Study of the effect of substrate holder temperature on the etching rate of monocrystalline silicon carbide

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Abstract. The paper touches upon the features of thermal stimulated plasma chemical etching (PCE) 6H-\textit{SiC} in fluorine-containing inductively coupled plasma (ICP) in the temperature range from 50 °C to 300 °C. It was found that the etching rate of silicon carbide increases linearly from 0.9 \textmu m/min to 1.3 \textmu m/min with an increase in the temperature of the substrate holder from 50 °C to 150 °C, and further temperature increase to 300 °C does not contribute to an increase in the etching rate of \textit{SiC}. On the basis of the obtained experimental data, the physicochemical regularities of plasma chemical etching of silicon carbide at elevated values of the substrate temperature were determined.

1. Introduction

The processes of plasma processing of materials are widely used in the production technology of microelectronics devices both for the formation of surface relief for creating various classes of devices and for cleaning the surface of a wide range of electronic equipment materials [1].

At present time, silicon carbide (\textit{SiC}) is used as substrates for the manufacture of various semiconductor devices operating at high temperatures (1000 °C), which simplifies the design and operating conditions of products for special purposes [2–5].

At the same time, the use of silicon carbide substrates requires the use of special technological processes and equipment for their processing. This is due to both the specific physical and chemical properties of this material, as well as the characteristics of the created products of microsystem and microelectronic technology for special purposes. In this regard, directional (anisotropic) plasma chemical etching of silicon carbide with high speeds, ensuring the formation of deep, defect-free surface relief, is a key technology for creating many devices and, in particular, high-power microwave transistors [2–9].

However, the use of commercially available plasma chemical equipment and conventional modes for solving such problems is impossible, since they are characterized by insufficiently high etching rates, as well as a rather low selectivity of etching the \textit{SiC} substrate with respect to the mask material.

Typical etching rates range from 200 to 700 nm/min [10–16] with an RF power source ICP less than 1000 W and a bias voltage less than -300 V, and from 700 nm/min to 1500 nm/min with RF power source more 1000 W and bias voltage more than 300 V [17, 18]. It is worth noting the authors of work [19, 20], who managed to achieve record etching rates for 4H-\textit{SiC} silicon carbide substrates, about 2 \textmu m/min, but these values were achieved at an RF power of 2 kW and a bias voltage of more than 500 V. The results obtained in the work [21], which authors report about achievement of etching rate of silicon carbide substrates 4H-\textit{SiC} about 0.95 \textmu m/min, at values of the absorbed power and bias...
voltage of 1200 W, 160 V, respectively deserve attention. It was succeeded to reach such rates due to the use of quite difficult and expensive helicon source of high-density plasma.

It should be noted that the above results were obtained in experiments where the substrate temperature was not considered as a parameter affecting the etching rate. At the same time, works on PCE etching of lithium niobate are known, in which experimentally proved the presence of temperature ranges, within which the etching rate increases significantly [22]. Therefore, we studied the effect of the temperature of the substrate holder on the etching rate of silicon carbide in this work.

2. Experimental part

The etching was carried out on a specially created original installation of plasma chemical etching (Fig. 1) [23]. The plasma chemical reactor of the installation is based on the use of a cylindrical source of inductively coupled plasma. The inductor of the plasma generator was located outside the working chamber and was separated from it by a wall made of alumina ceramics, which made it possible to avoid spraying the inductor material during the technological process. In the lower part of the reaction chamber, there was a mechanical substrate holder with a built-in heating element, providing the possibility of heating and stabilizing the surface of the table in the temperature range from 50 to 400°C with an accuracy of ± 1 °C (Fig. 2)[22].

![Figure 1](image.png)

**Figure 1.** The design of PCE SiC with an inductively coupled plasma source.

Power (up to 1000 W) from a high-frequency generator operating at a frequency of 6.78 MHz was fed to the plasma generator through a resonant matching device. The formation of a constant bias voltage on the substrate holder was provided by the supply of RF power to the sample holder at a frequency of 13.56 MHz from a separate generator.

Sulfur hexafluoride SF₆ of high purity 99.998 (GOST TU 6-02-1249-83) was used as the main etchant gas. Studying the morphology of the etching surface in mixtures of different composition (SF₆/O₂, SF₆/Ar, and SF₆/O₂/Ar) showed that the etching in the SF₆/O₂ mixture is characterized by the lowest defect density on the etching surface [24]. Therefore, experiments on the study of the thermal
stimulated process were carried out in this mixture. The working gases in the discharge chamber were supplied using gas flow regulators RRG-10 (Eltochpribor), providing the necessary amount of gas flow with an accuracy of ± 0.25%. The pressure in the chamber was measured with MKS Instruments vacuum gauge with a measurement accuracy of ± 0.001% (for precise pressure control in the etching process), the indications of which do not depend on the composition of the gaseous medium.

As samples, 6H-SiC plates with a diameter of 76 mm and a thickness of 110 μm with a metal mask (Ni) with a thickness of 7 μm were used, in which windows were created in the form of hexagonal holes with a distance between parallel faces of 60 μm (Fig.3).

A plate of monocrystalline SiC was tightly attached to the surface of the table and after sealing the reactor, the internal volume was pumped to the required pressure. Then the process of heating the substrate to a predetermined temperature began, at the end of which the surface of the plate was processed in argon plasma for 10 minutes ($Q_{Ar} = 21.75 \text{ cm}^3/\text{min}$, $P = 0.7 \text{ Pa}$, $W_{RF} = 750 \text{ W}$, $U = -25 \text{ V}$) in order to clean it from unwanted contaminants. After this cleaning, the process of plasma chemical etching began at the above indicated values of the technological parameters. The etching rate of silicon carbide was calculated from the results of measuring the etching depth ($d$), which, in turn, was determined by micrographs, obtained using a Supra 55VP scanning electron microscope by CarlZeiss.

| $W$ | $U_{bias}$ (V) | $P$ (Pa) | $h$ (cm) | $Q_{O_2}$ (%) | $T$ (°C) |
|-----|----------------|---------|---------|---------------|----------|
| 800 | -150           | 0.75    | 5       | 23            | 50       |
| 800 | -150           | 0.75    | 5       | 23            | 100      |
| 800 | -150           | 0.75    | 5       | 23            | 150      |
| 800 | -150           | 0.75    | 5       | 23            | 200      |
| 800 | -150           | 0.75    | 5       | 23            | 250      |
| 800 | -150           | 0.75    | 5       | 23            | 300      |
3. Results and discussion

The resulting dependence of the etching rate on the temperature of the substrate holder is shown in Fig. 4. As can be seen from the figure, the etching rate of silicon carbide is a nonlinear function of the temperature of the substrate holder and, in general, the resulting dependence can be conditionally divided into two sections: 50–150 °C and >150 °C. In the first section, the etching rate grows linearly with an increase in temperature from 0.9 µm/min to ~1.3 µm/min, and at temperatures above 150°C (the second segment), the etching rate does not depend on temperature and remains constant up to the highest value in the studied temperature range.

As you know, the removal of the substrate material in the PCE process is carried out both by spraying the material with plasma particles with sufficiently high energies for this (physical component), and as a result of reactions of chemically active particles (CAP) of the plasma with the surface to form volatile compounds (chemical component). Since an increase in the substrate holder temperature from 50 to 150 °C can not influence the physical component of the etching process, it can be assumed that the increase in the SiC etching rate in the first section is mainly due to the increase in the rate of chemical reactions on the surface of the sample being processed.

Figure 4. The dependence of the etching rate of SiC on the temperature of the substrate holder.
As for the second section of the dependence $V_{\text{etch}}(T)$, the efficiency of the PCE process is determined both by the conditions for the delivery of CAP to the surface of the etching material and by the conditions for the removal of the volatile products of CAP interaction with the material from the etching zone. The flow of gaseous products removed from the etching zone increases with an increase in the rate etching and, as a result, the conditions for delivering CAP to the etching zone change. On the basis of this, it can be assumed that the invariance of $V_{\text{etch}}$ in the temperature range from 150 to 300 °C is connected, apparently, with a significant increase in the number of gaseous etching products near the SiC surface, preventing the delivery of new CAP and ions to the etching zone.

4. Conclusions
The performed studies resulted in an increase in the temperature of the substrate holder led to a significant increase (approximately 1.4 times) in the etching rate of SiC in a certain temperature range (50–150°C). The increments of the etching rate were not found with a further increase in temperature. The presence of a temperature range, within which there is a significant increase in the etching rate, indicates that in the tasks of creating effective PCE processes of monocrystalline silicon carbide, the substrate temperature should be considered as a variable parameter.

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