Available online at www.sciencedirect.com

SCIENCE DIRECT®

Thin Solid Films 447–448 (2004) 100–104

www.elsevier.com/locate/tsf

# High rate etching of 6H–SiC in $SF_6$-based magnetically-enhanced inductively coupled plasmas

D.W. Kim[a], H.Y. Lee[a], B.J. Park[a], H.S. Kim[a], Y.J. Sung[b], S.H. Chae[b], Y.W. Ko[c], G.Y. Yeom[a,*]

[a]*Department of Materials Engineering, Sungkyunkwan University, 300 Chunchun-Dong, JangAn-Gu, Suwon, Kyounggi, South Korea*
[b]*M and D Laboratory, Samsung Advanced Institute of Technology, Suwon, Kyounggi, South Korea*
[c]*Basic Research Lab., Electronics and Telecommunications Research Institute, Yuseong, Daejeon, South Korea*

## Abstract

In this study, the etch characteristics of 6H–SiC were investigated in magnetically-enhanced $SF_6$ inductively-coupled-plasmas (ICP) with and without magnetic field. The etch characteristics of various metal films such as Ni, Al and Cu were also investigated to apply as the etch mask to the highly selective SiC etching process. With the magnetic field, the etch rates of SiC were increased 60% compared to those without the magnetic field. With the magnetic field, the etch rates of Ni and Al were also increased white the etch rates of Cu decreased. In fact, in the case of Cu etching using $SF_6$, deposition instead of etching occurred through the formation of etch products such as copper fluoride on the surface with fluorine in the plasma. Therefore, among the investigated mask materials, Cu showed infinite etch selectivity over SiC during etching using $SF_6$. The highest etch rate obtained for SiC was greater than 1500 nm/min at 1500 W of inductive power, −350 V of bias voltage, and 1.33 Pa of $SF_6$. SiC etching with the Cu mask showed highly anisotropic etch profiles.

*Keywords:* Etching; Silicon carbide; Sulfur hexafluoride; Magnetically-enhanced ICP; OES

## 1. Introduction

Silicon carbide (SiC) is widely used as a substrate for the epitaxial growth of GaN. Also, SiC is one of the attractive semiconductor materials with wide bandgap, high thermal conductivity, high temperature stability, etc. Due to its material properties, SiC-based electronic devices are expected to operate at high power, high frequency and high temperature conditions. For the fabrication of these various devices, high SiC etch rates with high selectivities to etch mask materials are required in many cases. Over the past several years, many researchers have investigated highly selective and high rate SiC etching [1–5]. For example, a study on the highly selective SiC etching over ITO, Al, Cr, $SnO_2$, etc. in $NF_3$, $SF_6$, $CF_4$-based inductivety-coupled-plasmas (ICPs), highly selective etching over Ni etch mask using a helicon reactor with $SF_6/O_2$ gas mixture, etc. have been reported [6–11].

In this study, 6H–SiC etching using a $SF_6$ magnetically-enhanced ICP has been investigated to further enhance SiC etch rates and etch selectivities over mask materials. SiC etch rates and etch selectivities over various etch masks with and without the magnetical enhancement of ICP have been studied as a function of inductive power, bias voltage, operating pressure, etc. and the etch mechanism has also been investigated.

## 2. Experiment

Fig. 1 shows the schematic diagram of the magnetically-enhanced inductiveiy-coupled-plasma etch system used in this study. To enhance the system magnetically, four pairs of permanent magnets were installed on the outer sidewall of the chamber. The measured magnetic field strength of the permanent magnets was 2000 G. Radio frequency (r.f.) power (13.56 MHz, 0–2 kW) was supplied to the center of a gold-coated five-turn spiral coil to generate inductive plasmas while different 13.56 MHz r.f. power was applied to the substrate to generate bias voltages on the wafer. Inductive power was varied from 700 to 1500 W and d.c. bias voltage

---

*Corresponding author. Tel.: +82-31-299-6562; fax: +82-31-299-6565.
*E-mail address:* gyyeom@yurim.skku.ac.kr (G.Y. Yeom).

0040-6090/04/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2003.09.030

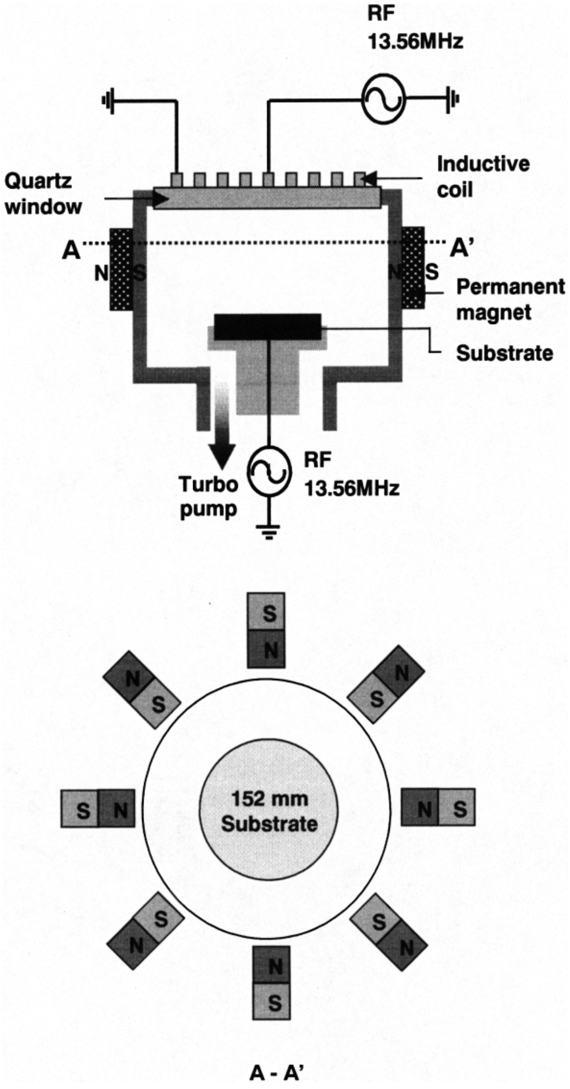

Fig. 1. Schematic diagram of the magnetically-enhanced inductively coupled plasma etch system used in this study.

to substrate was varied from −150 to −350 V. Silicon carbide (6H–SiC) was etched with/without the magnets using $SF_6$. Operating pressure of $SF_6$ was varied from 1.33 to 4 Pa while its gas flow rate was fixed at 50 sccm. The etch rates of various metals such as Cu, Ni and Al were also studied to investigate the SiC etch selectivity to various hard mask materials.

The etch rates were measured using a depth profilometer (Alpha-step 500, TENCOR) and the etch profiles were inspected using a scanning electron microscope (SEM), optical emission spectroscopy (OES) was used to measure optical intensities of reactive radicals during the etching of SiC using $SF_6$ plasma. To estimate F radical density, Ar actinometry was used by adding 5% of Ar to $SF_6$ and by taking the ratio of F(703.7 nm) to Ar(750.4 nm).

## 3. Results and discussion

Fig. 2 shows the etch rates of SiC and the ratios of F(703.7 nm)/Ar(750.4 nm) measured using OES with and without magnetic field as a function of inductive power from 700 to 1500 W. The operating pressure and bias voltage were fixed at 1.33 Pa and −150 V, respectively. SiC etch rate was increased with the increase of inductive power and the F radical density estimated by Ar actinometry also increased with the increase of inductive power. The SiC etch rates with the magnets showed higher etch rates compared to those without the magnets. Also, the F radical density with the magnets also showed an increase. The increase in inductive power increases the ion density and radical density in the plasma, therefore, the increase of SiC etch rate with inductive power is derived from both. The increase of SiC etch rate with the magnets also appears to be from the increase of both ion density and F radical density in the plasma by forming helical motion of energetic electrons and by confining the plasma in the chamber. The increased amount of SiC etch rates by the application of the magnet appears to be similar to that of F radical density with the magnet.

Fig. 3 shows the etch rates of Cu, Al and Ni that can be used as hard mask materials during the etching of SiC as a function of inductive power with and without the magnets. The etch conditions were the same as shown in Fig. 2. As shown in the figure, the etch rates of Al and Ni were slightly increased with increasing inductive power, however, the changes in the etch rates

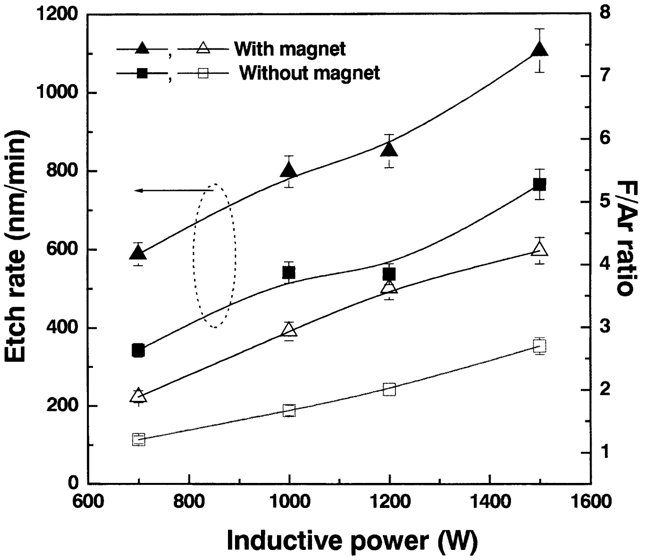

Fig. 2. SiC etch rates and optical emission ratios of F(703.7 nm)/Ar(750.4 nm) as a function of inductive power with and without magnetic field. (Operating pressure: $SF_6$ 1.33 Pa. bias voltage; −150 V.)

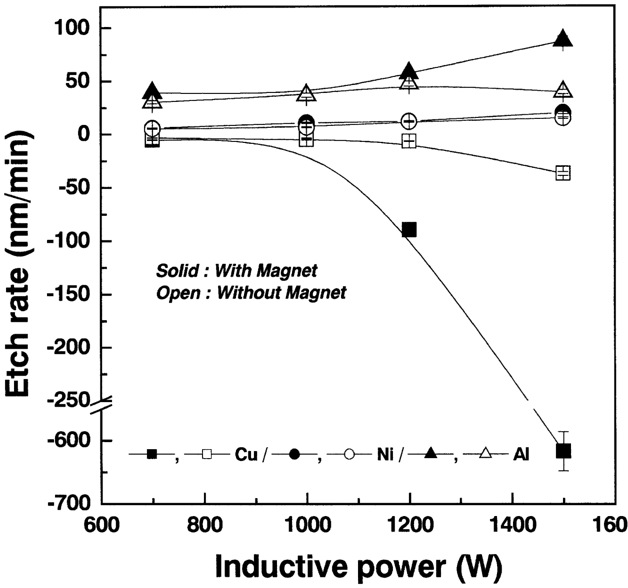

Fig. 3. Etch rates of Cu, Al and Ni as a function of inductive power with and without the magnetic field. (Operating pressure: $SF_6$ 1.33 Pa, bias voltage: −150 V.)

of Al and Ni were small. The etch rates of Ni were lower than those of Al. In the case of Cu, the etch rates of Cu were lower than those of Ni and the etch rates were decreased with the increase of inductive power and, at powers higher than 1200 W, deposition instead of etching of Cu was observed. The use of magnets increased the etch rates of Al and Ni slightly, however, it decreased Cu etch rates or increased the deposition rate. When $SF_6$ plasma is exposed to Al, Ni and Cu, the fluorides of these materials are formed on the surface and these fluoride are non-volatile (melting points of these compounds are higher than 1000 K) [12]. The increase of inductive power and the addition of magnetic field will increase of F density in the plasma; therefore, thicker fluorides of these materials will be formed on the surface. Also, the increase of inductive power and the addition of magnetic field also increase ion density in the plasma, therefore, the differences in the etch rates with inductive power and magnetic field appear related to the thickness of these fluorides and the sputter etching of the fluoride by ions. Therefore, the higher etch rate of Al compared to that of Ni might be related to the higher sputter yield of Al and $AlF_x$ compared to Ni and $NiF_x$. The sputter yield of Cu is higher than those of Ni and Al, however, Cu etch rates are lower than those of Ni and Al. The lower Cu etch rates and the deposition of materials shown in Fig. 3 appear related to the easier formation of copper fluoride, therefore, thicker fluoride with fluorine. Even though the results on the surface analysis for the etched Cu are not shown in this paper, X-ray photoelectron spectroscopy (XPS) analysis showed 34.4 at.% of fluorine contained on the etched copper surface. Therefore, the deposited material appears to be etch products made of copper fluoride. By the formation of thick copper fluoride, infinite SiC etch selectivity could be obtained when Cu was used as the etch mask.

Fig. 4 shows the etch rates of SiC and the ratio of F(703.7 nm)/Ar(750.4 nm) measured using OES with and without magnetic field as a function of $SF_6$ pressure from 1.33 to 4 Pa. Inductive power and bias voltage were fixed at 1500 W and −150 V, respectively. As shown in the figure, the SiC etch rates decreased with the increase of operating pressure. The SiC etch rates was higher with the magnet. The change of SiC etch rates was also similar to the change of F radical density. The increase in operating pressure decreases the efficiency of ICP, therefore, the decrease of F radical density with the increase of operating pressure appears to be related not only to decrease of F radical density but also decrease of ion density and increased scattering of incident ions to the substrate with pressure. However, the addition of magnetic field appears to be still effective in increasing ionization and dissociation of $SF_6$.

Fig. 5 shows the etch rates of Cu, Al and Ni as a function of operating pressure with and without magnets. The etch conditions were the same as shown in Fig. 4. As shown in the figure, the etch rates of Al and Ni did not change noticeably, however, the deposition rate of copper fluoride was decreased significantly with increasing pressure. The insignificant etch rate changes of Al and Ni appears to be both from the decreased formation

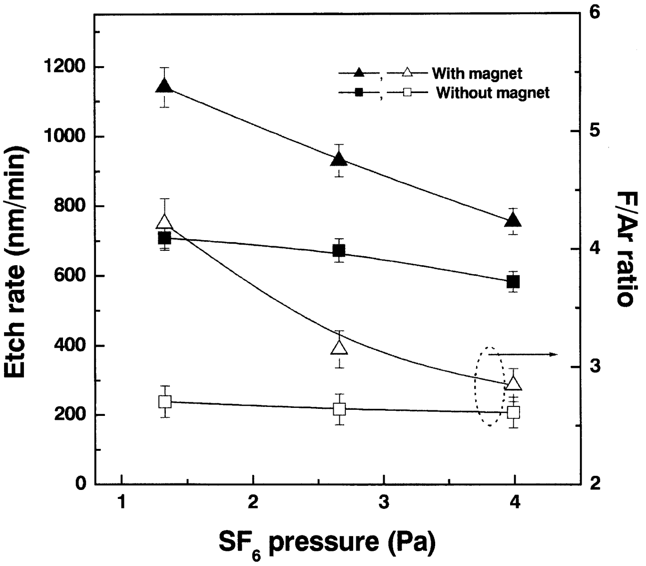

Fig. 4. The etch rates of SiC and the optical emission ratios of F(703.7 nm)/Ar(750.4 nm) as a function of operating pressure with and without magnetic field. (Inductive power: 1500 W, bias voltage: −150 V.)

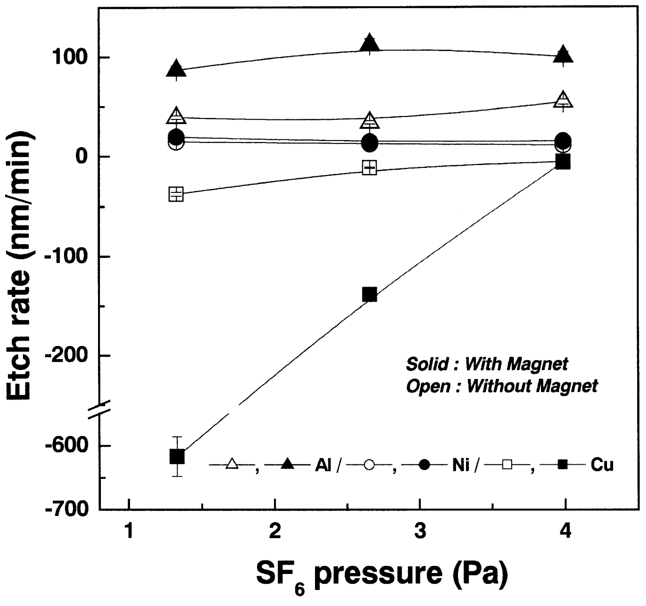

Fig. 5. Etch rates of Cu, Al and Ni as a function of operating pressure with and without the magnetic field. (Inductive power: 1500 W, bias voltage: −150 V in $SF_6$.)

of fluoride and the decreased sputter etching with pressure. In the case of Cu, however, the significant decrease in deposition rate with pressure appears to show the importance of fluorine radicals, therefore, the formation of copper fluoride compared to the sputter etching of copper fluoride in the etching of Cu.

Fig. 6 shows the etch rates of SiC, Cu, Al and Ni with increasing bias voltage with the magnetic field. The operating pressure and inductive power were fixed at 1.33 Pa and 1500 W, respectively. The SiC etch rates increased monotonically with increasing bias voltage. The etch rates of Al, Ni and Cu also increased with the increase in bias voltage. Especially, in the case of Cu, even at −350 V, small deposition instead of etching occurred. The increase in bias voltage increases the ion bombardment energy. Therefore, the increase in the etch rates of SiC, Al and Ni and the decrease of deposition rate for Cu appear related to the increased bond breaking of Si–C and the increased sputter etching of the fluorides of Al, Ni and Cu. At −350 V with 1.33 Pa of $SF_6$ and 1500 W of inductive power with the magnet, SiC etch rates higher than 1500 nm/min could be obtained with the infinite etch selectivity over Cu.

Fig. 7 shows a scanning electron micrograph of an etched SiC sample. The mask was 3-μm thick Cu thin film and the Cu mask was removed before taking SEM micrographs. The SiC etch was performed at 1500 W of inductive power and −150 V of bias voltage condition. Total $SF_6$ gas flow rate and working pressure were fixed at 50 sccm and 1.33 Pa, respectively. The etch depth of SiC was approximately 20 μm and, at this condition, Cu mask showed infinite etch selectivity. As shown in figure, the etch profile was highly anisotropic.

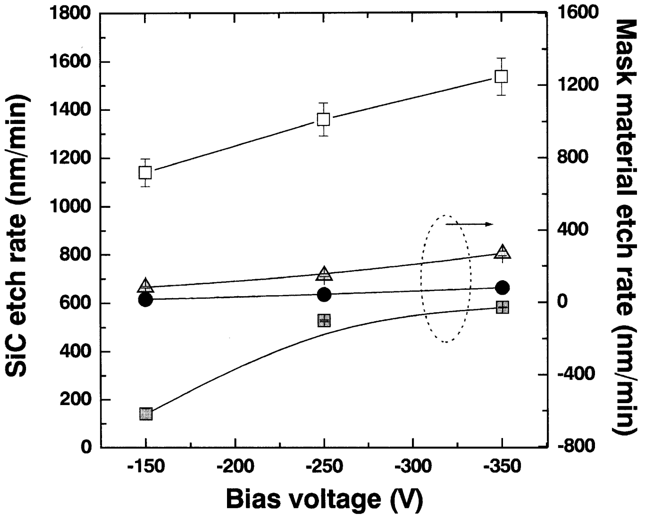

Fig. 6. The etch rates of SiC, Cu, Al and Ni as a function of bias voltage with magnetic field. (Inductive power: 1500 W, operating pressure: $SF_6$ 1.33 Pa.)

## 4. Conclusions

In this study, silicon carbide (6H–SiC) etching was performed in a magnetically-enhanced inductively-coupled $SF_6$ plasma. The etch characteristics of SiC were investigated as a function of inductive power, bias voltage and operating pressure. Also, the etch characteristics of various metal films were investigated to apply

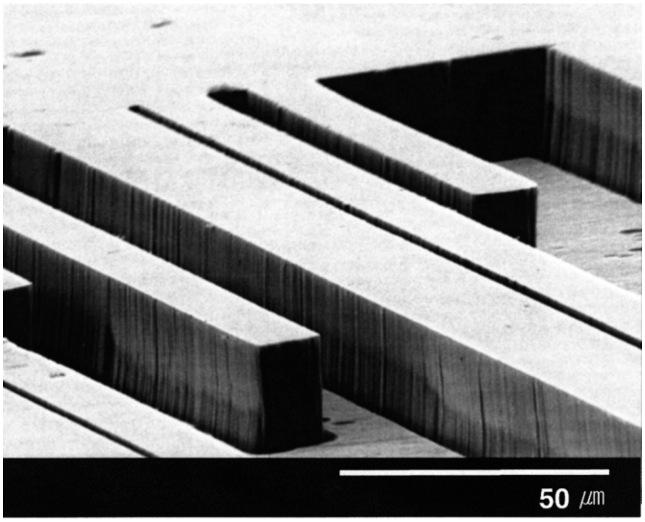

Fig. 7. The scanning electron micrograph of etched SiC. (Etch depth; 20 μm, inductive power: 1500 W, bias voltage: −150 V, operating pressure: 1.33 Pa.)

as etch masks for high selective, anisotropic SiC etch processes. At a pressure of 1.33 Pa in the magnetically-enhanced ICP, SiC etch rates higher than 1500 nm/min could be obtained at 1500 W of inductive power and −350 V of bias voltage. Also, an infinite etch selectivity could be obtained when Cu is used as the mask for SiC etching. From the OES measurement results, it could be confirmed that the SiC etch selectivity over Cu mask strongly depends on F radical density, therefore, the formation of copper fluoride. Using the Cu mask, highly anisotropic SiC etch profiles could be obtained.

## Acknowledgments

This work was supported by National Research Laboratory program (NRL) in Korea.

## References

[1] G. McDaniel, J.W. Lee, E.S. Lambers, S.J. Pearton, P.H. Holloway, F. Ran, J.M. Grow, M. Bhaskaran, R.G. Wilson, J. Vac. Sci. Technol. A 15 (3) (1997) 885.

[2] G.F. Mclane, R. Flemish, Appl. Phys. Lett. 68 (26) (1996) 3755.

[3] F.A. Khan, I. Adesida, Appl. Phys. Lett. 75 (15) (1999) 2268.

[4] H. Cho, K.P. Lee, P. Leerungnawarat, S.N.G. Chu, F. Ren, S.J. Pearton, C.-M. Zetterling, J. Vac. Sci. Technol. A 19 (4) (2001) 1878.

[5] P. Chabert, N. Proust, J. Perrin, R.W. Boswell, Appl. Phys. Lett. 76 (16) (2000) 2310.

[6] P.H. Yih, A.J. Steckl, J. Electrochem. Soc. 142 (8) (1995) 2853.

[7] J. Sugiura, W.-J. Lu, K.C. Cadien, A.J. Steckl, J. Vac. Sci. Technol. B 4 (1) (1986) 349.

[8] L. Cao, B. Li, J.H. Zhao, J. Electrochem. Soc. 145 (10) (1998) 3609.

[9] J.J. Wang, E.S. Lambers, S.J. Pearton, M. Ostling, C.-M. Zetterling, J.M. Grow, F. Ren, R.J. Shul, Solid State Electron. 42 (12) (1998) 2283.

[10] J.J. Wang, E.S. Lambers, S.J. Pearton, M. Ostling, C.-M. Zetterling, J.M. Grow, F. Ren, Solid State Electron. 42 (5) (1998) 743.

[11] J.B. Casady, E.D. Luckowski, M. Bozack, D. Sheridan, R.W. Johnson, J.R. Williams, J. Electrochem. Soc. 143 (5) (1996) 1750.

[12] M. Winter, WebElements, http://www.webelements.com, scholar edn. (2002).