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All-silicon elements of terahertz photonics obtained by plasma etching

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Abstract. In the presented study, nanostructures on a silicon substrate were experimentally formed using the plasma-chemical etching method in a combined discharge plasma. The main objective was to analyze the relationship between the plasma-chemical etching process parameters and the structure geometry, namely: the deviation angle from the vertical, the height of the elements, and deviations from the nominal dimensions. Particular attention was paid to the influence of the active gas concentration, the power of the inductively coupled plasma source (ICP), and the power of the capacitively coupled source (CCP, bias voltage) on the structure geometry. The resulting nanostructures are considered as potential elements of terahertz photonics of metasurfaces. For example, process settings with an ICP power of 400 W, an active gas volume fraction of 7%, and a bias voltage of 101 V made it possible to obtain structures with a height of 136 nm, deviating from the specified dimensions by only 2% (98% compliance).

Keywords: all-silicon elements, terahertz photonics, metamaterials, plasma etching, microelectronics

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Исследование формирования элементов терагерцовой фотоники методом плазменного травления

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Аннотация. Основная задача представленного исследования заключалась в исследовании связи параметров процесса плазмохимического травления с геометрией структур, а именно: углом отклонения от вертикали, высотой элементов и отклонениями от номинальных размеров. Особое внимание уделялось влиянию концентрации активного газа, мощности индуктивно-связанного плазменного источника (ICP) и мощности емкостно-связанного источника (CCP, напряжение смещения) на геометрию структур. Созданные наноструктуры рассматриваются как потенциальные элементы терагерцовой фотоники метаповерхностей. Например, настройки процесса с мощностью ICP 400 Вт, объемной долей активного газа 7% и напряжением смещения 101 В позволили получить структуры высотой 136 нм, отклоняющиеся от заданных размеров лишь на 2% (соответствие 98%).

Ключевые слова: кремниевая микроэлектроника, терагерцовая фотоника, метаматериалы, плазменное травление, микроэлектроника

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Introduction

The development of modern micro- and nanoelectronics technologies dictates the need to create materials with unique properties unattainable in nature. Metamaterials meet these requirements, they open new possibilities for photonics, plasmonic, sensors and stealth technology devices [1]. However, traditional lithography and etching methods are limited in creating the subwavelength structures required for metamaterials [2]. Plasma-chemical etching has several advantages, such as a high degree of control over the geometry of nanostructures, scalability and selectivity of the process [3]. Integration of metamaterials with silicon substrates can expand their functionality and lead to the creation of new optoelectronic devices, including ultra-sensitive sensors and elements of quantum computers. Thus, the study of plasma etching processes for the formation of metamaterials on silicon is of significant scientific and practical interest, opening the way to the development of innovative components for nanophotonic and microelectronics.

Materials and Methods

The samples were silicon wafers coated with a resistive masking aluminum film 500 nm thick, deposited by magnetron sputtering. A group of geometric structures simulating elements of terahertz lenses was formed on part of the surface. The pattern was created using standard photolithography with FP 9120-1 photoresist. Development was carried out in an aqueous NaOH solution (0.6%) until the aluminum areas not protected by the photoresist were completely etched. Complete removal of the photoresist was performed in inductive oxygen plasma for 3 minutes at a plasma source power of 650 W. The composition of the gas mixture during etching was a mixture of oxygen, argon, and dichlorodifluoromethane active gas. The ratio of the gas mixture was changed during the study, the dependence of which is given in the results. The silicon surface was etched using inductive RF plasma (13.56 MHz) with a constant bias generated by a CX-600 generator, the power of which was maintained constant at 100 W during the experiment. Three groups of samples were formed using a CCl_2F_2 gas mixture. In each group, the power of the plasma source and the percentage composition of the gas mixture were varied. The obtained structures were examined on a profilometer, and numerical results were obtained using the SensoVIEW 8.1 software package.

Results and Discussion

As a result of experimental studies, arrays of structures of various configurations were obtained on the silicon surface, some of which are shown in Figure 1.

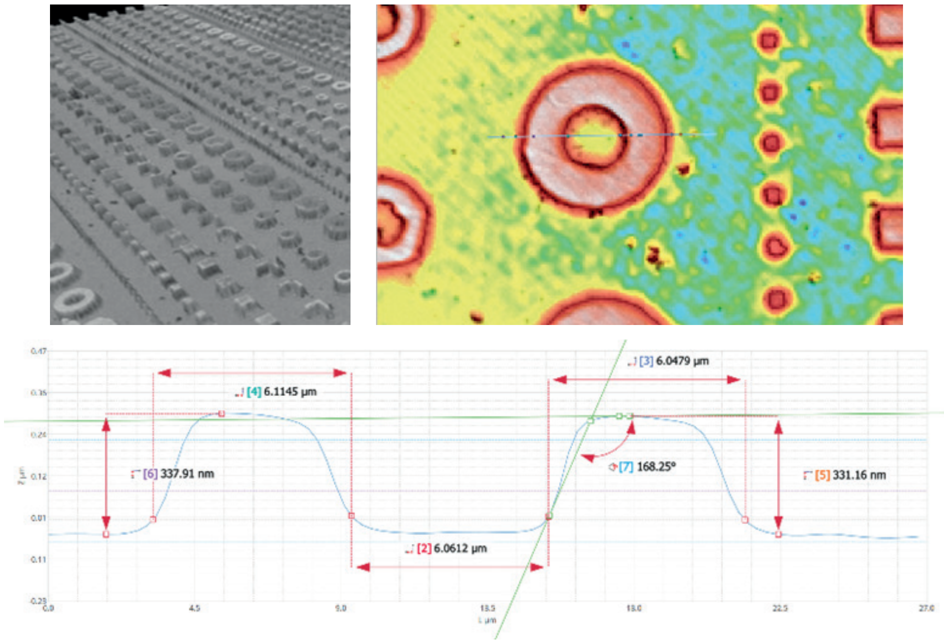

Fig. 1. Images of structures and profiles obtained on the silicon surface by plasma-chemical etching

During the work, the dependence of the height of the formed silicon structures on the power source of capacitive coupled plasma was obtained for different percentages of active gas in the mixture (Fig. 2).

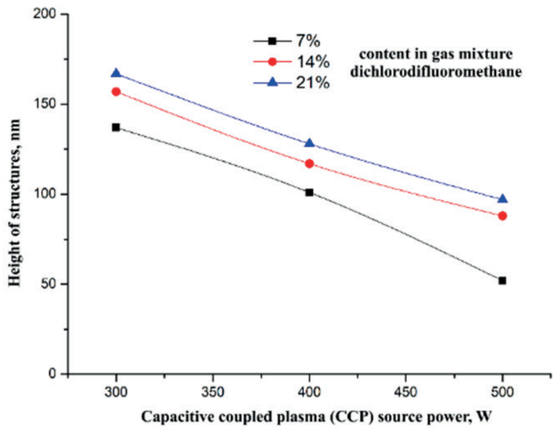

Fig. 2. Dependence of the height of the structures on the power source of capacitive coupled plasma, for different percentages of active gas in the mixture

During the studies, the dependences of the structure parameters on the plasma processing modes were obtained, so with a volume fraction of active gas of 14%, a bias voltage of 157 V, the height of the structures was 256 nm, and the correspondence of the sizes to the initially specified ones was 79%. At the same time, with a volume fraction of active gas of 21% and a bias voltage of 168 V, the height of the structures was 338 nm, and the correspondence of the sizes to the initially specified ones was 99%.

Conclusion

In this paper, we study the dependences of nanostructure parameters on plasma-chemical etching modes. The obtained dependences will allow us to form nanostructures of a given size and minimize deviations from the given size in terms of deviation angle and lateral dimensions. For example, with an inductively coupled plasma source power of 400 W, an active gas volume fraction of 7%, and a bias voltage of 101 V, we obtained structures measuring 136 nm with 98% compliance with the dimensions specified during design. The obtained structures can be used as metasurface structures for terahertz photonics.

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