12.1

Subwave textured surfaces for the radiation coupling from the waveguide

© G.V. Voznyuk[1,2], I.N. Grigorenko[1,3], M.I. Mitrofanov[1,2,4], V.V. Nikolaev[1], V.P. Evtikhiev[1,2]

[1] Ioffe Institute, St. Petersburg, Russia
[2] ITMO University, St. Petersburg, Russia
[3] St. Petersburg State Electrotechnical University „LETI", St. Petersburg, Russia
[4] Submicron Heterostructures for Microelectronics, Research & Engineering Center, RAS, Saint-Petersburg, Russia
E-mail: glebufa0@gmail.com

Received December 9, 2021
Revised January 12, 2022
Accepted January 13, 2022

The paper presents a procedure for creating on GaAs(100) substrates textured surfaces by ion−beam etching with a focused beam. The possibility of flexibly controlling the shape and profile of the formed submicron elements of textured media is shown; this will later allow formation of textured surfaces of almost any complexity for realizing the surface radiation coupling from the waveguide. Original lithographic masks were developed, and 3D lithography was accomplished. The obtained lithographic patterns were controlled by the methods of optical, electron and atomic force microscopy.

Keywords: ion−beam etching, metasurface, textured surface, lithography, surface coupling of radiation.

DOI: 10.21883/TPL.2022.03.52896.19103

Creation of lasers with the surface radiation coupling is widely demanded in many applications. For instance, the tasks of spectroscopy and gas analysis need efficient sources of IR laser radiation [1]. Among all the laser designs, ring−cavity lasers possess the maximum Q-factor and low divergence of the far−field radiation [2]. At present there are a number of approaches to realizing the surface radiation coupling: application of diffraction orders on the waveguide surface [3], formation of photonic crystals [4], creation of metasurfaces [3]. All these methods need high precision and uniformity of fabrication (e.g., the diffraction grating grooves); in addition, they are rather complicated and expensive in performance.

An alternative approach to creating surface-irradiating ring lasers may be formation of textured surfaces on the laser waveguide surface. The promising outlook of using textured surfaces for efficient radiation coupling is evidenced by some theoretical studies [5,6]. In addition, the textured surfaces may be used as templates for creating hybrid plasmon−dielectric structures [7].

The operating principle of textured surfaces is based on creating a gradually varying (gradient) reflection index at the waveguide−air interface; this enables reduction of the reflection by a few orders of magnitude and realization of the surface radiation coupling. The advantages of this approach are the possibility of the radiation coupling without changing the initial mode content of the laser, and also the absence of strict requirements for the uniformity of fabricating separate elements of the textured surface. As an example of the textured surface, a 2D array consisting of tapered elements (pyramids) may be regarded. The main requirements for the texture elements are subwave sizes (in respect to the radiation to be coupled) and as gradual as possible base−to−top narrowing of the element, which is necessary to prevent the reflection index discontinuity and, hence, conditions for light reflection [5]. Fig. 1 illustrates

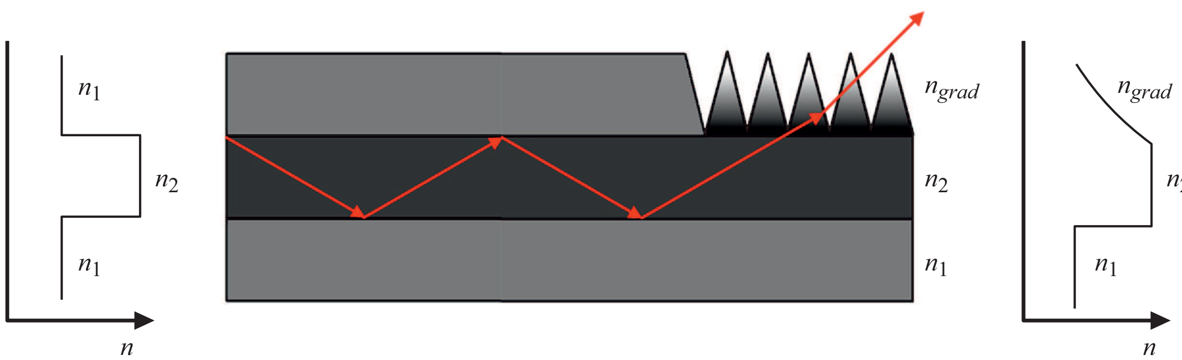

Figure 1. Operating principle of the textured surface formed in the waveguide top layer. The waveguide left part is an ordinary waveguide where light remains confined within the waveguide due to the total internal reflection. The waveguide right part contains a textured surface that provides gradually varying (gradient) reflection index, which results in the surface coupling of radiation.

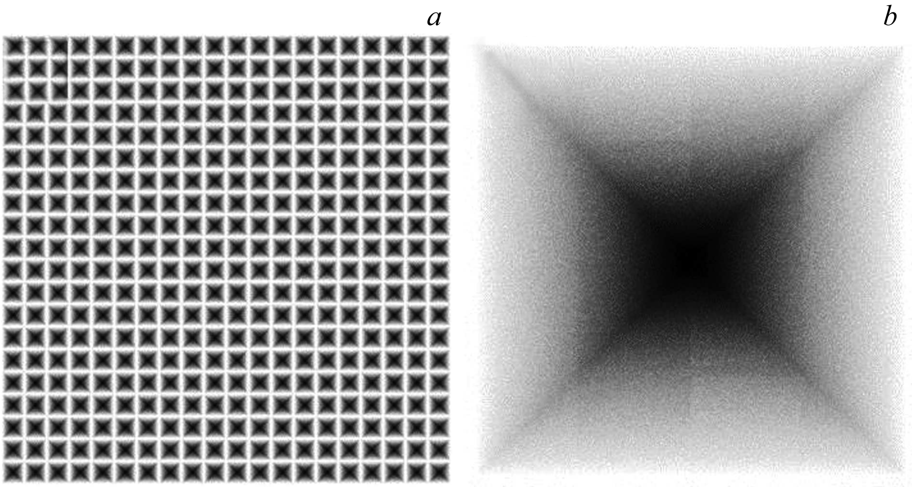

Figure 2. A lithographic mask used in formation of the textured medium by the focused ion–beam (FIB) lithography. *a* — the lithographic mask (general view), *b* — an amplified image of one of the array elements (pyramid).

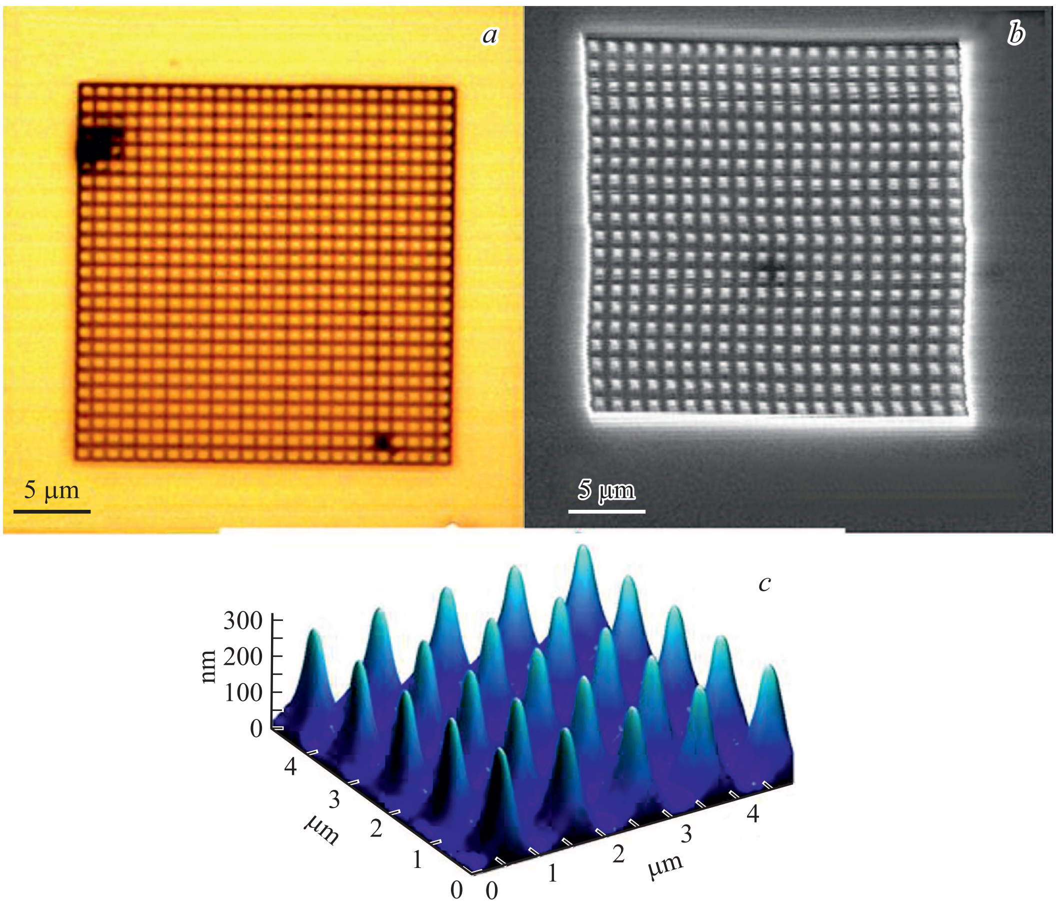

Figure 3. Images of the textured surface fabricated in GaAs by etching with the Ga^+ FIB 30 keV in energy; the images were obtained by optical (*a*) and scanning electron (*b*) microscopy. *c* — the 3D surface profile recorded using atomic force microscopy from an area of $5 \times 5\,\mu$m.

the textured surface operating principle in respect to the surface radiation coupling from the waveguide. To create the textured surfaces, we used the FIB etching method. The lithography was performed at the ultra–high–vacuum FIB etching setup „FIB-FEB UHV System"developed by CJSC „RDS" jointly with REC „Submicron Heterostructures for Microelectronics", RAS; the setup was equipped with ionization column „Cobra" produced by Orsay Physics.

The raster ion microscope resolution was 2.5 nm according to its certificate. As the etching targets, semi-insulating GaAs (100) substrates were taken.

To adjust the modes of the texture surface etching by the FIB lithography, a series of preparatory works was performed. By using the computer−aided design system Kompas 3D and graphical editors (Photoshop, GIMP), lithographic masks for the ion−beam lithography machine were designed and prepared. Fig. 2 presents the example of the developed lithographic mask $25 \times 25\,\mu$m in size containing a 2D array of pyramids. The key point of the procedure of etching via the presented mask is gradual increasing of the time of surface exposure to the focused beam in shifting from the pyramid center to its edges. The gray gradations forming the mask dictate the exposure time, which in its turn defines the profile shape and base type of the pyramid under formation. The exposure time varied from 0 s (black pixel) to $5 \cdot 10^{-5}$ s (white pixel). There was performed a series of experiments devoted to fitting the lithography performance characteristics. We succeeded in achieving the best roughness of the etched surface (> 2 nm) and uniformity of the texture elements at relatively low time expenditures at the operating current of 150 pA, maximum exposure time of $5 \cdot 10^{-5}$ s, and ion beam overlap of 75%. The lithography was performed in the presence of gas−precursor XeF_2 used to efficiently remove the etching residual products.

Figs. 3, *a*, *b* present images of the textured surface formed by the method of etching with the Ga^+ FIB 30 keV in energy; the images were obtained by optical and electron microscopy. The surface profile recorded by using scanning probe microscope „Smena“ produced by NT-MDT is given in Fig. 3, *c*.

Based on the results of this study, we have developed lithographic masks of different levels of complexity and adjusted technological regimes of ion−beam lithography employing the Ga^+ FIB. Optimal performance parameters have been determined, which allowed achieving a high quality of the produced textured surfaces. 2D arrays of pyramids with the ~ 500 nm base size and ~ 300 nm height of each element were formed on GaAs (100) substrates. The etched surfaces were controlled by optical, electron and atomic force microscopy. The perspectiveness of using FIBs for prototyping complex−geometry submicron elements has been demonstrated. Later we are going to conduct experiments on FIB−etching of submicron and subwave textured surfaces on the waveguide surface and investigate the possibility of the surface radiation coupling from such waveguides.

Financial support

The study was supported by the Russian Scientific Foundation (project № 21-12-00304).

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] D. Popa, F. Udrea, Sensors, **19**, 2076 (2019). DOI: 10.3390/s19092076
[2] R. Szedlak, C. Schwarzer, T. Zederbauer, H. Detz, A.M. Andrews, W. Schrenk, W. Strasser, Appl. Phys. Lett., **104**, 151105 (2014). DOI: 10.1063/1.4871520
[3] R. Szedlak, C. Schwarzer, T. Zederbauer, H. Detz, A.M. Andrews, W. Schrenk, W. Strasser, Opt. Express, **22**, 15829 (2014). DOI: 10.1364/OE.22.015829
[4] J. Semmel, L. Nähle, S. Höfling, A. Forchel, Appl. Phys. Lett., **91**, 071104 (2007). DOI: 10.1063/1.2771054
[5] A. Deinega, I. Valuev, B. Potapkin, Yu. Lozovik, J. Opt. Soc. Am. A, **28**, 770 (2011). DOI: 10.1364/JOSAA.28.000770
[6] J.A. Dobrowolski, D. Poitras, P. Ma, H. Vakil, M. Acree, Appl. Opt., **41**, 3075 (2002). DOI: 10.1364/AO.41.003075
[7] J. Gallant, M.A. Kaliteevski, D. Wood, M.C. Petty, R.A. Abram, S. Brand, G.P. Swift, D.A. Zeze, J.M. Chamberlain, Appl. Phys. Lett., **91**, 161115 (2007). DOI: 10.1063/1.2800381