Magnetically Enhanced Inductively Coupled Plasma Etching of 6H-SiC

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***Abstract*—In this study, 6H-SiC wafers were etched using a magnetically enhanced inductively coupled SF_6-based plasmas (MEICP) and their etch characteristics were investigated. The etch characteristics of SiC and the etch selectivities over metal thin films such as Cu and Ni were investigated as a function of inductive power, operating pressure, additive gas percentage, etc. To understand the etch mechanism, the etched SiC and Cu surfaces were examined by X-ray photoelectron spectroscopy (XPS) and the radical and ion densities in the plasmas were measured by optical emission spectroscopy (OES) and a Langmuir probe, respectively. The obtained highest etch rate was about 1.9 μm/min with 90%SF_6/10%O_2. By XPS analysis, it could be confirmed that the addition of small oxygen percentage assisted in forming volatile SiFx by the reaction with carbon on the SiC surface. In our experimental conditions, the increase of thickness by the formation of a reaction product instead of etching was observed on the Cu mask layer, therefore, the calculated selectivity of SiC to Cu was infinite. Using the Cu mask, 80–100 μm thick SiC substrates could be fully etched with vertical etch profiles and smooth etch sidewalls.**

***Index Terms*—Cu mask, inductively coupled plasma (ICP) etching, optical emission spectroscopy (OES), SiC, SF6, Via hole, X-ray photoelectron spectroscopy (XPS).**

I. INTRODUCTION

SILICON carbide (SiC) is one of the attractive wide band gap semiconductor materials due to its high temperature stability and high thermal conductivity. Therefore, it is used for electronic devices operating at high temperature, high frequency, and high power levels. Also, due to its excellent electrical, thermal, and mechanical properties, the SiC is used in the field of microelectromechanical system (MEMS) and as the substrate for GaN epitaxial growth. However, in the application of SiC to various device fabrication, due to these chemical and physical stable properties of SiC itself, the development of high rate and anisotropic plasma etching technique is prerequisite. To obtain high SiC etch rates, various dry etching methods such as inductively coupled plasma etching, electron cyclotron resonance plasma etching, and helicon plasma etching have been used [1]–[7]. For the etch gases of SiC, fluorine containing gases such as SF_6, NF_3, CF_4, CHF_3, etc., and the combinations of these gases have been usually employed [1]–[8]. Among these, the highest etch rate of SiC and high selectivity over etch mask materials have been reported in SF_6 or in a few O_2 added SF_6/O_2 [5], [6].

In our previous work [9], we reported that higher SiC etch rates could be obtained in a magnetically enhanced inductively coupled SF_6 plasmas than conventional inductively coupled SF_6 plasmas. In this study, 6H-SiC wafers were etched using the magnetically enhanced inductively coupled plasma in SF_6/O_2 chemistries and the etch characteristics of SiC and etch selectivities over metal thin films such as Cu and Ni were investigated as a function of operating pressure, additive gas percentage, etc.

II. EXPERIMENT

Fig. 1(a) shows the schematic diagram of the magnetically enhanced inductively coupled plasma (MEICP) etching system used in this experiment. Four pairs of permanent magnets were installed symmetrically on the outside of the sidewall of the conventional ICP reactor. The field strength of the permanent magnets was about 2000 G. 13.56 MHz radio frequency (rf) power (0–2 kW) was supplied to a gold-coated five-turn spiral coil for plasma generation through a 12.5 mm thick quartz window while different 13.56 MHz rf power was applied to the substrate for dc bias voltage generation. Silicon carbide (6H-SiC) was etched in SF_6/O_2 mixtures while total gas flow rate was fixed at 60 sccm. Inductive power was varied from 1000 to 1800 W and dc-bias voltage was fixed at -150 V. Substrate temperature was maintained at room temperature. To investigate the effects on the pressure and additive gas, SF_6 pressures and O_2 gas percentage in the SF_6/O_2 chemistry were varied from 10 to 50 mtorr and from 0 to 50%, respectively. Fig. 1(b) shows the uniformities of the magnetic field formed by the four pairs of magnet and the etch uniformity measured for one of the SiC etch conditions on the 4inch diameter substrate of our MEICP system. As shown in the figure, the measured magnetic field on the substrate surface was close to 0 and the etch uniformity was about 5%. The use of 4 pairs of permanent magnet did not significantly degrade the etch uniformity. In fact, the use of the magnet turned out to increase the etch rates and plasma stability significantly as investigated by a previous study [9].

Ni and Cu thin films which were used for the etch mask materials were deposited with an evaporator. After the deposition of the mask, the mask opening ratio was about 25%. The etch rates of these metals were measured to investigate the etch selectivities of SiC to these metal masks. Etch mask patterns were prepared by a lift-off process.

The etch rates were measured with a depth profilometer (Alpha-step 500, TENCOR) and the etch profiles were observed with a scanning electron microscope (SEM, S4700,

Manuscript received September 1, 2003; revised March 3, 2004. This work was supported by a National Research Laboratory program in Korea.

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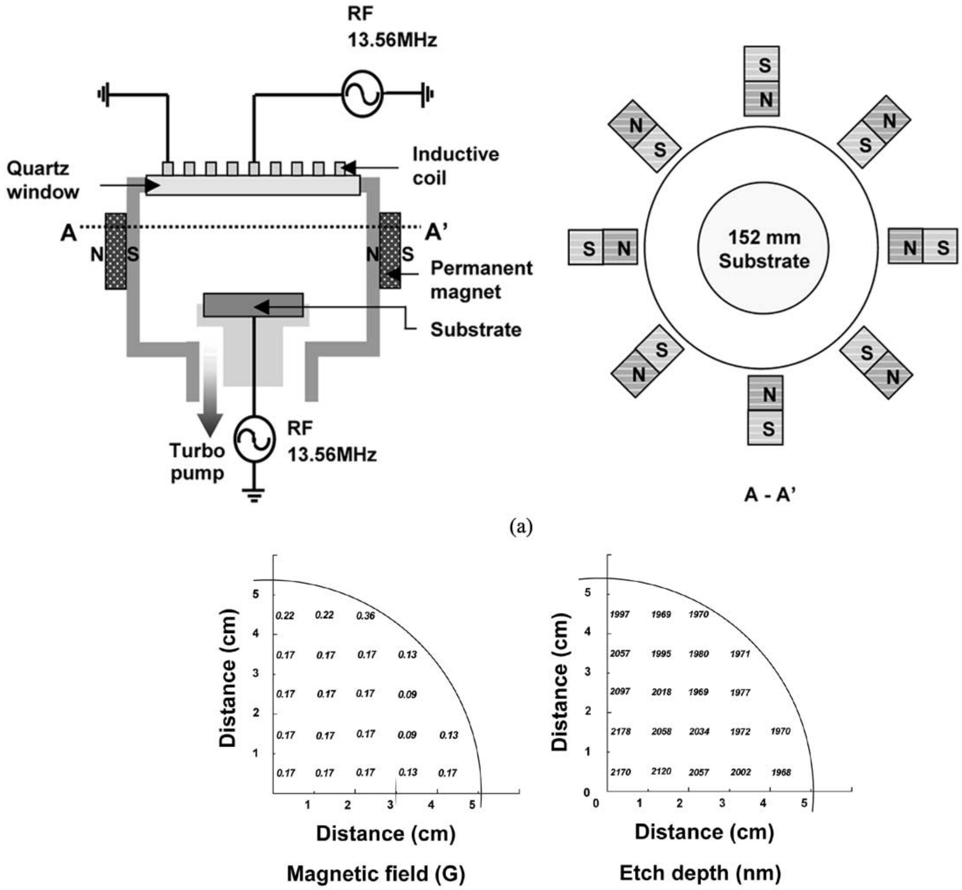
Digital Object Identifier 10.1109/TPS.2004.828821



(b)

Fig. 1. (a) Schematic diagram of the magnetically enhanced inductively coupled plasma etch system used in this study. (b) Measured uniformities of effective magnetic field and SiC etch rate in a 4inch diameter substrate for a SiC etch condition.

Hitachi Inc.). In addition, to understand the etch mechanism, the etched surfaces were investigated with X-ray photoelectron spectroscopy (XPS, ESCALAB-220i) using a Mg Ka source. To minimize the exposure time of the etched samples to the air, a vacuum transfer box was used for sample transfer from the etching chamber to the XPS chamber. Also, to measure the reactive radical densities in the SF_6-based plasmas, optical emission spectroscopy (OES, PCM403, SC Tech.) was used and Ar actinometry was applied. That is, 5% Ar was added to SF_6/O_2 mixtures and the ratios of F/Ar and O/Ar from the intensities of F (703.7 nm), O (844.6 nm), and Ar (750.4 nm) were used as the estimation of F and O atomic densities. A Langmuir probe (Hiden Inc. ESP) was used and the ion saturation currents were measured at -60 V as the estimation of the ion densities in the plasmas. The probe tip was made of a tantalum wire with 10 mm in length and 0.1 mm in diameter and was positioned 15 mm above the substrate surface.

III. Results and Discussion

Fig. 2(a) shows the effects of inductive power and operating pressure on the SiC etch rate. Pure SF_6 gas was used and total gas flow rate and applied bias voltage were fixed at 60 sccm and -150 V, respectively. As shown in Fig. 2(a), with increasing inductive power from 1000 to 1800 W, SiC etch rates were increased. However, with increasing operating pressure from 10 to 50 mtorr, SiC etch rates were decreased for the inductive power conditions of 1000 and 1400 W except for a higher power such as 1800 W. When 1800 W of inductive power was used, the SiC etch rates were increased with increasing operating pressure up to 40 mtorr and the further increase of operating pressure decreased SiC etch rates. The obtained highest etch rate was about 1.7 μm/min at 1800W of inductive power, -150 V of bias voltage, and 40 mtorr of operating pressure.

Fluorine densities and ion saturation currents were measured at the same operating conditions for Fig. 2(a) by Ar actinometry and a Langmuir probe, respectively. Fig. 2(b) shows the measured result of F atomic densities and ion saturation currents. As shown in the figure, both F atomic densities and ion saturation currents were increased with increasing inductive power. However, F atomic densities and ion saturation currents were decreased with increasing operating pressure for all of the conditions used in the experiment. The decrease of SiC etch rates with increasing operational pressure in low inductive powers shown in Fig. 2(a), therefore, is believed related to the decrease of F atomic densities and ion densities in the plasma. However, the increase of SiC etch rates with increasing operational pressure up to 40 mtorr in high inductive power of 1800 W does not agree with the variation of F atomic densities and ion saturation currents and the reason is not clear yet. Therefore, it needs more investigation.

Fig. 3(a) shows the measured etch rates of SiC and etch mask materials (Ni and Cu) as a function of O_2 percentage

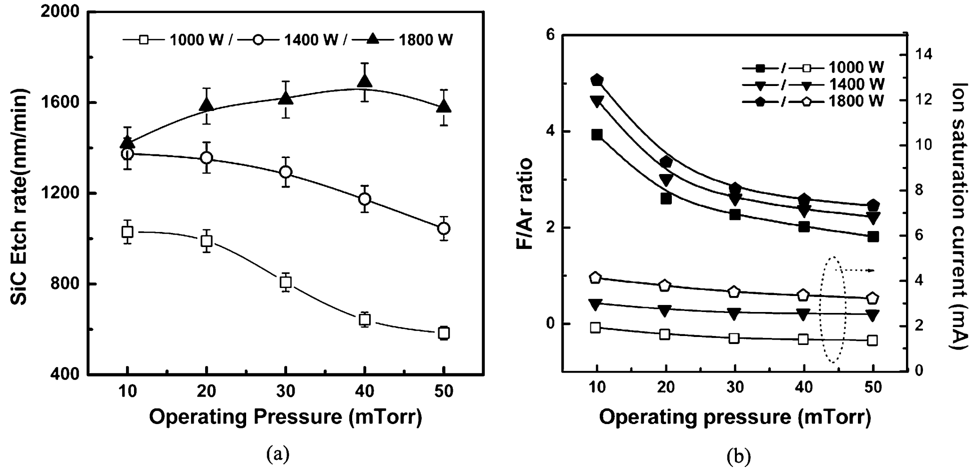


Fig. 2. Measured SiC etch rates (a) and optical emission ratios of F(703.7 nm)/Ar(750.4 nm) and ion saturation currents (b) as a function of inductive power and operating pressure. (inductive power: 1000–1800 W, bias voltage: -150 V, SF_6 60 sccm, operating pressure: 10–50 mtorr).

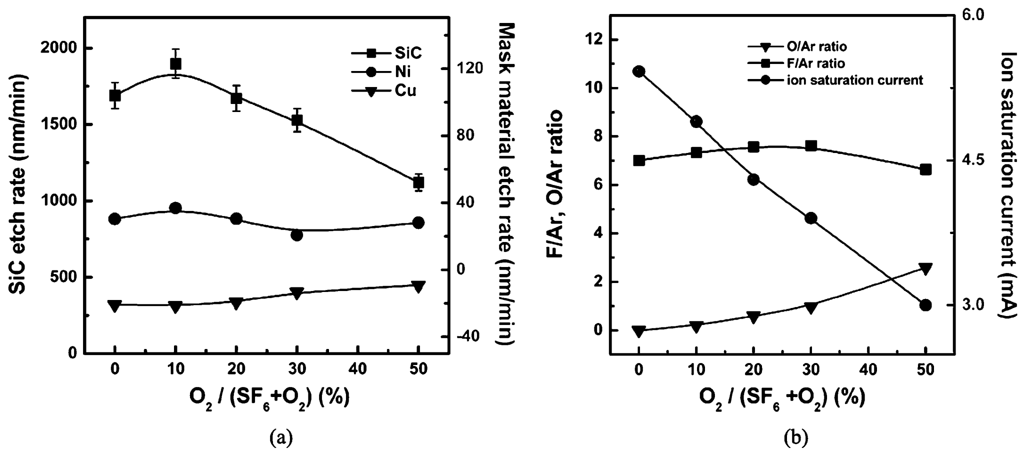


Fig. 3. Measured SiC etch rates (a) and optical emission ratios of F(703.7 nm)/Ar(750.4 nm) and O(844.6 nm)/Ar(750.4 nm) and ion saturation currents (b) as a function of O_2 percentage in the SF_6/O_2 mixture. (inductive power: 1800 W, bias voltage: -150 V, operating pressure: 40 mtorr).

in SF_6/O_2. Inductive power, dc bias voltage, total gas flow rate, and operating pressure were fixed at 1800 W, -150 V, 60 sccm, and 40 mtorr, respectively. The oxygen percentage in the gas mixture was varied from 0 to 50%. As shown in Fig. 3(a), the SiC etch rates were slightly increased with increasing O_2 percentage up to 10% in the SF_6/O_2 mixture. However, the further increase of O_2 over 10% decreased the SiC etch rates. The obtained highest etch rate was about 1.9 μm/min in the 90%SF_6/10% O_2 mixture. In the case of Ni, the etch rates were generally remained similar at about 30 nm/min with increasing O_2 up to 50%. In the case of Cu, the increase of thickness by forming reaction products on the Cu surface instead of etching of Cu was observed. The increase of thickness by the reaction on the Cu surface was decreased with increasing O_2, however, no etching of Cu was observed until 50% O_2 was mixed to SF_6/O_2. The calculated etch selectivity of SiC/Ni was in the range from 40 to 70 and that of SiC/Cu was infinite for our experimental conditions.

Fig. 3(b) shows the fluorine and oxygen atomic densities and ion saturation currents measured by Ar actinometry and a Langmuir probe, respectively for the operating conditions shown in Fig. 3(a). The fluorine atomic densities were slightly increased with increasing O_2 percentage up to 30% in the SF_6/O_2 mixture, however, the further increase of O_2 decreased F atomic densities. The increase of F atomic densities with increasing O_2 appears to be from the increased dissociation of SF_x by oxygen atoms. The decrease of F atomic density at the higher oxygen percentages is from the decrease of SF_6 partial pressure with increasing oxygen percentage in the SF_6/O_2 mixture. In the case of oxygen atomic density, it increased with increasing oxygen percentage due to the increased partial pressure of O_2 in the SF_6/O_2 mixture. However, the increase of oxygen percentage in the mixture decreased the positive ion densities as shown in Fig. 3(b). The increase of SiC etch rates with the increase of O_2 up to 10% shown in Fig. 3(a) appears related to the increase of F atomic density which forms volatile SiF_x compounds and also might be related to the increase of oxygen atoms forming volatile products such as CO, CO_2, and COF_2. However, the decrease of ion density and the increase of O atomic density with further O_2 addition appear to decrease the etch rate due to the decrease of ion bombardment flux and also partially by the formation of SiO_x oxide on the SiC surface which has lower etch rates than SiC (SiO_2 etch rates were about 90% of SiC etch rates for SF_6/O_2), respectively.

Fig. 4(a) shows XPS narrow scan data of C $1s$ and Si $2p$ peaks on the SiC surfaces etched with the conditions in Fig. 3(a). C0 peak found at 282.7 eV is from the carbon in the SiC bonding. C1 peak appears to be from $Si_4C_{4-x}O_2$ (283.6 eV) or graphitic

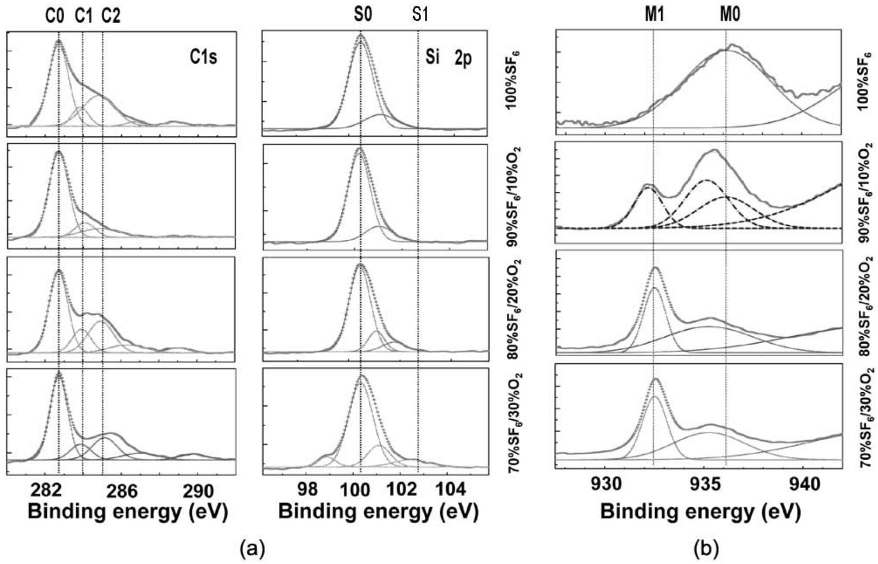


Fig. 4. Measured XPS spectra of C 1s and Si 2p peaks for SiC (a) and Cu 2p peaks for Cu (b) for the etch conditions in Fig. 3.

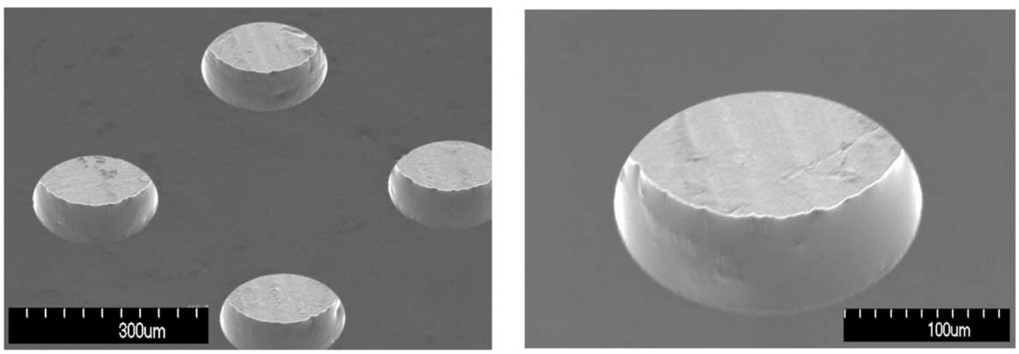


Fig. 5. SEM micrographs of etched SiC via hole structures. (etch depth: 80–100 μm, inductive power: 1800 W, bias voltage: -150 V, operating pressure: 40 mtorr) etch time was 50 min.

(284.3 eV) [10], [11] and C2 peak at binding energy of 285.2 eV from $Si_4C_4O_4$ which is formed by oxidation of $Si_4C_{4-x}O_2$ [10]. Also, these peaks (C1 and C2) composed of unsaturated C-C bonds were regarded as the surface carbon contamination [10], [12], [13]. In addition, this carbon contamination or oxide peaks were reported as an evidence to explain the difference of C-faced SiC surface situation from Si-faced SiC surface situation [12]. The peak intensities of C1 and C2 components showed the lowest value in the $90\%SF_6/10\%$ O_2 mixture suggesting the lowest unsaturated carbon contents on the SiC surface. In the case of Si 2p peaks, S0 and S1 peaks were observed. S0 peak observed at 100.7 eV is from the silicon in the SiC bonding [11], [14] and S1 peak located at 102.9 eV is from SiO_2 [11], [14]. The intensities of S1 oxide peak showed up when the oxygen in the plasma was higher than 20% in the SF_6/O_2 mixture. If the results in Fig. 4(a) are compared with the SiC etch rate results shown in Fig. 3(a), it could be confirmed that small percentage of oxygen reacts with carbon on the SiC surface and easily forms volatile products such as CO, CO_2, and COF_2. Therefore, small O_2 addition to SF_6 could help the increase of SiC etch rate. However, the further increase of oxygen percentage in the SF_6/O_2 mixture decreases SiC etch rates by the formation of silicon oxide on the SiC surface.

Fig. 4(b) shows the Cu 2p XPS data of the Cu mask material etched with the conditions in Fig. 3(a). M0 peaks (936.1 eV) related to CuF_2 were observed in 0–10% O_2 and M1 peaks (932.5 eV) related to Cu or Cu_2O [15] were observed in 10–30% O_2. From the results, it could be confirmed that the increase of thickness by a reaction product on the Cu surfaces in Fig. 3(a) was due to the formation of involatile CuF_2 (or due to Cu_2O with oxygen) on the Cu surface. It is believed that the etching of Ni and Cu in SF_6/O_2 appears related to the formation involatile fluorides and oxides such as $NiF_x(O_x)$ and $CuF_x(O_x)$ on the surfaces and also sputter yields of these involatile compounds.

Fig. 5 shows SEM micrographs of a SiC via hole structure of 200 μm in diameter. 80–100 μm thick SiC substrates were fully etched in 50 min. In this process, About 2 μm -thick Cu was used as the etch mask and removed before taking SEM micrographs. The $90\%SF_6/10\%O_2$ mixture was used, and applied inductive power, bias voltage, and operating pressure were 1800 W, -150 V, and 40 mtorr, respectively. The SEM picture was taken while the etched SiC substrate was tilted. So the picture appears the substrate is located upside down in the SEM micrographs. However, as you can see the SEM holder surface through the via holes of the etched sample, the picture was taken from the top of the etched samples. A SiC via hole structure with a vertical etch profile and very smooth etch sidewall could be formed with the high SiC etch rate of 1.9 μm/min and with infinite etch selectivity.

IV. Conclusions

In this study, SiC etch characteristics were investigated in magnetically enhanced inductively coupled SF_6/O_2 plasmas. Using $90\% SF_6/10\% O_2$, the highest SiC etch rate about 1.9 $\mu m/min$ could be obtained. In addition, using copper thin film as the etch mask, infinite SiC/Cu etch selectivity could be obtained. From the OES and XPS results, it could be confirmed that SiC etch rate and etch selectivity over Cu mask depend on the formation of volatile species such as SiF_x, CO_x, etc. and involatile species such as SiO_x, CuF_x, and Cu_xO_y, respectively. Using the etch condition with the highest SiC etch rate and the infinite etch selectivity, 80–100 μm thick SiC via hole structures were formed. The etched structure showed highly anisotropic etch profiles with smooth sidewalls.

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