# Quasi-optical characterization of low-dielectric constant thin film in the sub-terahertz region

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***Abstract*— Dielectric properties of materials important for production of high-speed electronic devices are studied in the sub-terahertz region. For characterization of a thin $SiO_2$ film we have developed the Grazing Angle Etalon (GAEA) method [1]. Theoretical calculations are based on recurrence relations for transmittance and reflectance coefficients of multilayer system [2].**

## I. Introduction

Let a *s*-polarized plane wave is incident at angle $\theta_0$ on a plane-parallel plate. Interference of electromagnetic waves in the plate results in periodically located maxima and minima in the transmittance spectra. Maximum intensity appears when the phase difference $\delta$ between the incident and transmitted beam fullfills the condition [2], [3]

$$\delta = \frac{2\pi}{\lambda} nd \cos\theta = m\pi, \quad m = 1, 2, 3, ... \tag{1}$$

where $\lambda$, $\theta$, $n$ and $d$ are wavelength of the incident light, angle of refraction, index of refraction and thickness of the plate, respectively. The maxima are sharper and the distance between them is larger for higher angle of incidence $\theta_0$, whilst their height remains constant (Fig. 1). The narrowing of peaks is caused by an increased reflectivity of the plate surfaces at grazing angles of incidence. The distance between the maxima is enlarged since the effective optical thickness is decreased by factor $\cos\theta$ and condition (1) is satisfied at higher frequencies.

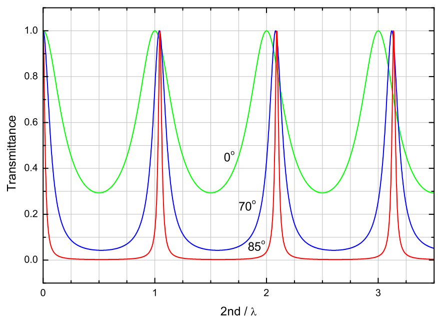


Fig. 1. Transmittance spectra calculated for a plane-parallel silicon substrate.

In Fig. 2 we show a transmission peak in the silicon substrate calculated for several angles of incidence and *s*-state of polarization. If the substrate is coated with a $SiO_2$ thin film, position of the peak shifts slightly towards lower frequencies. The presence of the small shift is manifested in the relative transmittance spectra by a maximum-to-minimum structure which becomes larger with increasing incident angle, as can be seen in Fig. 3. The best fit of the theoretical curves to measured relative transmission data may be used to determine the complex refractive index $n_\mathrm{f}$ and dielectric constant $\epsilon_\mathrm{f} = n_\mathrm{f}^2$ of the film. The technique described above is called Grazing Angle Etalon (GAEA) method [1].

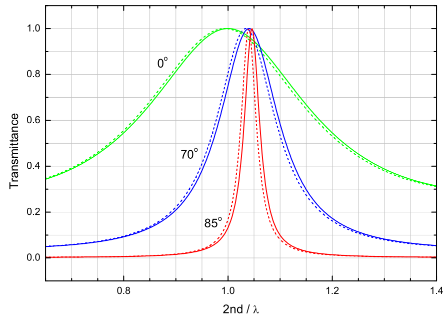


Fig. 2. Position of the transmission peak in bare (–) and coated (- -) substrates.

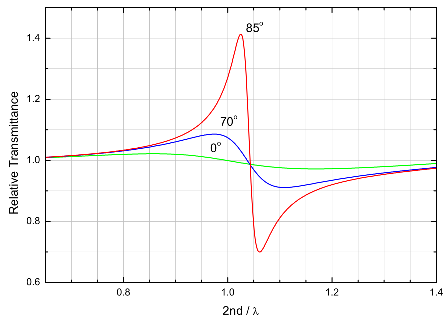


Fig. 3. Maximum-to-minimum structure in the relative transmission.

## II. Experiment

The sample was a non-doped silicon wafer 700 $\mu$m thick, 100 mm in diameter coated on both sides with 2 $\mu$m thin $SiO_2$ films. Thickness of the silicon substrate was selected to obtain one peak in the measured frequency range. The thin $SiO_2$ films were prepared by thermal oxidation of the Si wafer at 1200°C. Half of the films areas were removed from both sides of the wafer using hydrogen fluoride acid.

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The experimental setup used for measurement of transmission is shown in Fig. 4. The source of millimeter waves comprised the signal generator connected to the frequency multiplier chain by a RF cable. The waves in the 50-75 GHz frequency band were transmitted to a free space using a horn antenna, focused by lenses and, after passing through the sample, were focused to horn antenna receiver equipped with a Schottky diode detector. Amplitude modulation of the generator output at 20 kHz allowed easy signal detection by a lock-in amplifier and a fast spectra scanning.

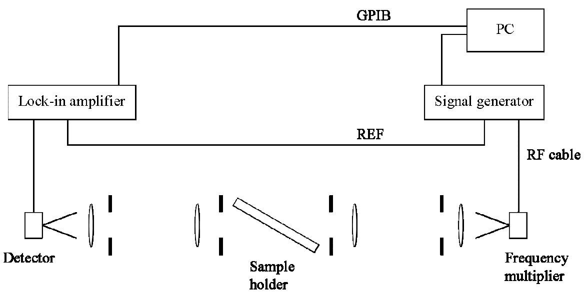


Fig. 4. The transmission measurement setup.

## III. Results

Measured spectra of relative transmission defined as the ratio of transmission of the substrate coated with the film to that of the substrate without film are shown in Fig. 5. Dashed lines represent theoretical calculations for $s$-polarized waves incident at grazing angles of 70°, 75° and 80°, film thickness $d_f = 2\mu$m on both sides of substrate, index of refraction $n_f$ =2.0+0.4$i$ and substrate parameters $d$ =700$\mu$m and $n$ = 3.4+0$i$. The theoretical curve agrees fairly well with the experimental data for $\theta_0 = 70°$. At higher angles of incidence the measured spectra are distorted by some additional oscillations, but their overall shape seems to be consistent with the theory. From the index of refraction we obtain the complex dielectric constant of the $SiO_2$ film $\epsilon_f = n_f^2 = 3.84 + 1.6i$. Whereas the real part of the dielectric constant shows good agreement with the data published by other authors [4], the imaginary part indicates rather high loss in the film under study. We estimate the complex refractive index on the assumption that there is only one maximum-to-minimum structure in the relative transmittance spectrum. With the increasing real part of refractive index, the difference between maximum and minimum of the relative transmittance is increasing. When the imaginary part is zero, the middle point of relative transmittance remains unity. However, with the increasing imaginary part of the refractive index, the middle point moves below unity. In our opinion a superposition with another structure, which is seen in Fig. 5 (b) and (c), may be responsible for the lower value of the middle point and the higher estimate of the imaginary part of the refractive index.

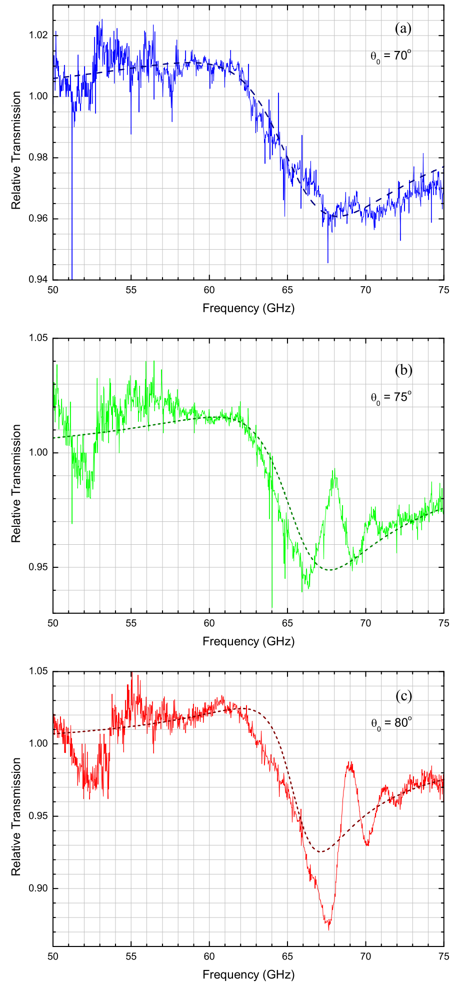


Fig. 5. Measured (–) and calculated (- -) relative transmission spectra of $SiO_2$ thin film on the silicon substrate.

## IV. Conclusion

Despite of the problems mentioned in the previous section, the Grazing Angle Etalon (GAEA) method [1] seems to be suitable for extracting material constants of thin films from the measured relative transmition spectra. The method attains enhanced sensitivity at grazing angles of incidence and makes possible to characterize low-dielectric constant thin films even when $n_f d_f \ll \lambda$ and other quasi-optical methods are hardly applicable.

## Acknowledgment

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