Formation of deep mesa-structures on SiC using fluoride plasma

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Abstract. A process of deep profiles formation on silicon carbide using ion-plasma etching in fluoride plasma is discussed. An industrial equipment «Caroline PE 15» (Russia) with ICP plasma source was used in experiments. The obtained experimental samples are perspective in power electronics applications.

1. Introduction
Silicon carbide shows an extreme hardness, which makes its mechanical and chemical processing. Ion-plasma processing in vacuum provides a new level for problem solving in many technological tasks, which is determined by selectivity, homogeneity and anisotropy of etching process (at high etching rate), as well as a possibility for generation of materials with various electrophysical properties.

At present time one of the principal methods for semiconductor structures micromaching is reactive ion-plasma etching (RIE). In microstructure formation this technology provides sufficiently high etching rate, possibility for realization of required profile of elements and low density of defects at subsurface area of the structures.

This article is devoted to micromaching of silicon carbide in fluoride containing plasma, revealing and optimization of processing regime in formation of deep mesa-structures using industrial RIPE-equipment «Caroline PE 15» (Russia) (figure 1).

Figure 1. Scheme of RIE equipment «Caroline PE 15»:
a – reactor chamber; b – ICP; c – cooled HF-electrode;
d – processed sample; e – spools of magnetic system;
g – flange for gas delivery; f – flange for pumping.
2. Experimental

Complex silicon carbide surface cleaning procedure was completed at a preparatory stage of work using liquid treatment with H₂SO₄ + H₂O₂ mixture at 60…70 °C. Then, multilayer metal deposition of Ti–Cu–Ni was performed using vacuum equipment for magnetron deposition «KONT» (Russia). Titanium was used in order to increase an adhesion, copper – as a general mask and nickel – as a protection metal for copper, to prevent oxidation of copper contacts.

In the next step photolithography was made using metallization as a mask, and after that deep mesa-structures were formed by RIE method. In experiments a mixture of sulfuric hexafluoride with oxygen was used. RIE process is an ion-stimulated one, because radicals and ions of SF₆ are capable for reacting with substrate surface. The processes in plasma and on the silicon carbide substrate surface could be schematically represented as follows:

\[
\begin{align*}
SF_6 + e^- & \Rightarrow SF_{6-n}^n + nF + e^-; \quad n = 0...6; \\
Si + 4F & \Rightarrow SiF_4; \\
Si + SF_4^{2+} & \Rightarrow SiF_4 + S; \\
C + 4F & \Rightarrow CF_4.
\end{align*}
\]

In the process of etching serum is precipitated on the substrate surface. It could be removed by physical nebulisation or by adding oxygen into the working gas mixture:

\[
S + O_2 \Rightarrow SO_2.
\]

Adding oxygen increases the rate of SiC etching, since oxygen reacts with carbonium yielding volatile compounds which prevents formation of polymer films on the surface:

\[
C + O_2 \Rightarrow CO_2.
\]

Generation of chemically active particles in plasma causes simultaneous development of various processes, such as etching, polymerization, gas-phase reactions. Furthermore etching rate depends practically of all parameters of the process: etching gas pressure, HF-generator power, temperature and working gas flow velocity.

In order to reveal optimal etching rate values, silicon carbide surface quality and wall slope angle a series of experiments were carried out. A fixation of delivery rate of SF₆ + O₂ mixture and spool current (Iₗ = 1,2 A), while power applied at upper (150…700 W) and lower (100…300 W) HF-electrodes varied (figure 2).

**Figure 2.** Dependence of etching rate for silicon carbide from: (a) – power at the upper HF-electrode (Wᵤ) at various power of lower HF-electrode values; (b) – power at the lower HF-electrode (Wₗ) at various power of upper HF-electrode values.
Figure 2(a) shows that under fixed power value at lower HF-electrode, increase of etching rate is observed along with increase of discharge initiation power, which could be explained by the increase of dissociation grade and ionization of working gases, and consequently – concentration of active particles.

There is a range of optimal power values, where etching rates are maximal. When power is increased, a free-path length of particles decreases, which makes delivery of active particles released in the dissociation process and responsible for etching, hard to reach the substrate. Under power lower than the optimal one concentration of above particles decreases.

Figure 2(b) shows, when power of lower HF-electrode is increased the intensity of the ion sputtering surface increases. Etching rates of mask layers in RIE were: for nickel – 15…17 nm/min, copper – 30…40 nm/min, titanium – 150 nm/min. These values provide etching rate ratio values within ~ 40…50.

3. Results and discussion

An optimal regime for deep silicon carbide etching was experimentally developed and tested:
– power at upper HF-electrode \( W_{up} = 350 \text{ W} \);
– power at lower HF-electrode \( W_{lo} = 200 \text{ W} \);
– spool current \( I_s = 1.2 \text{ A} \);
– gas mixture of \( \text{SF}_6 + \text{O}_2 \) pressure \( P = 1.5 \text{ Pa} \).

Fixed auto-offset voltage was \(-120 \text{ V}\). In figure 3 SEM images («Quanta Inspect», USA) of RIE processed silicon carbide are presented.

Figure 3. SEM-images: (a) – topological image formed at the surface of silicon carbide crystal after RIE; (b) – side wall of mesa-structure formed by RIE on silicon carbide.

Etching depth of \( \sim 15…16 \mu\text{m} \) is obtained for good quality of surface and side walls. Side-wall angle is \( \sim 90^\circ \).

4. Conclusions

Silicon carbide mesa-structures were formed using RIE method and RIE equipment «Caroline PE15» (Russia). The mesa-structures are perspective for use in devices of power electronics.

Optimized technological parameters of RIE process enabled a deep profiles to be formed in silicon carbide for preparation of semiconductor instruments. It has been shown that metals used as masking materials show sufficiently high selectivity, providing formation of deep profiles.