Optical performance of laser-patterned high-resistivity silicon wafer in the frequency range of 0.1 - 4.7 THz

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Abstract— **Optical performances of the high-resistivity silicon with laser-ablated surface were studied in the transmission mode in the frequency range of 0.1 -4.7 THz. It was demonstrated that surface irregularities causes THz waves to scatter significantly. This effect can be estimated using a THz wave scattering theory and the effective refractive index model.**

Index Terms—**terahertz transmittance, silicon optics, diffractive lenses, waves scattering, laser-ablation**

I. INTRODUCTION

DIRECT laser ablation (DLA) is a mask-less technology used for the research and development of optical components of various materials [1]. The relevance of the DLA technology has been verified demonstrating functional optical components including the multilevel phase Fresnel lenses on a high-resistivity (HR) silicon and the Soret zone plates developed on a free standing metal-foil [2-3]. In order to reduce reflection losses, the anti-reflection structures on the back side of a silicon wafer can be patterned by the same DLA technology as this has been proposed recently [4]. The effect of surface roughness on the performance of silicon diffractive components after laser ablation has been recently investigated [5]. In this work we extended the studies of optical transmission of laser ablated HR silicon in the frequency range from 0.1 THz up to 4.7 THz.

II. SAMPLES AND EXPERIMENTAL SETUP

The samples were prepared on a 500 μm thick, both-sides polished silicon wafer by varying the surrounding environment as well as the DLA parameters in order to modify the composition and roughness of the laser-ablated surface. Fig. 1 shows a photograph of the set samples. In total 38 samples were prepared changing the process parameters such as the pulse repetition rate, the pulse energy, the impulse overlap and the processing atmosphere. Most of the samples were fabricated in ambient air, while others were developed in an argon-rich atmosphere at pressures of 1 atm and 2 atm.

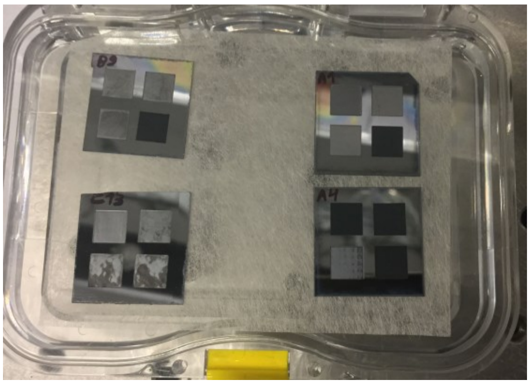

Fig. 1. Photo of four samples with four craters of 5x5 mm^2 area each. They wereabricated on 500 μm thick, both-sides polished silicon wafer using DLA technology.

A stylus profiler and a scanning electron microscope were employed to characterize the sample morphology. Optical transmittance was measured with a Golay cell detector employing the THz beam of a quantum cascade lasers (QCL) operating at 2.5 THz, 3.1 THz and 4.7 THz. The dielectric constants dispersion for each sample was obtained by a THz time domain spectroscopy (TDS).

III. RESULTS

The dependence of the transmittance on the surface roughness was measured at different frequencies. The results for 4.7 THz are presented in Fig. 2. The data allowed us to identify the critical value R_{acrit} at which the transmittance dropped by 20%. For example it was found that the critical R_{acrit} value at 4.7 THz was about 1.9 μm. Also R_{acrit} values were measured for different frequencies of the THz QCL and the THz TDS system. The results are summarized in Table I. And R_{acrit} decreases with increase of the frequency, i.e. smaller roughness on the surface changes the THz waves scattering at

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The work was supported by the European Regional Development Fund according to the supported activity 'Research Projects Implemented by World-class Researcher Groups' under Measure no. 01.2.2-LMT-K-718, supporting the project KOTERA-PLAZA (Grant no. DOTSUT-247).

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higher frequencies. The results are also shown in Fig. 3. Experimental data were fitted with an empirical expression that relates the critical surface roughness R_{acrit} and the radiation frequency f as following:

$$R_{acrit} = a + b \cdot \exp\left(-\frac{f}{c}\right), \qquad (1)$$

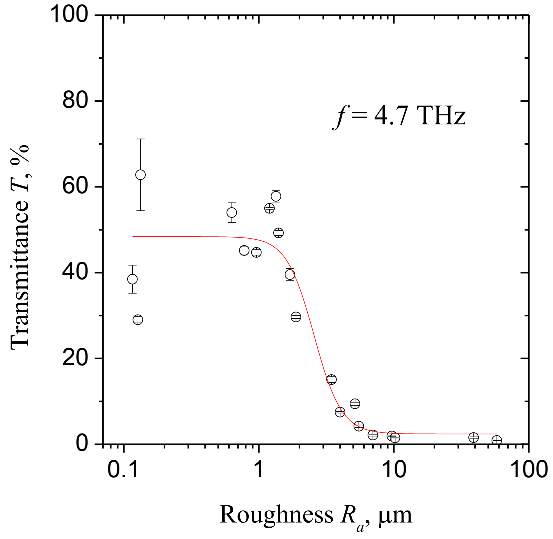

Fig. 2. Transmittance of the silicon wafers with different surface roughness (Ra) at frequency of 4.7 THz.

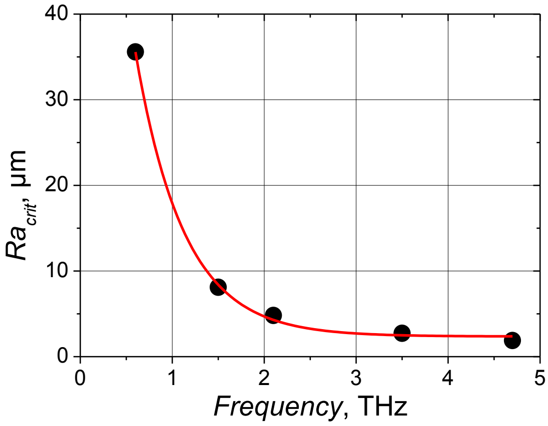

Fig. 3. The critical surface roughness R_{acrit} (at which the transmittance of laser ablated silicon droped by 20%) dependence on the radiation frequency f. Solid line shows data calculated using equation (1).

TABLE I

Critical R_a values, at which the transmittance dropped by 20%, obtained from experiment and modeling by using equation (1).

Frequency, THz	Experimental *Ra* value, µm	Calculated *Ra* value, µm
4.7	1.9	3.0
3.1	2.7	4.5
2.5	4.8	5.5
1.5	8.1	9.2
0.6	35.6	23.1

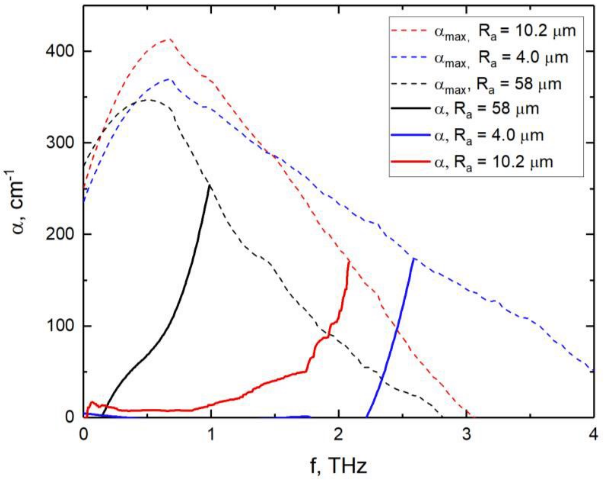

Fig. 4. The absorption coefficient spectra (solid lines) of laser-ablated silicon samples with a surface roughness (R_a) of about 4.0 µm, 10.2 µm and 10.2 µm. The maximum absorption coefficient values that can be measured with the THz TDS are indicated as dashed lines.

The data were fitted using parameter values of a = 2.4, b = 103.5, and c = 5.3. The measurement results allowed us to estimate the effective refractive index n_{eff} of the silicon with laser-ablated surface. Itit was found out to be $n_{eff} \approx 2$ [5].

The sample transmittance was measured with a THz TDS system. Results are shown in Fig. 4. It demonstrates that higher surface roughness leads to smaller critical frequency above which the value of the absorption coefficient can increase above 100 cm^{-1}. Moreover, no significant difference between the optical properties of samples fabricated either in ambient air or in argon enriched environment were found in the THz regime [5].

IV. CONCLUSION

To conclude, we have demonstrated that surface irregularities cause THz waves to scatter significantly. This effect can be estimated using a THz wave scattering theory and the effective refractive index model.

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