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Guided-wave THz time-domain spectroscopy of highly doped silicon using parallel-plate waveguides

R. Mendis

A novel spectroscopy technique that uses parallel-plate waveguides for the characterisation of highly conductive materials in the terahertz (THz) frequency regime is presented. This guided-wave technique resolves some of the fundamental problems associated with standard THz time-domain spectroscopy (THz-TDS) as applied to these optically dense materials. The technique is demonstrated by measuring the conductivity of highly phosphorus doped silicon.

Introduction: Ever since undistorted subpicosecond terahertz (THz) pulse propagation was demonstrated using parallel-plate metal waveguides [1, 2] there has been considerable interest in these waveguiding structures for THz applications. These parallel-plate structures have been used to demonstrate two-dimensional interconnect layers [3], sense nanometre water layers [4], study photonic crystals [5], and for building biosensing systems [6]. This Letter describes another novel use of these structures for the characterisation of highly conductive, optically dense materials resolving some of the fundamental problems associated with standard THz time-domain spectroscopy (THz-TDS) [7, 8].

THz-TDS is generally carried out in two configurations, one where the THz beam is transmitted through the sample [7], the other where the beam is reflected off of the sample [8]. The transmission method is not effective for highly conductive materials, as the sample thickness has to be reduced to impractical limits to obtain a measurable signal. In this case, the reflection method is preferred, provided it is possible to discriminate the sample signal from the reference signal. If this is not possible, this would also breakdown. Furthermore, obtaining precise sample and reference positioning for the reflection method is also quite challenging [8]. The guided-wave spectroscopy technique presented here overcomes these problems, and would be ideal for materials such as highly doped semiconductors, superconductors, and conducting polymers. To demonstrate the technique, highly phosphorus-doped silicon (Si) with a carrier density $>10^{18}$ cm^{-3} is used as the candidate material.

Experiment: The sample signal was obtained by substituting one of the metal plates in the parallel-plate waveguide [1, 2] by the Si wafer, as shown in Fig. 1. The plate separation was 130 µm and the propagation length was 5.75 mm. The reference signal was obtained using the usual all-metal parallel-plate waveguide having the same dimensions. Aluminium (Al) was used for the metal. In obtaining these signals, the waveguides were incorporated into a modified THz-TDS setup, similar to previous planar THz waveguide experiments [1, 2].

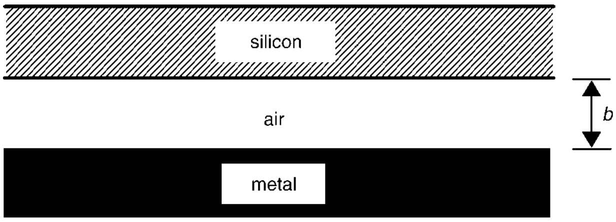

Fig. 1 *Cross-sectional view of parallel-plate waveguide*

The propagated pulses are shown in Fig. 2, where the reference and sample signals correspond to Figs. 2*a* and *b*, respectively. The amplitude spectra of these time scans are given in Fig. 3*a*, derived by taking the Fourier transforms. The clean propagated pulses having smooth spectra with no cutoff states, confirm the single TEM-mode nature of propagation [1, 2]. This is the dominant mode in the parallel-plate waveguide when the input electric field is polarised normal to the plane of the plates [9], as employed here. Realisation of single TEM-mode propagation allows the loss analysis to be carried out using well-known TEM-mode concepts as in the following Section.

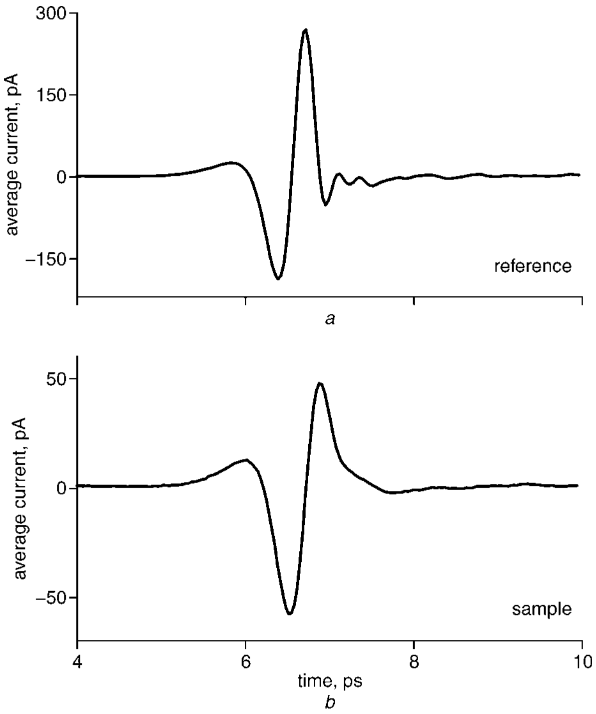

Fig. 2 *Propagated pulses*

a Reference signal
b Sample signal

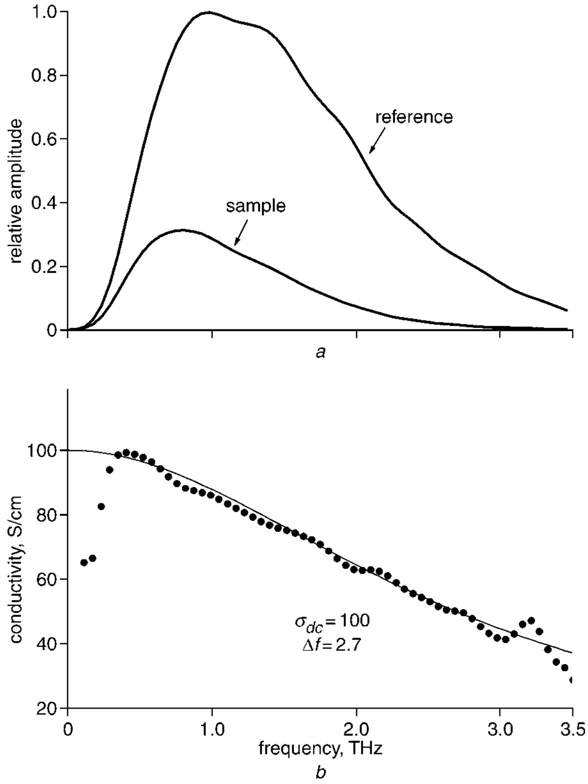

Fig. 3 *Amplitude spectra and conductivity of Si*

a Amplitude spectra of time scans
b Measured conductivity (dots) and theoretical fit (solid line)

Analysis: The input-output relationship of the singlemode waveguide system can be written in the frequency domain as [1]

$$E_{\rm out}(\omega) = E_{\rm in}(\omega) T C^2 e^{-j(\beta_z - \beta_o)L} e^{-\alpha L} \tag{1}$$

where $E_{\rm out}(\omega)$ and $E_{\rm in}(\omega)$ are the spectral components at frequency ω of the output (propagated) and input electric fields, T is the transmission coefficient, C is the coupling coefficient, L is the propagation distance, α is the attenuation constant, β_z is the phase constant, and $\beta_o = 2\pi/\lambda_o$, where λ_o is the free-space wavelength.

The propagation loss introduced by the electrical conductivity of the material forming the two plates, can be expressed as $\alpha = R/(\eta_o b)$, for the usual case where both plates are made of the same material [9]. Here, $R = 10.88 \times 10^{-3}[10^7/(\sigma\lambda_o)]^{0.5}$ is the surface resistance, η_o is the free-space wave impedance, b is the plate separation, and σ is the conductivity of the plate material. When the two plates are not made of the same material, the above expression for α can be modified to read as

$$\alpha = (R_{\mathrm{Al}} + R_{\mathrm{Si}})/(2\eta_o b) \tag{2}$$

since the overall loss is the sum of the losses due to each plate. Here, R_{Al} and R_{Si} stand for the surface resistances for Al and Si.

The difference between α's for the sample and reference signals can be obtained by applying (1) to their spectral components, taking the complex ratio, and then extracting the amplitude information. Looking at the same difference using (2), the conductivity of Si is solved to be

$$\sigma_{\mathrm{Si}} = \sigma_{\mathrm{Al}}[1 - \sqrt{\sigma_{\mathrm{Al}}\lambda_o/10}(\eta_o b/5.44L)\ln(E_{\mathrm{out2}}/E_{\mathrm{out1}})]^{-2} \tag{3}$$

where σ_{Al} is the conductivity of Al, and E_{out2} and E_{out1} correspond to the sample and reference signals, respectively. By knowing the conductivity of Al, the conductivity of Si can be derived via the sample and reference signals using (3). This is plotted (dots) in Fig. 3*b*, where σ_{Al} was taken to be constant and equal to the DC value of 3.96×10^7 S/m, since Al has a flat frequency response in this range. The validity of this measurement is conditional upon the thickness of the Si wafer being greater than the effective skin depth in Si. The skin depth can be estimated using the well-known expression, $\delta \simeq [2/(\omega\mu\sigma)]^{0.5}$, where μ is the permeability. For $\sigma = 100$ S/cm (upper-limit of measurement), $\delta \simeq 7$ µm at 0.5 THz, and decreases with increasing frequency. As the wafer thickness was 127 µm, this condition was well satisfied.

The experimentally deduced conductivity can be compared to the simple theoretical Drude model [7], where the frequency dependence of the real part of the complex conductivity (as measured here) is given by $\sigma = \sigma_{\mathrm{dc}}\,\Gamma^2/(\omega^2 + \Gamma^2)$, with the damping rate $\Gamma = 2\pi\Delta f$, where Δf is the collision frequency. The DC conductivity $\sigma_{\mathrm{dc}} = e\mu N$, with the mobility $\mu = e/(m^*\Gamma)$, where e is the electron charge, N is the carrier density, and m^* is the effective mass. Fig. 3*b* shows this comparison, where the solid line represents the theoretical curve, with the fitting parameters, $\sigma_{\mathrm{dc}} = 100$ S/cm and $\Delta f = 2.7$ THz. These parameters predict $N = 1.6 \times 10^{18}$ cm^{-3} and $\mu = 398$ cm^2 V^{-1} s^{-1}, which are found to be consistent with empirical mobility-density curves [10]. The measured conductivity is much higher than has been previously recorded for doped Si in the THz regime [7], representative of the high doping concentration. The minor fluctuations in the experimental curve can be attributed to surface-specific conditions such as roughness, oxidation, and water adsorption. The substantial deviations at the high and low frequency ends are due to low signal content.

Conclusion: A guided-wave THz time-domain spectroscopy technique that uses parallel-plate waveguides for the study of highly conductive materials is presented. Although demonstrated here using highly doped Si, this technique can be applied to virtually any material that is optically dense in the THz regime owing to high conductivity. It serves as a powerful tool for characterising such 'opaque' materials where standard THz-TDS would fail.

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