High-Sensitivity On-Chip Terahertz Time-Domain Spectroscopy with Tunable Sample Interaction for 2D Materials Analysis

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Terahertz Time-Domain Spectroscopy (THz-TDS) is a powerful technique for characterizing materials by probing spectral regions relevant to phonons, magnons, low-energy excitations, and molecular vibrations [1]. However, conventional free-space THz-TDS systems are primarily designed for bulk materials and thin films. They exhibit limited sensitivity for micro- or even nanoscale samples like biomolecules and two-dimensional (2D) materials due to inefficient THz field interaction [2,3]. In contrast, on-chip THz-TDS significantly enhances THz field interaction by confining the THz field within transmission lines, thereby increasing the interaction length and improving sensitivity [3,4]. We previously developed a low-loss on-chip THz-TDS platform using a coplanar stripline (CPS) on a low-permittivity cyclo-olefin polymer (COP) film, incorporating a separate COP film sample carrier [4]. This platform has been successfully applied under cryogenic conditions to determine the complex optical conductivity of superconducting materials [2].

In this work, we demonstrate a highly reproducible and sensitive on-chip THz-TDS system featuring tunable sample interaction. We validate this tunability through air-gap dependent measurements in a symmetric CPS structure, utilizing two COP films (Fig. 1a). Our sensor integrates a CPS on a COP motherboard with three low-temperature-grown GaAs photoconductive switches (emitter, detector1, detector2). The sample layer, positioned on a daughterboard, is placed directly onto the CPS on the motherboard between detector1 and detector2. Figures 1b and 1c present a comparison of THz time-domain spectra for graphene (Gr) and a 20 nm chromium layer (Cr), obtained using both on-chip and free-space THz-TDS, with a COP-only substrate as reference. In the on-chip system, both Gr and Cr samples show significant THz pulse amplitude reduction: 10.2 dB and 26.0 dB, respectively. These samples also exhibit substantial phase shifts (0.6 ps and 6.5 ps) and increased pulse duration. In contrast, free-space THz-TDS measurements reveal significantly lower absorption (1.4 dB and 7.5 dB for Gr and Cr, respectively) and only minimal changes in phase shift and pulse duration. These findings highlight the key advantages of our on-chip THz-TDS platform with the detachable daughterboard: enhanced interaction length and the capability to analyze ultra-thin films and 2D materials efficiently. While this highly sensitive on-chip THz-TDS system involves a trade-off in bandwidth, its limitations can be mitigated by optimizing emitter-detector distance and the CPS geometry.

We acknowledge funding from the German Ministry of Education and Research (BMBF) through NEUROTEC 2 (16ME0399 and 16ME0400).

References

[1] L. Ho, et al. *Nat. Photon*, 2, 541–543 (2008). [2] A. M. Potts, et al. *Nano Lett. 23* (9), 3835-3841 (2023). [3] B. Hong, et al. *Appl. Phys. Lett.* 4 125 (19): 191107 (2024). [4] J. Lee, et al. 2022 *47th International Conference on Infrared, Millimeter and Terahertz Waves* 1–2. (2022).

Figures

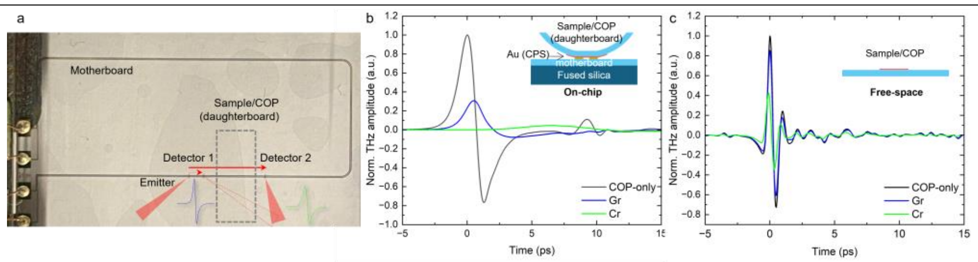

Figure 1: (a) Photograph of the on-chip THz sensor board, with an illustration of transient propagation direction along the CPS lines. THz time-domain transients of graphene (Gr), 20 nm thick Cr (Cr), and reference (COP-only) obtained from (b) on-chip THz-TDS and (c) free-space THz-TDS.