Microtrenching effect of SiC ICP etching in SF_6/O_2 plasma*

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Abstract: Inductively coupled plasma (ICP) etching of single crystal 6H-silicon carbide (SiC) is investigated using oxygen (O_2)-added sulfur hexafluoride (SF_6) plasmas. The relations between the microtrenching effect and ICP coil power, the composition of the etch gases and different bias voltages are discussed. Experimental results show that the microtrench is caused by the formation of a SiF_xO_y layer, which has a greater tendency to charge than SiC, after the addition of O_2. The microtrenching effect tends to increase as the ICP coil power and bias voltage increase. In addition, the angular distribution of the incident ions and radicals also affects the shape of the microtrench.

Key words: silicon carbide; microtrenching effect; inductively coupled plasma; etch rate

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1. Introduction

Silicon carbide is a wide-band gap semiconductor with potential applications for radiation resistant, high-power, high-frequency and high-temperature devices in the automotive, aerospace, power generation and petroleum industries[1]. Because of its great hardness, high wear resistivity, excellent thermal conductivity and chemical inertness, SiC also becomes an excellent candidate for the application of microsensors and microactuators in microelectromechanical systems (MEMS), especially in harsh environments[2]. Fabrication of the above mentioned SiC devices frequently requires a narrow line width, an extremely high aspect ratio, and a high degree of anisotropy. Patterns with high aspect ratio yield an increased area ratio of the sidewall to the bottom, thus increasing the importance of phenomena that are affected by the sidewall. Microtrenching is one of these phenomena and refers to a V-shaped groove formed on the bottom adjacent to the sidewall due to an enhancement in local etch rates. Microtrenching can punch the etch-stop layer during contact-hole etching, thus inducing the formation of a void in the subsequent filling process.

Microtrenching has usually been explained by ions reflected from the sidewall surface[3]. The contribution of these reflected ions to the etching of other surfaces is referred to as secondary etching[4]. Westerheim *et al*. reported that the microtrench depth increased with RF bias power and that the shape was consistent with simulation results obtained by assuming the specular reflection of ions on the sidewall surface[3]. On the other hand, sidewall charging of microstructures has also been suggested to produce microtrenching[5,6]. Schaepkens *et al*. concluded that differential charging was an important effect in microstructure fabrication using high-density plasma. In this paper, we report our work on the etching of SiC using ICP in O_2-added SF_6 gas mixture plasma. The microtrenching effect has been measured as a function of ICP coil power, bias voltage and the composition of the etch gases. The reasons for formation of a microtrench are analyzed in detail, which is helpful for broadening the application ranges of MEMS and other devices.

2. Experiment

The single-crystal 6H-SiC used in our experiments is obtained from SiCrystal AG Inc; its band gap and thickness are 3.27 eV and 430 μm, respectively. An ICP-98A high density plasma ICP etcher from CAS was used to etch the patterned SiC substrates. After the regular cleaning, the wafer was bombarded for 2 min by Ar^+, and a Ti/Ni structure was used for profile study. First, a thin layer of Ti was deposited on the wafer by the electron beam evaporation technique, and then Ni of 1.5 μm thickness. The metal lift-off technique was used to pattern the sample with a Ni mask. The samples were then etched in an SF_6+O_2 mixture ICP. Combining with the practical process conditions, the total gas flow rate is 30 sccm, the range of ICP coil power is 300–800 W, the bias voltage is –100 to −500 V, the composition of the etch gases (%O_2) is 0–50% and the chamber pressure remains constant at 1.6 Pa. The etch rate is determined by a scanning electron microscope (SEM).

3. Results and discussion

Figure 1 shows the etch rate of the microtrench as a function of the composition of the etch gases (%O_2). Etching is carried out at an ICP coil power of 500 W and bias voltage of −300 V. The impact of adding oxygen to SF_6 plasma for the etching of SiC is multifarious. The liberation of additional F species and the provision of another pathway for volatilizing

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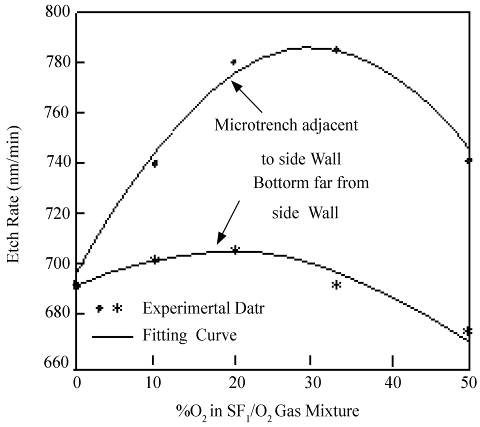

Fig.1. Etch rate versus gas mixture composition.

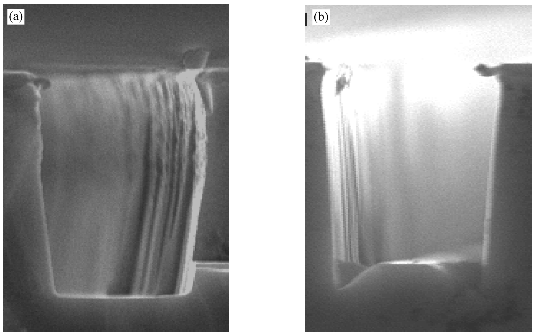

Fig.2. SEM images with different gas mixture compositions: (a) O_2: 0%; (b) O_2: 20%.

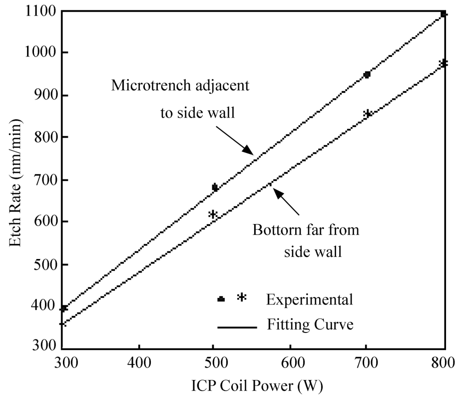

Fig.3. Etch rate versus ICP coil power.

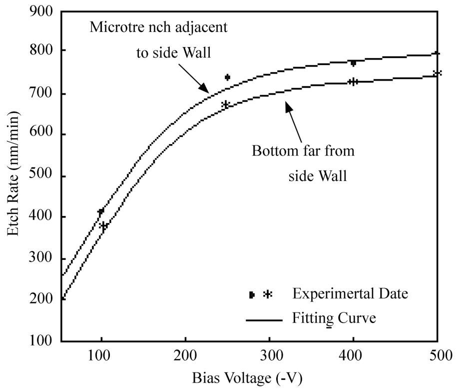

Fig.4. Etch rate versus bias voltage.

C in the form of CO, CO_2 and COF_2[7] leads to an increase in etch rates. However, it also produces SiO_x on the surface which, if not removed readily, inhibits etch rates especially at high oxygen flow rates. In addition, the increase of oxide concentration will lead to the decrease of SF_6 concentration, in turn affecting the etch rate due to the reduced density of F species. This competition leads to the SiC etch rate peaking at 30% O_2 in SF_6/O_2 gas mixture. When there is almost no O_2 in the gas mixture, the etch rate of the microtrench and middle bottom is almost equal. At low O_2 flow rate (0–30%), increasing the content of O_2 in the gas mixture causes the etch rate of the microtrench to increase obviously. When the content of O_2 is 30%, the etch rate of the microtrench is nearly 100 nm/min higher than that of the middle bottom, which demonstrates that O_2 significantly influences the formation of the microtrench. Beheim*et al.* pointed out that the formation of the microtrench was caused by a SiF_xO_y layer[8]. Standaert *et al.* concluded that the fluorocarbon film played the role of an etchant source as well as an etch-inhibiting layer during SiO_2 etching in fluorocarbon plasmas[9]. Based on the above studies, it is believed that the addition of O_2 in etching gases results in the formation of an SiF_xO_y layer, which would have a greater tendency to charge than SiC. The charged SiF_xO_y layer attracts more ions as the sidewall slope is larger, which leads to an increase in ion concentration at the substrate adjacent to the sidewall and results in an increase in the rate of chemical reactions on the microtrench[10]. From the profile images of the etched surface (Fig.2), we can also find that there is no microtrench in the etching surface when the gas mixture does not contain O_2 (Fig.2 (a)). But when the O_2 concentration is 20% in the gas mixture, a microtrench is detected obviously, proving that the addition of O_2 enhances the microtrenching effect.

Figure 3 shows the etch rate of the microtrench as a function of ICP coil power. Etching is carried out at a bias voltage of −200 V, SF_6 flow rate of 24 sccm and O_2 flow rate of 6 sccm. As shown in Fig.3, the etch rate of the microtrench is higher than that of middle bottom, and exhibits a linear tendency as the ICP coil power increases. The larger the ICP coil power, the higher density of the reactive ions and neutrals in the chamber, the easier the formation of a charged layer and the more the reactive ions are reflected from the sidewall, which will accelerate the etching of the microtrench.

Figure 4 shows the etch rate of the microtrench as a function of bias voltage. Etching is carried out at an ICP coil power of 500 W, SF_6 flow rate of 24 sccm and O_2 flow rate of 6 sccm. From Fig 4, the difference in etch rate between the microtrench and the bottom is kept almost constant except the etch rate is a little larger at the microtrench, which may result from the increase in energetic ion activity caused by the high bias voltage. The enhancement of physical sputtering increases the concentration of ions reflected from the sidewall and ions attracted by the charged layer, which leads ultimately to an increase in etch rate of the microtrench.

Additionally, the bottom etch profile is simultaneously affected by factors other than secondary etching by ions reflected from the sidewall. For example, the sidewall shields the flux of ions and radicals from reaching the bottom adjacent to the sidewall, and this is influenced by the angular

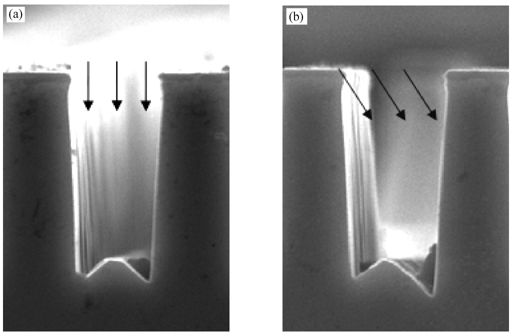

Fig.5. SEM images with different chamber positions: (a) At the center of the chamber; (b) At the margin of the chamber.

distribution of the incident ions and radicals. This results in a decrease in the local etch rate on the bottom (referred to as a "shadowing effect"), which is in contrast to secondary etching by reflected ions. Figure 5 shows the profile images of etched SiC surface at different chamber positions. It is found that the two microtrenches located on either side of the central sample have the same depth and shape (Fig.5 (a)). The scale of depth and shape of the left microtrench in the sample at the chamber margin are smaller than the right one (Fig.5 (b)). This may be attributed to difference in the angular distribution of the incident ions. At the center of chamber, the incident ions were perpendicular to the sample surface. But the ions at the margin of the chamber will have an angle of incidence. Below a certain depth, the left sidewall will shield the flux of ions and radicals from reaching the microtrench, hampering the etching of the left microtrench.

In summary, the formation of a microtrench is due chiefly to a charged SiF_xO_y layer after addition of O_2 in etching gases.But as the etched depth increases, the surface area, angle and roughness of the sidewall will change, leading to another change in the angle and energy distribution of reflected ions momentarily. We have analyzed the microtrenching based on the SEM images. A further study with more detailed experimental results is required to explain the effect of the above-mentioned factors on the microtrenching effect.

4. Conclusions

In order to investigate the microtrenching effect of ICP etching for single crystal 6H-silicon carbide (SiC), SF_6 mixed with O_2 plasma is used as an etching atmosphere. The relationship between the microtrenching effect and ICP coil power, composition of etching gases and bias voltage is discussed. Experimental results show that the microtrench is caused by the addition of O_2. The addition of O_2 influences the effect of the microtrench due to the formation of a SiF_xO_y layer, which has a greater tendency to charge than SiC. The microtrench would become obvious as the ICP coil power and bias voltage increase. In addition, the angular distribution of incident ions is another factor to affect the shape of the microtrench. The experimental data as well as the results reported here can provide useful insights in controlling the microtrenching effect in etching of SiC, and should be helpful in broadening the application ranges of SiC in MEMS and other devices.

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