh. Lyu[1], D.-W. Zhang[1], Y.-D. Huang[3], C. Meng[4], Z.-X. Zhao[1], J.-M. Yuan[1,5]

[1]*College of Liberal Arts and Sciences, National University of Defense Technology, 410073, Changsha, Hunan, China*
jmyuan@nudt.edu.cn

[2]*School of Materials Science and Engineering, Xiangtan University, 411105, Hunan, China*

[3]*Advanced Interdisciplinary Technology Research Center, National Innovation Institute of Defense Technology, 100071, Beijing, China.*

[4]*Xi'an Research Institute of High-tech, 710025, Xi'an, Shaanxi, China*

[5]*Graduate School of China Academic of Engineering Physics, 100193, Beijing, China*

Terahertz (THz) spectroscopy covers numerous interactions in physical, chemical, and biological systems. For opaque materials in the THz band, spectroscopy is generally performed with THz time-domain reflection spectroscopy (THz-TDRS), which compares the relative amplitudes and phases of reflected THz waveforms from a sample with those from a reference. The reference is often a flat metal mirror. This method is straightforward but the front surfaces of the reference and the sample must be positioned, within a fraction of a micron, in exactly the same location to obtain the accurate phase of the reflection. Such precise *in situ* positioning is difficult, although various methods have tried to overcome phase uncertainty [1-3].

Spectroscopic ellipsometry is a promising way to solve this problem and there have been attempts to establish THz time-domain spectroscopic ellipsometry (THz-TDSE) [4,5]. Here, we present a new instrumentation for THz ellipsometer, THz-TDSE with simultaneous measurements of orthogonal polarizations, which extends the reliable frequency range with a low dynamic range photoconductive antenna THz source. In order to realize simultaneous measurement of orthogonal polarizations, the method of splitting the circularly polarized probe laser pulses was employed [6]. This method made the apparatus capable of measuring orthogonal polarizations with very high extinction ratios and without rotating the polarizer. In the calibration, the TDSE response function was obtained via the simultaneous polarization measurements reflected by a flat metal mirror, adapted in conventional TDRS, and used here for THz-TDSE without problems of position accuracy. The calibration could be used to determine accurate ellipsometric parameters with a high tolerance of imperfect polarizer extinction ratios and of non-ideality in the THz reflection components. As a proof of principle demonstration, results were presented for an opaque, heavily p-doped Si (0.01~0.05 $\Omega\cdot$cm) wafer and highlighted the advanced potential of our THz-TDSE for reflection-based measurements.

The optical layout of our THz-TDSE system is shown in Figure 1a for simultaneous measurements of p- and s-polarizations. The THz pulses, generated from a photoconductive-antenna radiated by a commercial Ti:sapphire laser, were collimated and focused into the reflection module with an incident angle of 60°, which was similar to a periscope, for easy placement of the sample. In the detection part, the probe pulses were then split by a 5:5 non-polarizing beam splitter (NPB) into a detector for the X-polarized electric field (DX) and a detector for the Y-polarized electric field (DY). With proper azimuths of half-wave plates ($\lambda/2$), DX and DY could simultaneously measure THz waveforms with different polarizations. The frequency-dependent ellipsometric parameters ($\tan\Psi$ and Δ) of the Si wafer are shown in Figure 1b. The measured results (red circles and blue rectangles) are consistent with the Drude fitting (red solid lines and blue dashed lines). Figure 1c presents the relative errors of $\tan\Psi$ measured by simultaneous and non- simultaneous measurements of orthogonal polarizations. The relative errors of $\tan\Psi$ (magenta pentagrams) measured by our system were below 1% over the entire frequency range, because of the one-run detection of the two polarized components, which meant that the flicker noise of the system was greatly reduced. In contrast, limited by the low dynamic range of the THz source in the high frequency range, the relative errors in the normal THz-TDSE increased quickly with frequency beyond 1THz. The simultaneous measurements rejected significant common-mode

noise from the laser, and it extended reliable THz spectra into the frequency range with a low dynamic range of a photoconductive-antenna THz source, which is a fundamental breakthrough for reflection-based measurements and overcomes the hurdle of phase uncertainty.

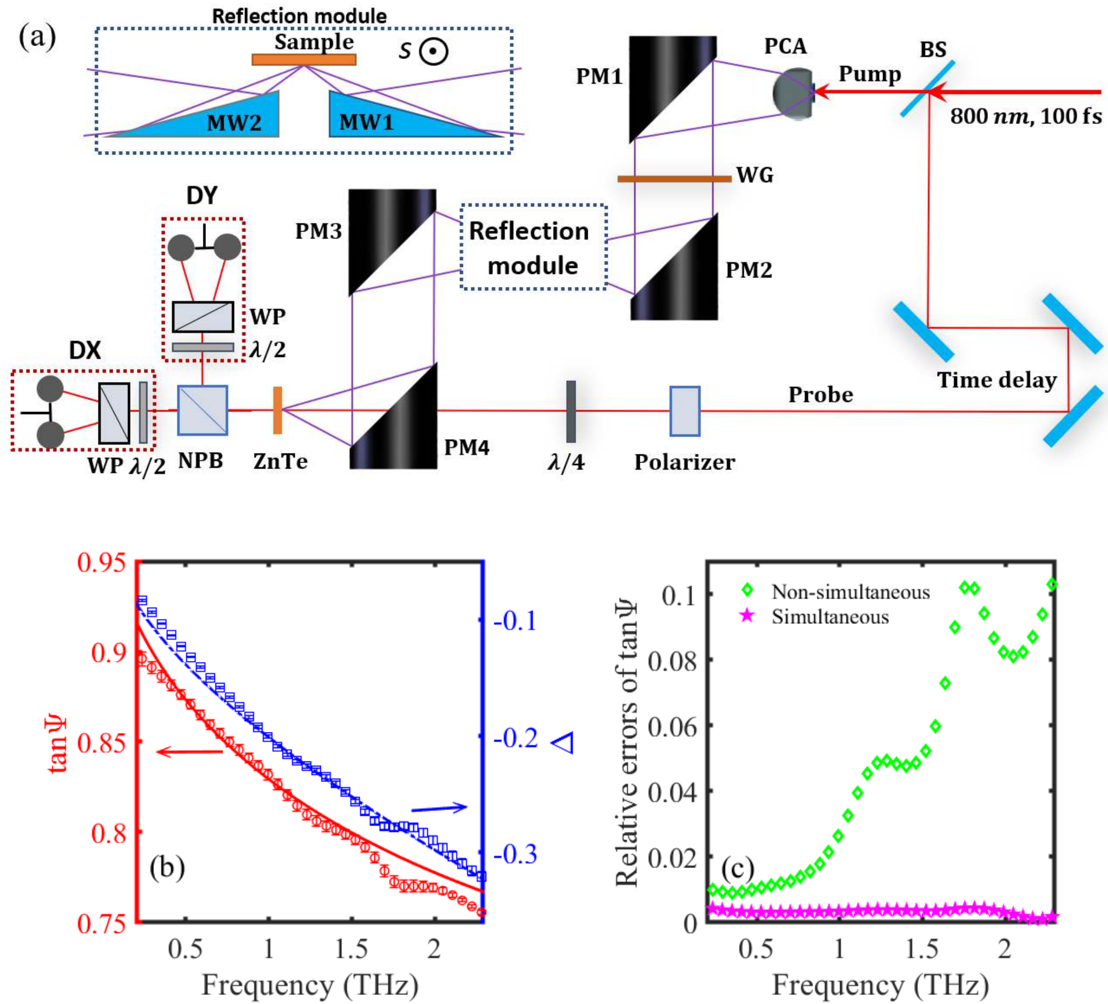

Figure 1. (a) Optical diagram of the THz-TDSE. (b) Ellipsometric parameters ($\tan\Psi$ and Δ) of the Si wafer. The red circles and blue rectangles are experimental data. The red solid lines and blue dashed lines are the Drude fitting results. (c) The relative errors of $\tan\Psi$ were calculated from the simultaneous and non-simultaneous measurements of two orthogonal polarizations. The relative error was defined as the relative standard deviation.

1. A. Pashkin, M. Kempa et al., *Review of Scientific Instruments* **74**, 4711 (2003).
2. S. Nashima, O. Morikawa et al., *Applied Physics Letters* **79**, 3923 (2001).
3. Hikaru Igawa, Tatsuya Mori et al., *Japanese Journal of Applied Physics* **53**, 05FE01 (2014).
4. Mohammad Neshat and NP Armitage, *Optics Express* **20**, 29063 (2012).
5. Nicholas Karl, Martin S Heimbeck et al., *Applied Physics Letters* **111**, 191101 (2017).
6. Nick C. J. van der Valk, Willemine A. M. van der Marel et al., *Optics Letters* **30**, 2802 (2005).