Features of the formation of non-vertical profiles on the surface of 4H-SiC by the reactive-ion etching

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Abstract. The features of the formation of non-vertical profiles on 4H-SiC by reactive-ion etching (RIE) using various masking coatings are studied. The formation of 4H-SiC mesa structures was carried out using automated airlock reactive-ion etching and plasma etching system “Caroline PE 15” with the ICP-source of plasma in a gas mixture of SF6, O2 and Ar. Using photoresist AZ4533 as a mask, mesa structures with a wall inclination angle of more than 130° were obtained at the etching rate of 4H-SiC was ~0.5 μm/min. The developed technology of dry etching can be further used in the preparation of avalanche photodiodes or power electronics devices.

1. Introduction

The problem of detecting weak signals (up to individual photons) has been very relevant for many years. This problem has been solved by means of photoelectron multipliers in the form of a diode system or tubes with a very high secondary electron emission coefficient, which, as a result of multiplying the number of electrons as they move toward the anode, significantly increase the initial signal. However, the cost and dimensions of such devices are quite large.

In recent years, solid-state analogs of these devices, so-called avalanche photodetectors (APDs) based on diodes, have started to develop rapidly. Small size, compatibility with standard CMOS technology, low voltage, lack of sensitivity to magnetic fields and low cost make this class of photo electronic devices promising [1]. The advantage of avalanche photodetectors based on the wide-band silicon carbide (SiC) is that they are able to detect ultraviolet (UV) radiation up to gamma radiation [2].

When creating an APD, one of the important conditions is to ensure stable operation when high voltages are applied. The main danger in the application of which is the breakdown of the structure, and in the case of avalanche photodiodes - premature breakdown. Such a breakdown is most likely at the periphery of the structure, where the surface and its quality play a big role. To ensure a fully volumetric breakdown, it is necessary to reduce the intensity of the electric field at the boundary of the mesa structure.

There are many ways to provide a volumetric breakdown, such as security rings, additional metallization to reduce the field strength inside the structure, stepwise limitation of MJTE structures (figure 1(a)), as well as the formation of mesa structures with a large inclination angle (more than 100°) (figure 1(b)) and others.

This article is devoted to the formation of mesa structures on 4H-SiC with a large angle of inclination of the walls by ion-etching using fluorine, oxygen, and argon-containing plasma. The main
technological parameters during the RIE process: the current of magnetic coils \( I_k = 1.2 \) A; gas consumption: argon - 2.5 l/h, oxygen - 1.5 l/h, sulfur hexafluoride - 3.5 l/h; the total pressure in the chamber is \( P = 1.7 \) Pa. Formation of mesa structures was carried out automated airlock reactive-ion etching and plasma etching system “Caroline PE 15” (Zelenograd Development Corporation, Moscow, Russian Federation) with the ICP-source of plasma and a lower RF-electrode, to which RF power (13.56 MHz) can be separately applied. This design of the equipment provides the ability to control the chemical and physical components of the etching process.

**Figure 1.** Methods for providing bulk breakdown – a step-by-step limitation of MJTE structures (a) and mesa structure with a large angle of inclination of the walls (b).

When forming mesa structures with a large angle of inclination of the walls by the RIE, it is necessary to choose a masking coating. The following materials were studied as a mask material: metallic (two-layer Ti-Ni composition), polymer (photo resist AZ4533).

At the preparatory stage, complex cleaning of the 4H-SiC surface was carried out by liquid treatment with a mixture of \( \text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2 \) at a temperature of 60...70 °C.

**2. Formation of mesa structures using the metallic mask**

At the first stage, studies were carried out on formation non-vertical mesa structures in 4H-SiC using a masking coating based on metal. Two-layer metallization of Ti-Ni, with thicknesses of 20 and 200 nm, respectively, was deposited using modified equipment for vacuum magnetron sputtering "KONT" (Zelenograd, Russian Federation). Nickel was used as the main masking coating, and titanium — as under layer to improve adhesion of Ni. The photolithography was carried out via metallic mask and then the mesa structures were formed by RIE in the medium of gas mixture comprising \( \text{SF}_6, \text{O}_2, \) and \( \text{Ar} \).

According to data published earlier [3, 4], an increase of power at the lower electrode (from 0 to 400 W) increases the anisotropy of the etching process. This effect is due to the increase in the energy of ions moving perpendicular to the working surface, which provides the almost vertical slope of the mesa structure (figure 3(a)).

**Figure 2.** SEM image of mesa structures formed in 4H-SiC: vertical (a) and inclined (b).

On the other hand, by varying the power on the ICP-source of plasma (from 100 to 700 W), it is possible to control the chemical component of the etching process, forming thus the non-vertical mesa structures (figure 3(b)). Figure 2(b) shows a SEM image of the mesa structure with a non-vertical slope of the walls formed using a metal masking coating and variation of ICP-plasma source power.
Figure 3. Relationship of mesa structure slope versus power at lower HF-electrode (a) and upper ICP-source of plasma (b).

As can be seen from figure 3(b), the mesa structure slope angle depends on the ICP-source of plasma power. When the ICP-source power increases, the amount of high energy and chemically active particles increases, which leads to increase of chemical component of the process and consequently the increase of horizontal etching speed.

3. Formation of mesa structures using photo resistive mask

Further studies were conducted towards the formation non-vertical mesa structures on 4H-SiC surface using a polymer masking coating based on photo resist AZ4533. A thick layer of viscous photo resist AZ4533 was deposited, followed by photolithography and annealing operations. The angle of the photo resist mask can be controlled by the temperature and time of annealing (table 1). The thickness of the photo resist is sensitive to the speed of rotation of the substrate during application. As a result, it is possible to obtain the edge of the applied photo resist in the form of a chamfer. The shape of the photo resist mask and the topological pattern formed after photolithography are transferred to 4H-SiC by RIE using the gas composition as above (figure 4).

Table 1. Dependence of the slope angle of photo resist AZ4533 versus temperature and time of annealing.

| Slope angle (deg.) | Annealing temperature (°C) |
|--------------------|----------------------------|
|                    | 135                        |
|                    | 150                        |
| Annealing time (min) | 1                         | 30 | 25 |
| 20                 | 35                         | 25 |

The selection of a thick photo resist layer is due to the fact that this type of photo resist is not resistant enough (selectivity to 4H-SiC is 0.2) during RIE of 4H-SiC particularly if the plasma medium contains oxygen. On the other hand, without oxygen, the rate of 4H-SiC etching decreases several times, due to the lack of some volatiles (such as CO, CO₂ etc.) which are generated in the presence of oxygen. Therefore, the AZ4533 photo resist, as a masking coating, can only be used for the forming of shallow (up to 2 μm) mesa structures.

Figure 4. SEM image of non-vertical mesa structure formed on 4H-SiC surface using photoresist AZ4533 mask.
The experiments showed that the etching rate of the photo resist AZ4533 depends not only on the presence of oxygen in the plasma medium but on the temperature in the reaction chamber as well. Under the selected process parameters (current in magnetic coils is $I_k = 1.2$ A, gas flow rate is: for argon – 2.5 l/h, for oxygen – 1.5 l/h, for sulfur hexafluoride – 3.5 l/h, total chamber pressure is $P = 1.7$ Pa), the etching rate of photo resist AZ4533 is 2.5 μm/min at power applied to the ICP plasma source and to the lower RF electrode of 350 W and 200 W, respectively.

4. Conclusions

The possibility of formation of non-vertical mesa structures on the surface of 4H-SiC using various masking materials by the RIE in fluorine-, oxygen- and argon-containing plasma was studied using the technological installation "Caroline PE 15" with the ICP plasma source.

It has been shown that using a metal masking coating based on nickel with titanium sublayer, it is possible to obtain non-vertical mesa structures (with walls slope of more than 100°) by increasing the power applied to the ICP source of plasma (at 600 W the angle of inclination of the mesa structure is 120°). The effect is due to the increase of energy and number of chemically active particles and thus overall increase of the chemical component of the process, i.e. the etching speed is increased horizontally. If the power applied at the lower electrode is increased (from 0 to 400 W), the anisotropy of the etching process increases. This effect is due to the increase of energy of ions moving perpendicular to the working surface; as a result the slope angle of the mesa structure remains almost vertical.

Using photo resist AZ4533 as a masking coating, it is possible to form the non-vertical mesa structures of the slope angle more than 130°. After technological processing (the temperature and the annealing time are 150° and 20 min, respectively), the angle of the photo resist mask is 25°. The shape of the photo resist and the topological pattern formed after photolithography are transferred to 4H-SiC with RIE.

The technology developed can be applied in manufacturing of avalanche photodiodes and power electronics devices.

References

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