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Influence of plasma power and gas mixture composition on the formation of structures on silicon carbide

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This work investigates the processes of structure formation on silicon carbide (SiC) surfaces. The influence of plasma-chemical processing parameters on the geometric characteristics of fabricated structures was examined. Correlations were established between the power of the inductively coupled plasma (ICP) source, the composition of the gas mixture (O₂/SF₆/Ar), and key structural parameters: height, surface roughness, and wall inclination angle. It was demonstrated that increasing ICP power and SF₆ concentration in the gas mixture enhances the etching rate. Processing conditions correspond to extremes in surface roughness and specific wall inclination angles were identified. Notably, under conditions of 300 W ICP power and a gas ratio of O₂/SF₆/Ar = 81/7/11, the following results were achieved: structure height of 983.62 ± 37.64 nm, surface roughness of 14.13 ± 2.15 nm, and inclination angle of 74.63 ± 1.87°.

Keywords: silicon carbide, plasma-chemical etching, fluoride plasma, structure formation, microelectronics.

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Introduction

Silicon carbide retains the status of a key material not only for power electronics and Hf-devices but also for promising elements of gas sensors which is attributed to its unique combination of properties: wide band gap, high electric strength and exceptional chemical stability in the corrosive media [1–3]. The latter property is especially important for sensors where silicon carbide elements can function for a long time at increased temperatures ensuring the detection of flammable gases and toxins under the conditions inaccessible to traditional materials [4].

However, the use of silicone carbide in standard technology is limited by its high hardness and chemical inertness making it difficult to form micro- and nanostructures with the specified geometry and low surface defectiveness [4–6].

Plasma-chemical etching is one of the most promising methods of creating functional elements of devices on silicon carbide including parts of MOS transistors, MEMS and optical waveguides [4–7]. The parameters of the surface morphology of the etched surface directly affecting the sorption capacity and response speed are critical for gas sensors [7].

The key controlled parameters of the process determining the resulting characteristics of the structures are the power of plasma source and gas mixture composition [8–13]. The studies confirm complex interdependence of these parameters. Variation of gas mixture composition (SF₆/O₂/N₂, Cl₂/Ar) affects the chemical etching processes, the material removal rate and the formation of passivating layers which determines the anisotropy and morphology [8, 10, 14–16]. Oxygen additives affect the inclination angle of

the structure [13], and nitrogen – remodeling of the profile through the deposition of by-products [15]. For sensor applications it allows to create nanostructured surfaces with increased active area. The power of plasma source regulates the density of ions and radicals determining the balance of chemical etching and physical spraying. Its optimization is critical to achieve high speeds [12], minimize defects [5, 10, 17] and form structures with high aspectual ratio [18–21], which is important for the miniaturization of sensor elements. However, combination of high power and temperature can cause mask degradation [19, 22] and surface amorphization [5, 10, 20, 22], which degrades the electronic properties of sensitive layers.

Despite the progress [1–6], the quantitative investigation of the effect of combined variation of power and composition of gas mixtures on the parameters of the structures remains valid, especially in terms of application for technological processes of creating micro- and nanostructures in the new generation sensorics [7, 14, 9, 23–25].

The purpose of this work is to establish the experimental dependencies of parameters of the form structures on the modes of plasmachemical treatment at different powers of the inductive coupled plasma sources and gas mixture composition, including roughness and the inclination angle of the structure, which are critically important for the effectiveness of gas-sensitive elements.

Experiment procedure

Silicon carbon plates of hexagonal polytype 6H-SiC were used as samples in the experimental studies. A thin Al film with a thickness of 1 μm applied on the surface of silicon carbide by magnetron sputtering method. FP 9120-1

photoresist was used in work and it was dried at 110 $^{\circ}\text{C}$ for 15 min. Development is conducted in aqueous solution NaOH (0.6 %) until the aluminum surface not protected by photoresist was completely etched. Newly applied FP 9120-1 photoresist layer ensured protection of plate surface against contamination during separation of samples by laser cutting. Complete removal of the photoresist was conducted in the oxygen inductively-coupled plasma for 3 min. at plasma power source of 650 W. Mixture composition O_2/Ar (87/13).

Plasmachemical treatment of silicone carbide samples was performed for three groups of samples. Gas mixture for creating plasma for the first group of samples had the following composition $\text{O}_2/\text{SF}_6/\text{Ar}$ (81/7/11); for the second group – $\text{O}_2/\text{SF}_6/\text{Ar}$ (74/14/11); for the third group – $\text{O}_2/\text{SF}_6/\text{Ar}$ (67/21/11). The power values of the inductive coupled plasma source for each group of samples varied from 300 W to 500 W. The power of the source of capacitively-coupled plasma equal to 150 W and shift voltage of 109 W. Operating pressure in the reactor was 2.5 Pa.

Upon completion of the plasmachemical treatment process the remnants of the protective Al mask were removed by etching in the NaOH (0.6 %) solution. Then the sample was scanned on the profilometer. The scanning was carried out in the area formed during the etching of the step to identify its parameters. A repeated scanning of the silicon carbide surface exposed to plasma during etching was also performed.

Experimental Results

Fig. 1 shows the image of the formed structure on the silicon carbide surface from the first experimental group (step in fig. 1a, the profile of the etched structure in fig. 1b).

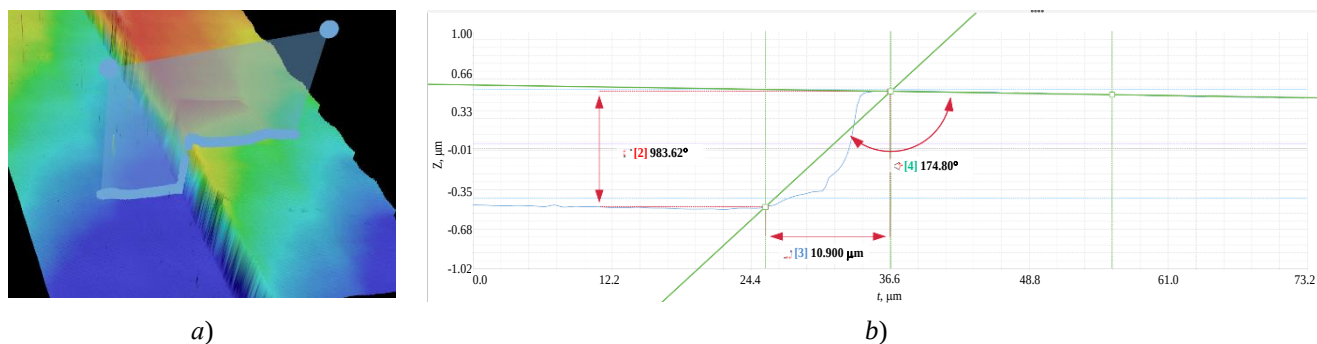


Fig. 1. Image (a) and profile (b) of one of the obtained structures

Fig. 2 shows the results of experimental studies reflecting dependencies of the height of the obtained structures on the power of the inductive coupled plasma source at different ratios of gas mixture.

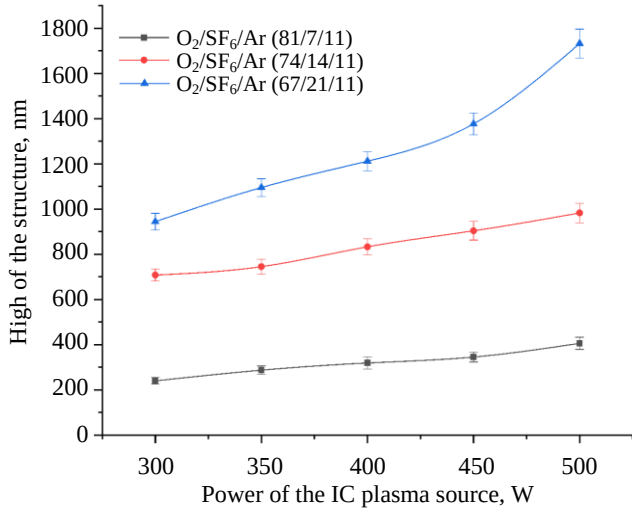


Fig. 2. Dependence of the height of the etched silicon carbide layer on the inductive coupled plasma source at different ratios of gas mixture

Analysis of the dependencies showed that under the given modes dependencies are actually linear. As the power of the plasma source increases, the structure height also increases which can be explained by the energy of particles and degree of decomposition of the reactive has mixtures that intensifies the process. It can also be seen that when increasing the proportion of the F-gas, the number of active fluorine ions in the plasma also increases and they in turn interact with the silicon component of the silicon carbide structure and provide heavy ions for the process of reactive ions etching which in turn results in the increase of height of the formed structures.

Fig. 3 shows the results pf experimental studies reflecting the effect of the power of the inductive coupled plasma source at different gas mixture rations on the inclination angle of the formed structure.

The obtained dependency shows that a decrease in oxygen in the mixture significantly affects the structure's angle which was measured as shown in fig. 1. It can be concluded from the dependency show that with a lower oxygen value and an increase in the power of the inductive coupled plasma source, the inclination angle

value of the structure decreases. With an increase in the percentage of oxygen in the mixture, the inclination angle value changed slightly and has a virtually linear nature which correlates with theoretical studies.

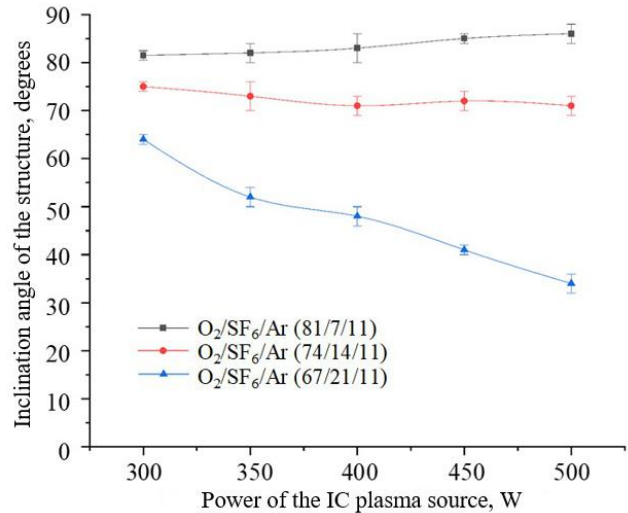


Fig. 3. Dependence of the angle of the structure formed on the surface of silicone carbide on the power of the inductive coupled plasma source at different gas mixture ratios

Fig. 4 shows the results of experimental studies reflecting the effect of the power of the inductive coupled plasma source at different gas mixture ratios on the roughness of the etched surface.

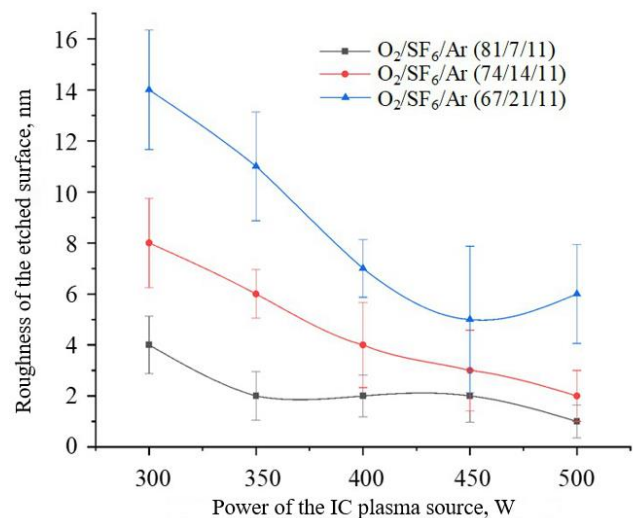


Fig. 4. Dependence of the roughness of the etched silicone carbide surface on the power of the inductive coupled plasma source at different ratios of gas mixture

The obtained dependency shows that when increasing the proportion of F-gas the number of heavy ions also increases and the roughness of the etched surfaces increases, when increasing the power, the process of chemical plasma polishing probably occurs and the component responsible for physical spraying decreases, respectively, the roughness of the etched surface decreases.

Conclusion

Thus the conducted experimental studies made it possible to establish patterns of the height of the structures formed by plasma etching and the roughness of the etched surface on the power of the inductive coupled plasma source at different gas mixture ratios. Dependence of the inclination angle of the structure on the power of the inductive coupled plasma source at different gas mixture ratios was established. The modes corresponding to the minimum and maximum roughness of the etched surface at specified heights of the structure, as well as modes of

formation of inclined structures. The identified experimental dependencies showed that the power increase of the inductive coupled plasma source, as well as increase of F-gas content result in the increase of plasmachemical etching rate, for example, at the ICP source power of 300 W and gas mixture composition of $O_2/SF_6/Ar$ (81/7/11), the height of the structure on the silicon carbide was 983.62 ± 37.64 nm and the roughness of the etched surface was 14.13 ± 2.15 nm, the inclination angle was 74.63 ± 1.87 degrees. It is shown that the increase in oxygen in the mixtures results in the increase of inclination angle of the structure, while the effect of power on the inclination angle of the structure decreases with the oxygen increase.

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