Thin-Film Measurements with THz-Radiation

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***Abstract*—The potential of short terahertz pulses for thin-film measurements of materials opaque in the visible range is demonstrated. Layer thicknesses down to 10 µm have been determined in transmission as well as in reflection measuring mode and complex multilayer structures in the sub-wavelength range have been resolved with this technique.**

I. Introduction

THERE are different measurement methods to determine thicknesses of thin films in the sub-millimeter to micrometer range. They are based for example on electromagnetic radiation in the visible or in the microwave and millimeter region. Also ultrasonic techniques and methods using eddy currents are well established for the measurement of opaque materials. However, these methods require mechanical contact with the object to be measured.

The use of ultra short pulsed terahertz (THz) techniques allows for non-contact measurements of opaque (in the visible and infrared region) objects and provides a number of advantages. These are in particular: non-contact measurements of e.g. hot materials (ceramics in liquid phase) or touch-sensitive surfaces (wet painting [1]), measurements of water-free fluids and powders [2] and in general measurements of non-conductive materials.

In contrast to most existing measurement methods for thin films the THz technique also allows to resolve complex multilayer structures made out of different materials.

II. Transmission Measurements

The propagation velocity of THz waves in a medium depends on the refractive index of the material. Therefore a pulse which propagates through a THz-transparent medium is retarded. A sample with a thickness D and a refractive index n_{THz} delays the THz pulse in single-pass by $\Delta T = D \cdot (n_{\mathrm{THz}} - 1)/c_0$ (c_0: speed of light in vacuum). Measuring the run-time difference ΔT to a certain reference the thickness of the sample can be determined by

$$D = \frac{c_0 \cdot \Delta T}{n_{\mathrm{THz}} - 1}. \qquad (1)$$

In Fig. 1 transmission measurements of different numbers of adhesive tape layers are shown. The pulse detected without any layer is set as reference. Since each single film has a fixed thickness of about 50 µm, the time shift of consecutive pulses is nearly constant. Only small deviations are detectable due to different conditions in preparation. With the refractive index of the adhesive tape $n_{\mathrm{THz}} = 1.5$ the layers' thicknesses D can be calculated using equation (1). It is possible to resolve thicknesses down to 10 µm even without special data evaluation software. Since the absorption is rising with the number of adhesive layers the amplitude slightly reduces. The surface losses due to Fresnel reflections are constant for all numbers of layers.

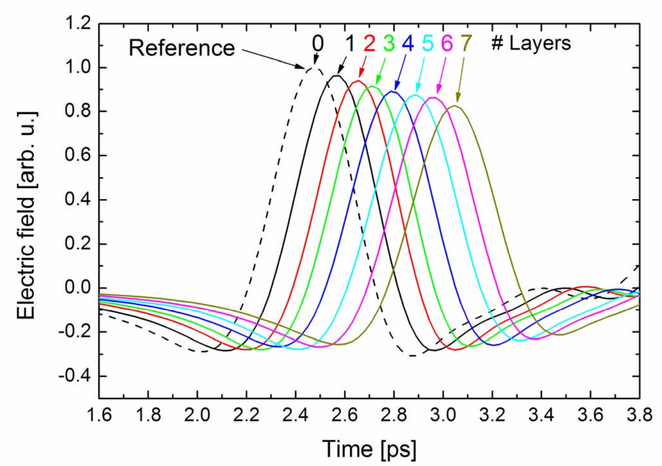

Fig. 1. Transmission measurements of different numbers of adhesive tape layers. Dashed line: Reference.

III. Reflection Measurements

To measure the thickness of materials on substrates which are not transparent for THz waves the measurements have to be performed in reflection mode. Here the THz pulse is incident under an angle of α to the normal. The time shift ΔT between the reflected part and the transmitted part, which after reflection on the layer's backside propagates for the second time through the material, contains the thickness information of the medium. Since this technique is self-referencing there is no need for a second reference measurement. The knowledge of the refractive index n_{THz} of the medium and the angle of incidence α is required to calculate the thickness D which is now given by [3]

$$D = \frac{c_0 \cdot \Delta T}{2 \cdot n_{\mathrm{THz}} \cdot \cos\left[\arcsin\left(\sin(\alpha)/n_{\mathrm{THz}}\right)\right]}\,. \qquad (2)$$

In Fig. 2 reflection measurements under 45° of different numbers of adhesive tape layers on a metallic substrate are shown. For more than one layer the pulses can be easily separated and the thicknesses can be calculated by equation (2). The results are in good agreement with the transmission measurements presented above and the values measured mechanically.

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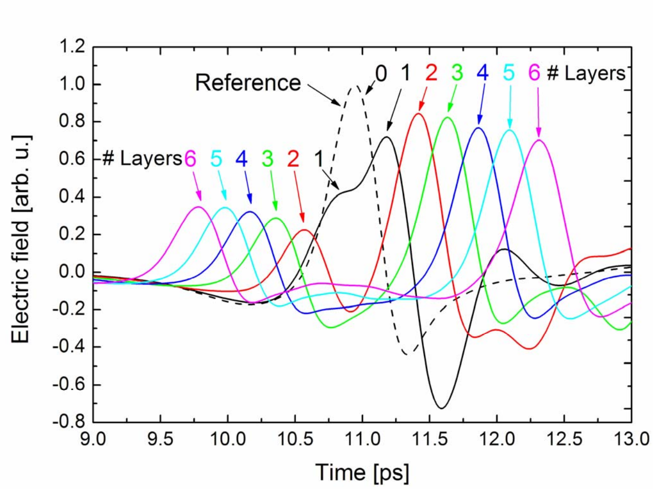

Fig. 2. Reflection measurements of different numbers of adhesive tape layers under an angle of incidence of $\alpha = 45°$.

In contrast to the previous presented transmission measurements the separation of the two pulses cannot be evaluated clearly for one single layer without additional analysis. Taking into account that the thin film corresponds to a low Finesse Fabry-Pérot etalon, the thickness of the film can be calculated out of the superposition of the multiple pulse reflections. To be more precise the setup with the high reflecting metallic substrate corresponds to a Gires-Tournois interferometer (GTI). We have shown both, experimentally as well as numerically, that in this case no additional group-velocity dispersion is generated. Hence no GTI-effect has to be considered for our thin-film measurements, and also in reflection measuring mode we are able to resolve film thicknesses down to 10 µm.

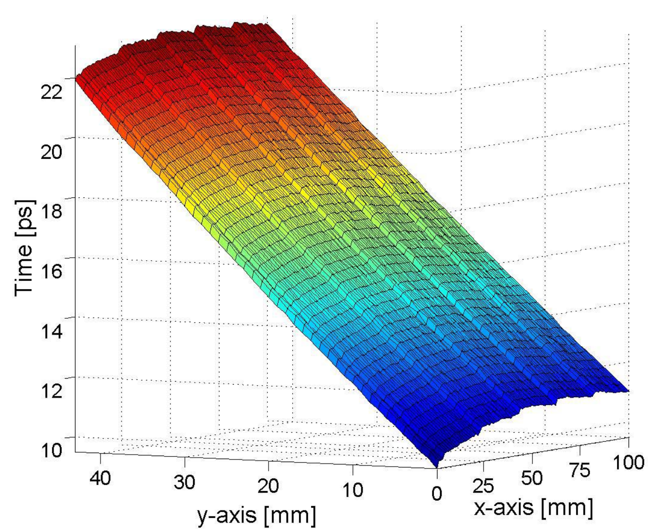

Fig. 3. 2-dimensional THz image of the sample used in Fig. 2: run-time plot of pulse maximum versus x- and y-coordinate of the sample.

In Fig. 3 the results of a THz imaging measurement under an angle of incidence of $\alpha = 0°$ of the same sample used in Fig. 2 is shown. The run-time of the pulse maximum is plotted versus the x- and y-coordinate of the sample. The tilted position of the sample related to the THz beam and the slight bending of the metallic substrate towards its edges can be seen very well.

With the THz measurement technique it is also possible to identify multilayer structures if the layers are transparent in the THz region and have different refractive indices. In the case of a change from an optically thinner to a thicker medium the phase of the reflected pulse changes by 180 degrees. As an example the reflected THz pulses from a silicon wafer covered with different layers of plastic films on both sides are shown in Fig. 4. The thickness of the 380 µm thick wafer was determined with a tolerance of 5 µm. In addition the sub-wavelength thicknesses of the covering plastic films (approximately 85 µm for one film layer) on and behind the optically opaque wafer were clearly measured. Since each plastic film has the same refraction index the THz pulse sees instead of three single covering layers only one more or less homogeneous layer with a thickness of three times a single layer (see graph "3 x film – wafer – 3 x film" in Fig. 4).

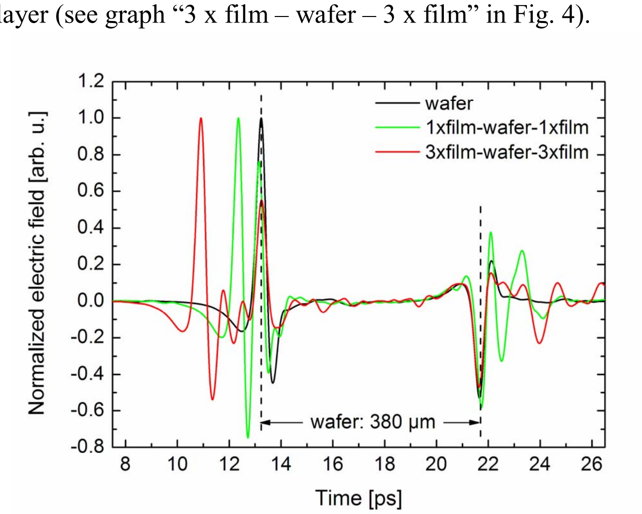

Fig. 4. Reflection measurements of a silicon wafer covered with non, one and three layers of plastic films on both sides.

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