

# Broadband Silicon Absorber of Terahertz Radiation

V. S. Pavelyev<sup>a, b, \*</sup>, K. N. Tukmakov<sup>a, b</sup>, A. S. Reshetnikov<sup>a, b</sup>, I. A. Tsibizov<sup>c</sup>, and G. I. Kropotov<sup>c</sup>

<sup>a</sup>Samara National Research University, Samara, Russia

<sup>b</sup>Image Processing System Institute, Russian Academy of Sciences, Samara, Russia

<sup>c</sup>Tydex, LLC, St. Petersburg, Russia

\*e-mail: pavelyev10@mail.ru

Received February 27, 2019; revised March 17, 2019; accepted March 28, 2019

**Abstract**—A three-layer structure is fabricated on a low-resistance silicon substrate using plasma chemical etching. We study it experimentally and show that a substrate with such a structure can be used as an absorber of terahertz (THz) radiation in the frequency range of 0.5–2.0 THz. For this structure, absorbance in the indicated frequency range is measured to be more than 95%.

**Keywords:** three-layer sub-wavelength antireflective structure, terahertz range, Bosch process

**DOI:** 10.1134/S1027451019060466

## INTRODUCTION

Recently, the design and development of efficient absorbers of terahertz radiation has been attracting more and more attention due to their prospective use in terahertz radiation sensors [1]. Terahertz absorbers known to date, which are based on terahertz metamaterials, have relatively narrow absorption bands. In this work, we fabricate an absorber operating in a broad range of THz frequencies and investigate its properties. The absorber consists of a three-level sub-wavelength structure assembled on a low-resistance silicon substrate using plasma chemical etching. Low-resistance boron-doped silicon was chosen as the substrate material because of its high absorption in the THz range. The absorption of THz radiation by the low-resistance silicon substrate increases with increasing substrate thickness, and the transmission of THz radiation decreases to nearly zero as the substrate thickness reaches 200–400  $\mu\text{m}$ . However, the low-resistance silicon substrate as such is not a good THz absorber because of considerable Fresnel reflection at the silicon–air interface. Fresnel reflection losses do not depend on the substrate thickness and amount to 28–30% in the frequency range of 0.5–2.0 THz. To reduce the Fresnel losses and increase absorption, we must use antireflective coatings [2] or antireflective structures [3]. Modeling and calculation of antireflective structures were addressed in works [4, 5].

## FABRICATING THE ANTIREFLECTIVE STRUCTURE

To ensure absorption in a broad range of frequencies, we created a three-layer sub-wavelength

antireflective structure on one side of the silicon substrate using plasma chemical etching (the Bosch process [6]).

The fabricated three-layer antireflective structure had the following parameters: the structure period was 100  $\mu\text{m}$ ; the (square) side of the lower layer was 80  $\mu\text{m}$ ; the side of the upper layer was 45  $\mu\text{m}$ ; the height of the lower layer was 40  $\mu\text{m}$ ; and the height of the upper layer was 40  $\mu\text{m}$  (Fig. 1). The results of numerical modeling reported in [5] showed that an antireflective structure with such parameters reduces Fresnel reflection to below 5% for radiation in the range of 0.50–2.58 THz.

The substrate was a disk of *p*-silicon with the resistance  $\rho = 0.54 \Omega \text{ cm}$ ; it had a diameter of 50 mm and a thickness of 500  $\mu\text{m}$ . The process of fabrication of the antireflective structure included the following stages:

- (1) coating the entire substrate surface with an aluminum layer with a thickness of 50 nm using physical vapor deposition;
- (2) creating an aluminum mask for the upper layer, corresponding to a square side of 45  $\mu\text{m}$ , on the substrate surface by photolithography (an FP-2512 photoresist was used);
- (3) removal of the FP-2512 photoresist residues and application of a layer of FP-3520 photoresist on top of the created aluminum mask;
- (4) applying a pattern with a square side of 80  $\mu\text{m}$  and creating a photoresist mask for the lower level by photolithography;
- (5) applying the Bosch process to etch the silicon to a depth of 40  $\mu\text{m}$  through the photoresist mask of the lower level;

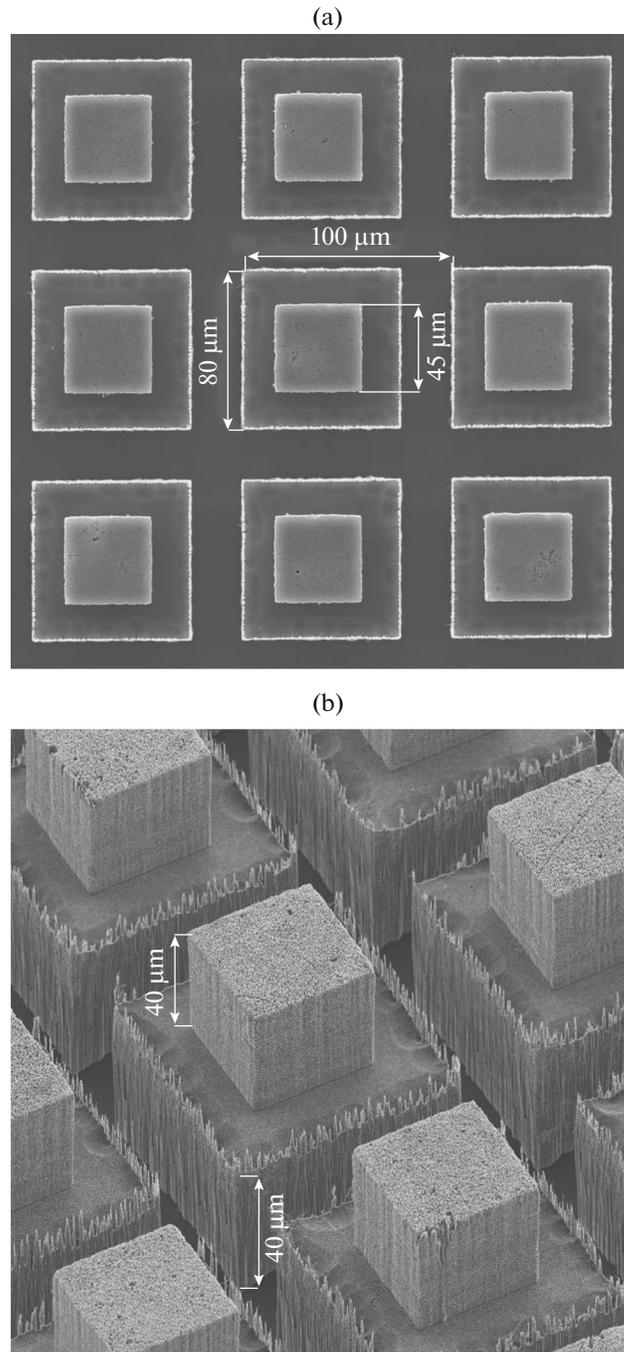


Fig. 1. Electron microscopy images of the fabricated antireflective structure.

(6) removal of residues of the lower-level photoresist mask by etching in oxygen plasma and 1-methyl-2-pyrrolidone (NMP);

(7) applying a Bosch process to etch the silicon to a depth of  $40\ \mu\text{m}$  through the upper level aluminum mask;

(8) removal of the aluminum mask residues.

Plasma chemical etching (Bosch process) was carried out using an ETNA-100-PT unit (NT MDT, Zelengrad, Russia).

An electron microscopy image of the fabricated antireflective structure is shown in Fig. 1.

#### EXPERIMENTAL CHARACTERIZATION OF THE FABRICATED ABSORBER

The fabricated absorber was studied by recording its reflection and transmission spectra using a Tera K8 system (Menlo Systems GmbH, Germany) for terahertz time-domain spectroscopy. The working range

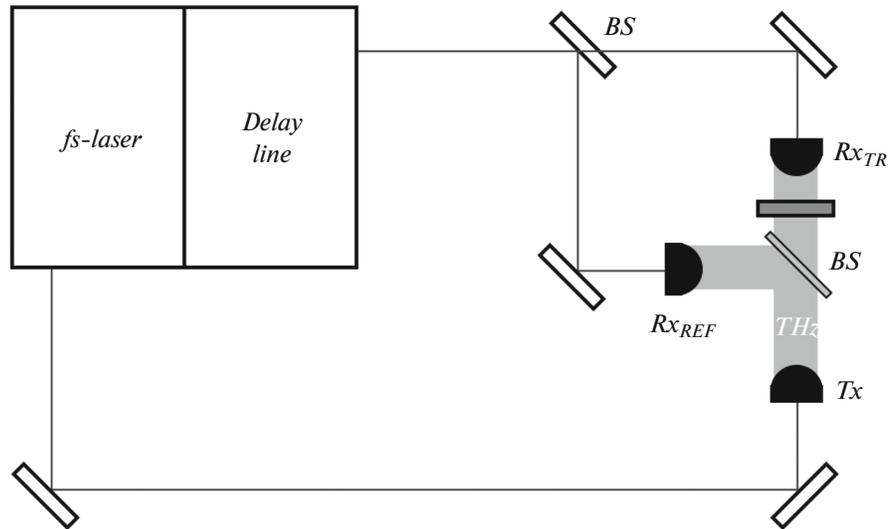


Fig. 2. Experimental setup.

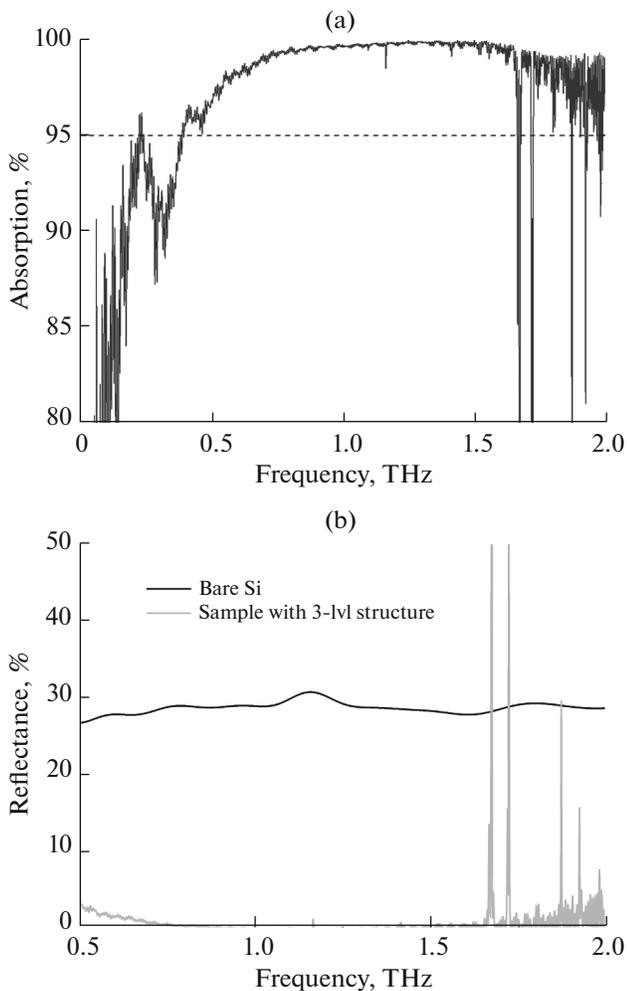


Fig. 3. (a) Absorption and (b) reflection spectra of the fabricated sample.

of the spectrometer spans frequencies from 0.2 to 2.5 THz. The spectral resolution was 5 GHz. The experimental setup was assembled so that both transmission and reflection measurements can be performed without the need to dismount the unit and remove the sample between measurements (Fig. 2). Transmission and reflection measurements were carried out at the normal incidence angle. Absorbance was calculated by the formula  $A = 1 - T - R$ , where  $T$  is the transmittance and  $R$  is the reflectance. The measured absorbance was 95% in the range of 0.5–2.0 THz. We also found that the fabricated three-layer structure functioned as a broadband antireflective coating in the THz range (Fig. 3). Fresnel reflection in the working-frequency range fell from 28–30% to below 3%.

## CONCLUSIONS

We studied a three-layer structure fabricated on the surface of low-resistance silicon using plasma chemical etching. The measured absorption was found to be more than 95% in the frequency range of 0.5–2.0 THz. The fabricated element can therefore be used in terahertz radiation sensors as a broadband spectral absorber operating in the terahertz range. Additionally, similar structures can be used to reduce Fresnel losses from the surfaces of transmissive silicon-based optical elements operating in the terahertz range [2, 7] (in this case, high-resistance silicon must be used as the substrate).

## FUNDING

The work was supported partly by Russian Foundation for Basic Research (grant no. 18-29-03303).

## REFERENCES

1. J. Lehman, A. Sanders, L. Hanssen, B. Wilthan, J. Zeng, and C. Jensen, *Nano Lett.* **10** (3), 3261 (2010).
2. A. N. Agafonov, B. O. Volodkin, A. K. Kaveev, B. A. Knyazev, G. I. Kropotov, V. S. Pavel'ev, V. A. Soifer, K. N. Tukmakov, E. V. Tsygankova, and Yu. Yu. Choporova, *Optoelectron. Instrument. Proc.* **49**, 189 (2013).
3. C. Brückner, T. Käsebier, B. Pradarutti, S. Riehemann, G. Notni, E. B. Kley, A. Tunnermann, *Opt. Express* **17** (5), 3064 (2009).
4. D. H. Raguin and G. M. Morris, *1990 OSA Technical Digest Series* (Optical Society of America, Washington, DC, 1990), **Vol. 15**, p. 122.
5. Y. Peng, X. Zang, Y. Zhu, C. Shi, L. Chen, B. Cai, and S. Zhuang, *Opt. Express*, **23** (3), 2032 (2015).
6. F. Laermer and A. Schilp, U.S. Patent No. 5 501 893 (26 March 1996).
7. A. N. Agafonov, B. O. Volodkin, D. G. Kachalov, B. A. Knyazev, G. I. Kropotov, K. N. Tukmakov, V. S. Pavelyev, D. I. Tsypishka, Yu. Yu. Choporova, and A. K. Kaveev, *J. Modern Opt.* **63** (11), 1051 (2016).

*Translated by A. Kukharuk*