Time-Domain Reflection THz Spectroscopy of Heated c-Si for Radiometric Applications

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***Abstract*—THz time-domain reflection spectroscopy experiments of crystalline Si samples of different doping and heated to temperatures up to 475 K have been performed to measure their electric permittivity, absorptivity and resistivity dispersion spectra. Free charge carrier volume concentration and scattering time have also been extracted from the measurements, as a function of temperature, to best fit the Drude model to the complex resistivity spectra. The dependence of these microscopic parameters to the temperature resembles the curves from the unified model for the carriers mobility, based on past dc measurements. The high-frequency data acquired with these measurements constitute the fundamental information and parameters, necessary for the characterization of crystalline Si thermal radiation emission.**

I. INTRODUCTION

THE characterization and modelling of dispersion, absorption and conductivity properties of crystalline Silicon (c-Si), in the (sub-)THz range are crucial for the design of Si-based lenses [1], waveguides [2] and filters [3], which are becoming the cornerstone components of the emerging high-frequency antenna-on-chip technology. Moreover, given the high precision and reproducibility in controlling the c-Si conductivity over several decades, it has a paradigmatic value for thermal radiometry experiments [4] [5]. In fact, c-Si wafers have been recently used by the authors for emitted thermal radiation measurements [6] , in order to investigate whether the Planck black body law is truly a universal function [7]. Time-domain (TD) transmission [8] and reflection [9] spectroscopy have been proved to be a reliable and accurate technique to measure the high-frequency electric permittivity, absorptivity and conductivity of c-Si. However, THz TD measurements, so far, have been limited only to room and cryogenic temperatures [10], thus, only dc characterization of c-Si conductivity parameters are available above room temperature [11] [12]. In this work, we employed THz TD reflection spectroscopy of c-Si wafers, heated at temperatures between 300 K and 475 K: 1) to measure the reflection coefficient and electric permittivity spectra; 2) to measure the absorptivity spectra; 3) to extrapolate the free charge carrier volume concentration n and average scattering time τ, that best fit the Drude model [13] to the conductivity/resistivity spectra. The information acquired in this experimental campaign complemented the already available dc models for heated c-Si [11] [12] and provided the fundamental parameters used in [6] to investigate the validity of the Planck's thermal radiation law, in a range of temperatures and frequencies never studied before.

II. RESULTS

The setup to generate the THz pulse and to coherently acquire, by time gating, the electric field of the reflected radiation is the TERA K15 from Menlo Systems [14]. The c-Si samples are firmly attached to a hotplate, facing the THz transmitter and receiver in a quasi-orthogonal configuration (incident half-angle less than 10 degrees). The generated THz pulse is collimated before reaching the sample surface by a polymeric lens. The same kind of lens is used to focus the reflected pulse on the receiver. The characterized n-type c-Si samples are described in Table I. The effective thickness of each sample is chosen to minimize, by attenuation, the echoes generated by the internal multiple reflections. The total sample thickness has been reached, depending on the wafers availability, by using a single wafer or stacking, in intimate contact, two or more wafers of almost equal properties.

TABLE I: SILICON SAMPLES OVERVIEW

Sample	ρ_{4PP} $[\Omega \cdot cm]$	Thickness $[\mu m]$	Note
VLRS	0.04	286	Single wafer
LRS	0.4	610	2 bonded wafers
MRS	2	6300	12 stacked wafers
HRS	30	15000	5 stacked wafers

The backside of every sample has been coated with a thick layer of highly conductive, hence reflecting, Al. The pulse reflected from the metallized surface is acquired for each sample and temperature as the reference signal.

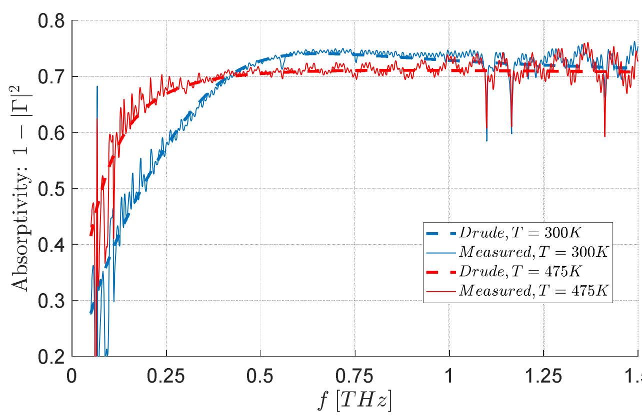

Fig. 1. Absorptivity $a_{bs}(f, T)$ of the LRS sample as a function of frequency for $T = 300\ K$ (blue curves) and for $T = 475\ K$ (red curves). The dashed curves correspond to the absorptivity calculated using the best fitted Drude parameters, in absence of internal multiple reflections echoes.

to calculate the sample reflection coefficient. The transmission line formalisms are employed to make these calculations. Fig. 1 shows the measured and simulated absorptivity of the Low Resistivity Si (LRS) sample for two different temperatures. The simulated curves are obtained using n and τ extracted from fitting the Drude model to our experimental resistivity spectra. Ripples in the simulated absorptivity spectrum are absent since the curves have been generated assuming a semi-infinite Si slab (no multiple internal reflections). On average, the measured and simulated absorptivities are the same over the entire frequency range.

Similar curves and agreement have been observed for the other samples. The solid curves of Fig. 2 report the resistivity spectra, real and imaginary parts, extracted using the measured reflection coefficient $\Gamma(f)$ and the electric permittivity $\varepsilon(f)$.

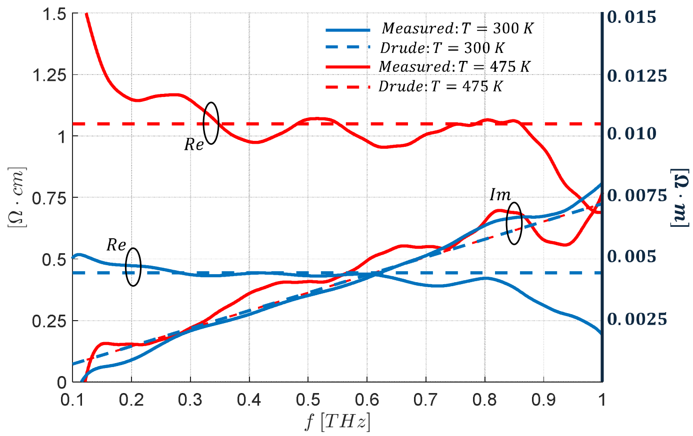

Fig. 2. Real and imaginary parts of the resistivity of the LRS sample for $T = 300\ K$ and $T = 475\ K$ as a function of frequency. The solid curves correspond to the resistivity components extracted from the experimental data, while the dashed curves to the best fit Drude equations.

The dashed curves are calculated from the Drude equations (1) and (2), respectively for the real and imaginary components ρ_r and ρ_i.

$$\rho_r = \frac{m^*}{e^2} \cdot \frac{1}{n \cdot \tau} \tag{1}$$

$$\rho_i(\omega) = \rho_r \omega \tau = \frac{m^*}{e^2} \cdot \frac{\omega}{n} \tag{2}$$

In these expressions, m^* is the electrons effective mass, e is the elementary charge, n is the electron volume concentration, τ is the average scattering time and ω is the frequency. The parameters n and τ have been extracted from the best fit of (1) and (2) to the experimental curves. The agreement is remarkably good over a large range of frequency, demonstrating that the simple Drude theory models c-Si well for all the investigated temperatures. The same fitting procedures are conducted for the other samples.

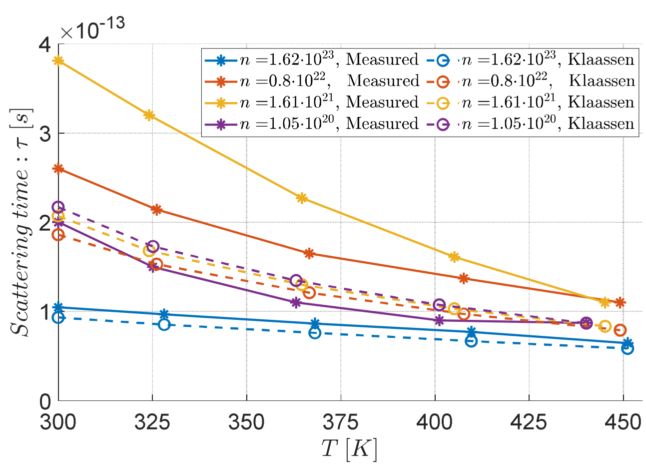

Fig. 3. Conduction electrons scattering time as a function of samples temperature. The filled dots (continuous curves) represent the data obtained from fitting the Drude model to our resistivity spectra, while the open dots (dashed curves) are the values taken from the dc measurements [11] and [12].

Finally, Fig. 3 reports the conduction electrons scattering time, as a function of temperature, for all the samples (full dots and solid lines). The figure shows also the values from [11] and [12], which have been taken in the past doing Hall and dc measurements. For the three lowest resistivity samples, comparing the literature values with the ones we extracted from the TD measurements, it appears that there is always an off-set of the former data. However, for all samples, the trend of decreasing scattering time with respect to the temperature increasing is the same, in other words, the high-frequency response is affected by the same microscopic scattering mechanism. The origin of the off-set should be investigated further, most probably employing a more refined Drude model and/or identifying any possible fundamental difference in the probing or response dynamics between the dc and the high-frequency techniques. The presented (sub-)THz dispersion, absorption and fundamental parameters of c-Si samples, of different conductivity, have been eventually used to accurately assess and model their emitted thermal radiation, when heated at the same temperatures.

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