Reactive Ion Etching of SiC Using $\text{C}_2\text{F}_6/\text{O}_2$ Inductively Coupled Plasma

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The inductively coupled plasma–reactive ion etching (ICP–RIE) of SiC single crystals using the $\text{C}_2\text{F}_6/\text{O}_2$ gas mixture was investigated. It was observed that the etch rate increased as the ICP power and bias power increased. With increasing sample-coil distance, $\text{O}_2$ concentration, and chamber pressure, the etch rate initially increased, reached a maximum, and then decreased. Mesas with smooth surfaces (roughness $\leq 1$ nm) and vertical sidewalls ($\sim 85^\circ$) were obtained at low bias conditions with a reasonable etch rate of about 100 nm/min. A maximum etch rate of 300 nm/min could be obtained by etching at high bias conditions ($\geq 300$ V), in which case rough surfaces and the trenched sidewall base were observed. The trenching effect could be suppressed by etching the samples on anodized Al plates, although mesas with sloped (60–70°) sidewalls were obtained. Results of various surface characterization indicated little contamination and damage on the etched SiC surfaces.

Key words: SiC, ICP-RIE, mesa profile, electrode effects

INTRODUCTION

Silicon carbide is being actively investigated as a substrate material for the high-power, high-temperature, and high-frequency electronic devices. Reactive ion etching (RIE) techniques have been studied to provide a reliable patterning method for the SiC devices, as the simple wet etch techniques are not yet available due to the chemical stability of this material.1

The high-density plasma using the fluorine-containing gas mixtures was recently studied to improve problems of the conventional RIE technique, such as the micromasking surface residue formation and the low etch rate.2 Inductively coupled plasma (ICP) RIE is mainly studied, as it is simple to operate, easy to obtain large-size etch uniformity, and capable of independent control of the plasma density and the sample bias.2

Detailed results on the ICP-RIE of SiC single crystals have been previously reported, using the $\text{CF}_4$, $\text{SF}_6$, $\text{NF}_3$, and their mixtures with oxygen, argon, hydrogen, and helium.3,4 In this work, etch characteristics of SiC using the $\text{C}_2\text{F}_6/\text{O}_2$ inductively coupled plasma were investigated. The $\text{C}_2\text{F}_6$ gas, with lower PFC emission than the $\text{CF}_4$ and the $\text{SF}_6$, is one of the widely used gases for the Si etching and for the chemical vapor deposition chamber cleaning. The etch rate, the mesa profile, and the surface morphology were observed as a function of various process variables, using scanning electron microscopy (SEM) and atomic force microscopy (AFM). The surface damage and contamination were also studied using Auger electron spectroscopy (AES), Schottky barrier measurement by I–V test, and transmission electron microscopy (TEM).

EXPERIMENTAL

Commercial 4H- and 6H-SiC wafers with the (0001) C-face plane polished were mainly used in this study. An n$^+$-4H-SiC wafer ($1.2 \times 10^{18}$/cm$^2$) with a 12-$\mu$m-thick low-doped ($1 \times 10^{13}$/cm$^2$) n-type epitaxial layer was used to perform the Schottky barrier measurement. A homemade ICP chamber operating at 13.56 MHz was employed for the experiment, with the sample bias applied by a separate 13.56 MHz RF supply. Most of the experiments were performed on the lower (sample) electrode covered with a quartz plate, but two other materials, stainless steel and anodized Al, were also used to investigate effects of the cover material. The diameter of the lower electrode was about 15 cm.

The process parameters studied in this work are ICP source power (600–900 W), rf bias power
(50–200 W), chamber pressure (4–16 mtorr), O₂ percentage in C₂F₆/O₂ (0–80% O₂), and the distance between the ICP coil and the sample (3–12 cm), with the total gas flow fixed at 30 sccm. Three to four experiments were performed for each etch condition and the obtained results were averaged. Stripes of Ti(30 nm)/Ni(300 nm) films were used as the etch mask, after RF sputter deposition and patterning by conventional photolithography using the lift-off technique.

Scanning electron microscopy (JEOL JSM5200, Japan Electron Optics Ltd., Tokyo) and AFM (Digital Instruments, Multimode SPM) were used to examine the cross sections and the surfaces of the etched features, and AES (VG ESCALab210) and TEM (JEOL 2000FX) were used to observe the surface contamination. For the Schottky barrier diode study, Ni was first sputtered onto the sample backside and annealed at 950°C to form the ohmic contact. Samples were then etched at various conditions, the Au films were evaporated on the etched surfaces and patterned into a ring shape, and the I–V test was performed.

RESULTS AND DISCUSSION

Figure 1 shows ICP-RIE characteristics of 6H-SiC and 4H-SiC mesas as a function of various process parameters. Figure 1a shows the effects of the ICP source power, when etched at the 100 W bias power, 8 mtorr pressure, 60% O₂, and the sample-coil distance of 9 cm (100 W–8 mtorr–60%–9 cm). It is observed that the etch rate increases as the ICP power is increased, while the surface roughness and the sidewall angle are not critically affected. Notice that the dc bias on the sample decreases with the ICP power, due to an increase in the plasma density.

Figure 1b shows etch results as a function of sample bias power, etched at 800 W ICP power, 8 mtorr chamber pressure, 60% O₂, and 9 cm sample-coil distance (800 W–8 mtorr–60%–9 cm). It is shown that the etch rate increases as the bias power is increased, and the surface roughness and the sidewall angle are slightly improved. The “trenching” effect was observed at high bias conditions (>~300 V). This point will be further discussed later.

Figure 1c shows the effects of the process pressure on the mesa characteristics, etched at 800 W–100 W–60%–9 cm. The etch rate initially increases with increasing pressure but then begins to decrease, resulting in a maximum rate at about 8 mtorr. It is also observed that the bias voltage monotonically increases with the pressure. Figure 1d illustrates the effects of O₂ content within the C₂F₆/O₂ gas, etched at 800 W–100 W–8 mtorr–9 cm. The etch rate increases as more O₂ is added, reaches a maximum at around 60% O₂, and then decreases.

Figure 1e shows the mesa characteristics as a function of the distance between the source coil and the substrate holder, etched at 800 W–100 W–60%–8 mtorr. The etch rate increases considerably until the distance decreases to 6 cm, but then decreases at 3 cm distance.

The observed etch rate enhancement due to the increase in the ICP and the bias power is natural, because the density and the energy of the C–F radicals and ions increase with higher ICP and bias power. In the case of the process pressure, it is believed that the initial increase in the etch rate is due to the increase in the self bias (as observed in Fig. 1c) and the following decrease due to reduced ion density in the plasma. It has been reported that the ion density within the C₂F₆ plasma decreases with increasing pressure.5

The observed effects of the O₂ concentration on the etch rate (Fig. 1d) is consistent with the previous reports3–6 that the oxygen addition into the carbon-fluoride plasma results in higher etch rate by enhancing the C–F dissociation and the removal of carbon atoms in the form of CO and CO₂.2 When the oxygen percentage is increased above 60%, however, the C₂F₆ gas plasma is diluted and the overall etch rate decreases.2

Fig. 1. Etch characteristics of 6H-SiC and 4H-SiC as a function of (a) ICP source power, (b) bias power, (c) pressure, (d) O₂ percentage in C₂F₆/O₂, and (e) the distance between the substrate holder and the source coil.