Sensors

The silicon model photonic structure for a full-function thermal photodetector

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Abstract. The out-of-plane optical properties of a combined one-two-dimensional comb-type photonic structure based on macroporous silicon under illumination with polarized normally incident light have been experimentally investigated. Technologically simple quasi-periodic structure with parallel air grooves in the form of mutually overlapping macropores (*i.e*., one-dimensional air/Si type structure) together with macropores arbitrarily distributed over the crystal surface (two-dimensional air/Si structure) was studied in comparison with the calculated one-dimensional periodic metal lattice on silicon. It is shown that this combined air/Si photonic structure has significant polarization selectivity and can serve as a basis for developing the full-function out-of-plane thermal photodetector on macroporous silicon.

Keywords: thermal photodetector, macroporous silicon, polarization-sensitive device.

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1. Introduction

Macroporous silicon (ma-Si) has unique physical properties and serves as a basis for many original engineering solutions. One of the first fundamental works was a 1979-year article from D.L. Kendall [1] describing the physical and technological features of anisotropic etching of silicon and its practical possibilities. Investigations of these possibilities led later to the ideology of photonic crystals (PC) and then to the practice of photonic microsystems. Macroporous silicon technology enables to create one-dimensional (1D) and two-dimensional (2D) air/Si structures. The review [2] demonstrates significant progress in fabrication of micro-systems by electrochemical micromachining of silicon, complex functionally completed structures of various shapes and sizes, including those with comb fingers, with spring suspensions to the substrate, were fabricated. And review [3] is devoted to several non-photonic applications of ma-Si; in particular, new electronic devices and micro-electro-mechanical systems and applications are described. The in-plane optical properties of both 1D and 2D PC have been mainly investigated. This is due to the tasks of integrated optics and photonics in creation of complete devices for telecommunications [4], chemical [5], or biological analytics and other applications without final assembly – the so-called “lab-on-chip technology”. Our goal is to impart polarization sensitivity to the simplest out-of-plane photodetector; the 1D grating must be obviously present in its structure. At the same time, the 1D structure was proposed as an in-plane polarizer [1], which was later patented. Many exclusively 1D silicon integrated devices are demonstrated [6], which increase the density of integration and improve performances of devices. Then it provides an overview of the applications of 1D PC in silicon photonics, including grating couplers, waveguide crossings, polarization-independent directional couplers, hybrid lasers, polarizers, and high-order mode filters, but all this is developed for in-plane photonics. An idea of the state of modern research and development in the field of infrared photodetectors, in particular thermal ones, can be formulated being based on the works [7–12]. The functionality of these devices is limited by the response to the amplitude and frequency of the optical signal. They are aimed at maximum sensitivity (for security, military and other critical systems), which is not a critical parameter in some applications. Often simplicity and economy determine the choice of photodetector design. We have previously

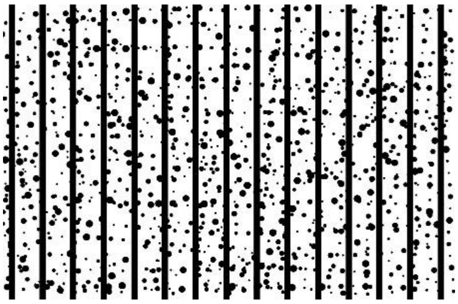

Fig. 1. The scheme of combined structure on 1D lattice with some period, *d*, for the full-function thermal photodetector.

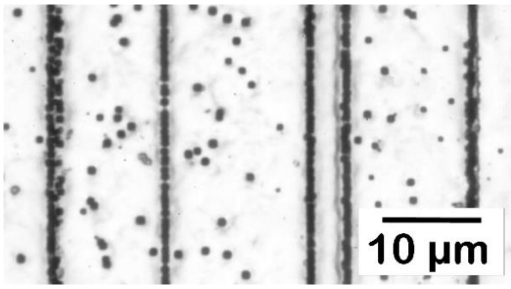

Fig. 2. The prepared and tested structure – plan view, microphoto (optical microscope).

developed and patented a thermal ma-Si-based photodetector (bolometer) [13]. In this work, we offered a similar structure with a modified topology of such photodetector and check the possibility of creating a full-function thermal photodetector. Photonic structures based on ma-Si are technologically simple and compatible with modern integrated circuits. To extend the functionality of the out-of-plane photodetector [13], its structure should be supplemented with a 1D air/Si lattice. Traditionally, it would be necessary to lithographically make a 1D lattice blank on the source crystal, *i.e*., shallow linear seeds. After subsequent photo-electro-chemical etching, the photonic structure would have the view of a combined 1D-2D structure shown in Fig. 1. This combined 1D-2D photonic structure has to be fabricated and tested. Being based on works [14, 15], it can be assumed that the optical properties of quasi-periodic and periodic structures do not differ significantly. At the same time, quasi-periodic structure – quasi-photonic crystal (QPC) – in the form of parallel air grooves is the technologically simplest structure. We were fabricated and tested such a combined simple 1D-2D structure.

2. Experimental

Sample preparation. The initial material was the *n*-type Si (100), $n_e = 10^{15}$ in the form of crystals 17×17 mm with the thickness 500 μm. 1D pattern in the form of quasi-periodically located scratches was created on the crystal by scribing. Thus, were created the linear defects of the crystal structure which initiate the etching of strongly overlapping macropores along them during subsequent photo-electro-chemical process (for details see [16]). The fabricated structure contains 1D QPC based on air grooves of densely packed overlapping macropores together with 2D subsystem of macropores arbitrarily distributed over the crystal. Thus, we fabricated 1D–2D combined QPC (Fig. 2). The depth of the macropores is proportional to the etching time; according to the chosen etching time, the depth of the macropores and, respectively, of the grooves was close to 40 μm. The average period was $d_{aver} = 9.7$ μm with a standard deviation of 0.4 μm.

3. Results and discussion

The polarization selectivity of the experimental 1D–2D air/Si QPC with artificially blurred period was studied in comparison with the calculated 1D strongly periodic structure in the form of parallel metal strips on silicon – 1D me/Si PC. Fig. 3 shows the transmission spectra of the 1D–2D air/Si QPC within the 3…16 μm spectral range at two mutually orthogonal polarizations: along the grooves – E_l, and perpendicular to them – E_t. It can be seen that within the range of measurements the curves grow linearly at the wavelengths commensurate with the average value of the 1D lattice period. The dependences of the polarized light transmission on the relative wavelength λ/d for the model 1D metal on Si (me/Si) PC with $d = 10$ μm, as the closest analog of our 1D-2D air/Si QPC, were calculated using the empirical formulas [17]. These formulas are rather cumbersome, and there is no need to present them. These formulas express the dependences for transmission of radiation polarized perpendicularly E_t and in parallel E_l to metal strips of the polarizer on the wavelength λ and on polarizer parameters – width of metal strips *a*, lattice period *d*, and substrate refractive index *n*. It is important to note the лfollowing things. According to these formulas, the calculation inaccuracy is about 1% at $\lambda/d \approx 2$ and decreases sharply with increasing λ. Since we are interested to study the region $\lambda/d >> 1$ (the sub-wavelength one), the accuracy is quite high. The corresponding curves are shown in Fig. 4 for $1 \leq \lambda/d \leq 225$. It can be seen that these curves become practically saturated already at $\lambda/d \approx 15$. The arrows on the right side of Fig. 4 indicate the measurement data for the investigated 1D–2D air/Si QPC at the wavelength λ = 2.14 μm for the longitudinal, E_l, and transverse, E_t, light polarizations. The mutually opposite nature of the polarized light transmission for the metal lattice and the air one observed. We can say that the simplest ma-Si-based photonic structure showed surprisingly high polarization selectivity. The quality of QPC can be significantly improved by optimization of the QPC structure and Si doping level. As the density of macropores and their transverse size increase, light reflection decreases in accordance with the effective

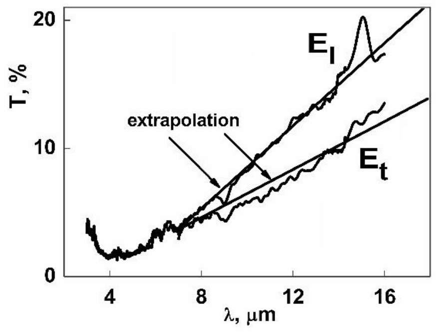

Fig. 3. The measured transmission spectra of QPC for the longitudinal polarization of the incident radiation, E_l, relatively to the grooves and for the transverse one, E_t.

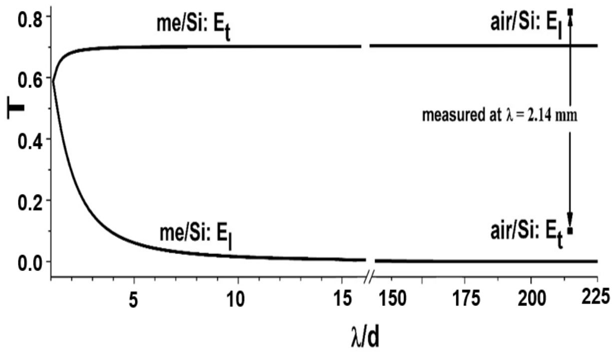

Fig. 4. The calculated data for 1D me/Si transmittance for the polarizations E_l and E_t; dots indicate the experimental data for the structure 1D–2D air/Si QPC.

medium theory, and absorption increases. At the same time, the polarization contrast – the ratio between the maximum and minimum light transmission at the corresponding orthogonal polarizations (transmission/non-transmission) – is improved. The technological simplicity and low cost of fabricating these non-ideal photonic ma-Si structures indicate their perspectivity and competitiveness. Thus, the prerequisites were obtained for the development of a full-function thermal photodetector based on the ma-Si structure.

4. Conclusion

Even the simple unoptimized structure 1D–2D air/Si-based QPC have shown surprisingly high polarization selectivity. In the sub-wavelength range, the combined 1D–2D ma-Si photonic structure can be used as a fully-functional thermal type (wideband) photodetector after optimization. According to the calculated data shown above, the transmission curves saturate at the relative wavelengths $\lambda/d > 15$ for both longitudinal and transverse polarizations of radiation. This enables to vary the period of the structure by following a specific task without distorting the spectrum of transmitted radiation. And the polarization properties remain the same in the sub-wavelength and deep sub-wavelength regions.

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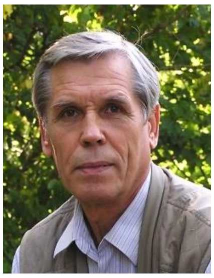

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Liptuga A.I.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation.
Morozovska D.V.: Validation, Resources, Formal analysis, Investigation, Writing - Review & Editing.
Lytvynenko O.O.: Experimental, Methodology, Investigation, Resources, Writing - Review & Editing.

Кремнієва модельна структура повнофункціонального теплового фотоприймача

К.В. Андрєєва, Л.А. Карачевцева, К.П. Конін, А.І. Ліптуга, О.О. Литвиненко, Д.В. Морозовська

Анотація. Експериментально досліджено out-of-plane оптичні властивості комбінованої одно-двовимірної фотонної структури гребінчастого типу на основі макропористого кремнію при освітленні поляризованим нормально падаючим світлом. Досліджено технологічно просту квазіперіодичну структуру з паралельними повітряними канавками у вигляді макропор, що взаємно перекриваються (одновимірна структура типу повітря/Si), разом з макропорами, довільно розподіленими по площі кристала (двовимірна структура), у порівнянні з розрахунковою одновимірною періодичною металевою ґраткою на кремнії. Показано, що така комбінована фотонна структура повітря/Si має значну поляризаційну селективність і може бути основою для розробки повнофункціонального out-of-plane теплового фотодетектора на макропористому кремнії.

Ключові слова: тепловий фотодетектор, макропористий кремній, поляризаційно чутливий прилад.