Korean J. Chem. Eng., **19**(2), 347-350 (2002)

Heat Transfer between Wafer and Electrode in a High Density Plasma Etcher

Yeon Ho Im and Yoon-Bong Hahn†

School of Chemical Engineering and Technology, Semiconductor Physics Research Center,
Chonbuk National University, Chonju 561-756, Korea
(*Received 4 September 2001 • accepted 30 November 2001*)

Abstract−Heat transfer between a wafer and electrode has been studied in a planar-type inductively coupled plasma reactor in terms of temperatures of wafer, chamber wall and electrode. A substantial increase in the wafer temperature was attributed mainly to bombardment of incident ions onto the wafer surface. The decrease in the wafer temperature at a higher pressure was attributed to the decrease in plasma density and a resistance to heat transfer in a micro gap formed between the wafer and the electrode. Compared to the case of no rf-chuck power applied, the wafer temperature when the electrode was biased with 13.56 MHz rf power showed a greater increase mainly due to increased ion bombardment. Since the electrode having a water-cooled-backside geometry gains heat from the bulk plasma, it may lead to fast etch rates of hard materials whose etch products are less volatile at low temperatures, but not be good for photoresist materials.

Key words: Wafer Heating, High Denisity Plasma, Inductively Coupled Plasma

INTRODUCTION

In recent years, ultra-large integrated circuit and electronic device fabrication has relied heavily on plasma etching and deposition of thin films on semiconductor wafers [Liberman and Lichtenberg, 1994; Givens et al., 1994; Hahn et al., 1999, 2000, 2001; Lee et al., 1999]. In plasma processing, the wafer temperature and its spatial variation across the wafer surface are important parameters. Process outcome, such as etch rate, etching uniformity and selectivity, can be a strong function of the wafer temperature because etch reaction rate depends exponentially on temperature. Because of this strong temperature dependence, even minor variation in wafer temperature is magnified, causing a large variation in etching rates across the wafer [Kiilamaki and Franssila, 1999].

In general, parameters of bulk plasma are the dominant sources of wafer heating [Givens et al., 1994]. The effect of wafer heating is thus connected to the plasma ion temperature that is essentially equal to the one of background neutral gas species. It is worthwhile to note that the ion temperature also has an effect of ion directionality causing a large variation in etching profile [Ono and Tuda, 1997].

Fig. 1 shows a typical scheme of a wafer sitting on a susceptor (or electrode) in a plasma reactor. The wafer receives energy from the plasma by two major mechanisms, an exothermic chemical reaction and an energetic ion bombardment. The dominant heating mechanism in high-density plasma reactors, such as electron cyclotron resonance, helicon, and inductively coupled plasmas, involves collisions of particles with accelerated electrons and ion bombardment, whereas heat released by etch reactions is more important in high-pressure plasma systems. During the plasma processing, the wafer is kept at a constant temperature by cooling from the backside. Under typical conditions, energy loss by the backside cooling is the dominant heat transfer mechanism out of the wafer. However, if precautions are not taken to increase the contact area between the wafer and the electrode, a large resistance to heat transfer can exist between the bottom surface of the wafer and the cooled electrode [Pearton et al., 1989]. For example, when the wafer is directly placed on the cooled electrode, it contacts the electrode surface. Thus a micro gap exists between the bottom surface of the wafer and the top surface of the cooled electrode, as shown in Fig. 1. Under vacuum, this gap contains very few molecules to transfer heat from the wafer to the electrode, resulting in a large resistance to heat transfer [Tretheway and Aydil, 1996].

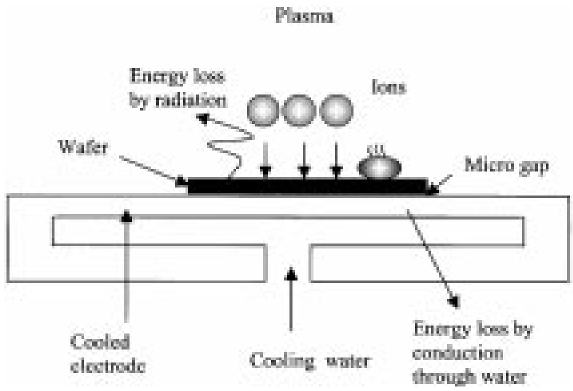

Fig. 1. Schematic diagram of an electrode cooling system in a plasma etcher.

Although it is important to understand the heat transfer between the wafer and susceptor surfaces, little work has been reported, especially in a high-density plasma system. In this paper, to elucidate the heat transfer between the wafer and the electrode an experimental study has been carried out in a planar-type inductively coupled plasma (ICP) reactor.

EXPERIMENTAL

The wafer temperature was measured with a k-type thermocou-

†To whom correspondence should be addressed.
E-mail: ybhahn@moak.chonbuk.ac.kr

ple that was inserted into the ICP chamber through a port on the sidewall. The wafer was placed on the sample chuck (or the bottom electrode) of which the backside was cooled by cold water. We used a Vacuum Science ICP etcher (VSICP 1250A), in which 13.56 MHz radio frequency (rf) source power and rf chuck power were applied to control plasma density and ion energy (or dc-bias voltage) respectively. Detailed descriptions of the ICP system are available elsewhere [Cho et al., 2000]. Unless mentioned, the ICP power was fixed at 700 W and gas feed rates were held at 5 sccm Cl_2/15 sccm Ar, but the rf chuck power was varied from 0 to 150 W. When the thermocouple was inserted into the rf plasma, the accuracy of temperature measurement was reduced mainly due to rf noise. Therefore, to minimize such a noise problem, we used a single detector with low pass filter circuits (Hanyoung Co., HYP-100). Accuracy of temperature measurements was then identified by comparing the values of temperature measured when "plasma on" with those measured in "plasma off" phase. Since there was no difference observed between the two values, we were able to confirm that the effect of rf noise was diminished. Temperatures of the wafer, chamber wall, and the cooling water were measured before and after plasma ignition. In order to facilitate the interpretation of measured results, plasma density and electron temperature were also measured by using a Langmuir probe system.

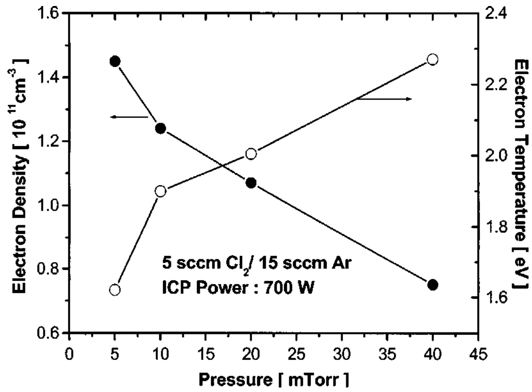

Fig. 3. Effect of the reactor pressure on electron density and electron temperature, measured by a Langmuir probe in Cl_2/Ar inductively coupled plasma.

RESULTS AND DISCUSSION

Fig. 2 shows the effect of pressure on temperatures of the GaN wafer, the chamber wall, and the backside of electrode that is cooled by cold water. During these experiments Cl_2/Ar plasmas were generated at 700 W ICP power without applying the rf power to the electrode. Initial temperatures (i.e., temperatures before plasma ignition) were 10, 21, and 5 °C for the wafer, the chamber wall, and the electrode-cooling water, respectively. Temperatures were measured at 1 minute after ignition. Compared to the cold wafer, a substantial increase in the wafer temperature resulted from the plasma. The temperature of GaN remained relatively constant at 103 °C up to 20 mTorr, but decreased to 85 °C at higher pressures (>20 mTorr). However, the chamber wall and the cooling water showed little dependency of pressure, kept almost constant at 25 °C and 5 °C, respectively. This result indicates that there is a substantial heat transfer from the plasma to the wafer to the electrode. The decrease in the wafer temperature at a higher pressure is attributed to two reasons: the decrease in plasma density (or electron density) and less resistance to heat transfer between the wafer and the electrode at a higher pressure. First, the plasma density generally decreases with pressure, resulting in less ion flux toward the wafer with pressure (see Fig. 3). Less flux of incident ions onto the wafer surface means less energy transfer from the bulk plasma. Second, a micro gap formed between the wafer and the electrode causes a resistance to heat transfer. In this work, the wafer was placed directly on the top of the cooled electrode. Under vacuum, the micro gap contains very few molecules that play a role in transferring heat from the wafer to the electrode, which results in a large resistance to heat transfer. As the resistance is reduced by increasing the number of molecules in the micro gap, a decrease in the wafer temperature is expected at higher pressures (>20 mTorr).

In order to examine the effect of rf chuck power on wafer heating, the rf chuck power of 13.56 MHz was applied to the electrode. Measured temperatures for the cases of 100 W and 150 W are shown in Figs. 4 and 5, respectively. Compared to the case of no rf-chuck power (Fig. 2), the wafer temperature decreased grad-

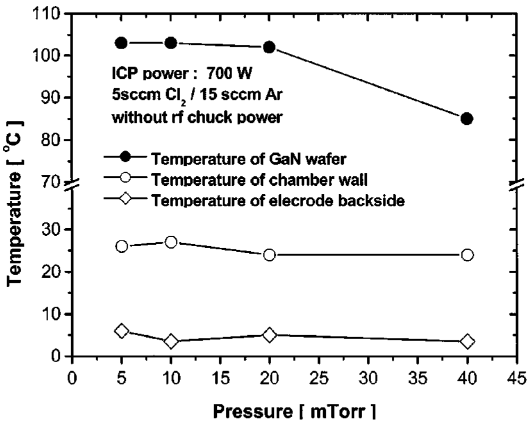

Fig. 2. Effect of the reactor pressure on temperatures of the wafer, the chamber wall, and the electrode backside when no rf chuck power was applied.

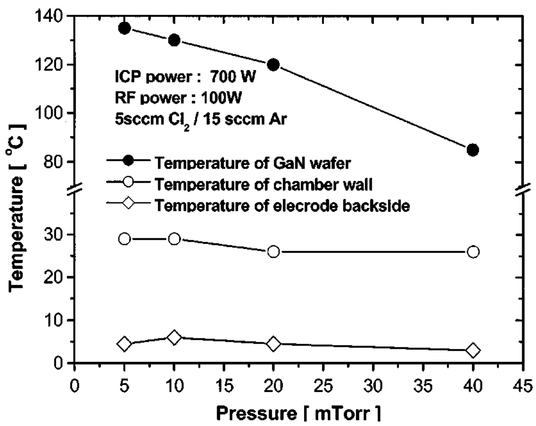

Fig. 4. Effect of the reactor pressure on temperatures of the wafer, the chamber wall, and the electrode backside when the rf chuck power of 100 W was applied.

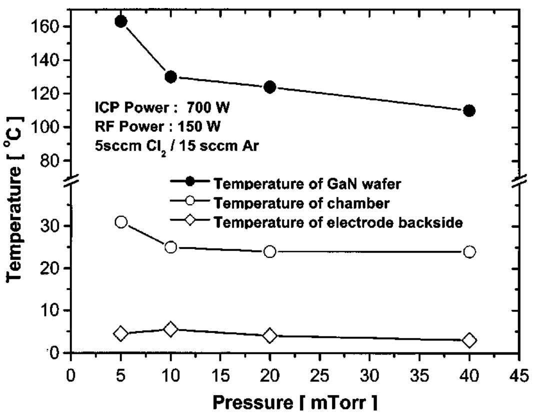

Fig. 5. Effect of the reactor pressure on temperatures of the wafer, the chamber wall, and the electrode backside when the rf chuck power of 150 W was applied.

ually with the pressure, but greater increase in temperatures was obtained. The highest temperatures of the wafer were obtained at the lowest pressure of 5 mTorr: 130 °C at 100 W and 162 °C at 150 W. The wall temperature somewhat decreased with pressure up to 20 mTorr and remained constant above 20 mTorr, while the cooling water showed little change. The temperature of the chamber wall was also greater than that of the case of no rf-chuck power. The increase in temperatures of the wafer and the wall is mainly due to the increased bombardment energy of ions, which is enhanced by applying the rf power to the electrode.

To examine the effect of ion bombardment on heating mechanism, caused by dc bias, the temperature of cooling water was varied from 5 to 23 °C for the cases of rf chuck power on and off, and the results are shown in Fig. 6. The wafer showed almost the same temperature of the cooling water before plasma ignition. However, after ignition, the wafer temperature increased up to 103 °C and kept almost constant until the rf chuck power was applied. When the rf power of 100 W was applied to the electrode the wafer showed a further increase in temperature, indicating that ion bombardment enhanced the heating of the wafer.

Fig. 7 shows the effect of the ICP source power on the temperatures of wafer, chamber wall, and electron density. The wafer tem-

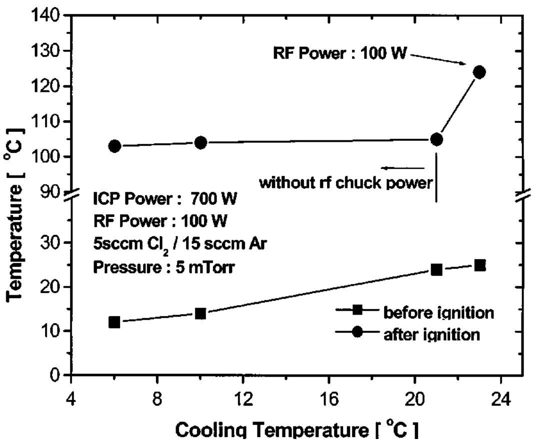

Fig. 6. The temperature of wafer vs. the cooling water temperature with and without applying the rf chuck power.

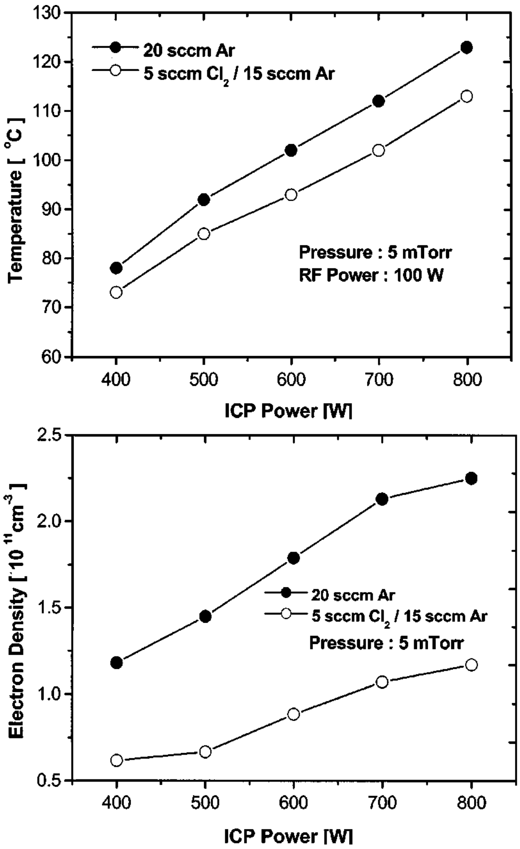

Fig. 7. Effect of the ICP source power on temperatures, electron density, and dc bias in Ar plasma.

perature increased monotonically with the ICP source power in both Ar and Cl_2/Ar plasmas. Electron density substantially increased with the source power, while the dc bias decreased with it, typical phenomena in a high-density plasma system [Hahn et al., 1999, 2000]. The increase in the wafer temperature is attributed mainly to an increase in electron density with the source power, indicating that a dominant mechanism of the wafer heating effect is bombardment of incident ions onto the wafer surface.

Fig. 8 represents the wafer temperature as a function of time, measured with varying the ICP source power in Ar discharges. Although not illustrated the Cl_2/Ar plasma showed similar results to the Ar

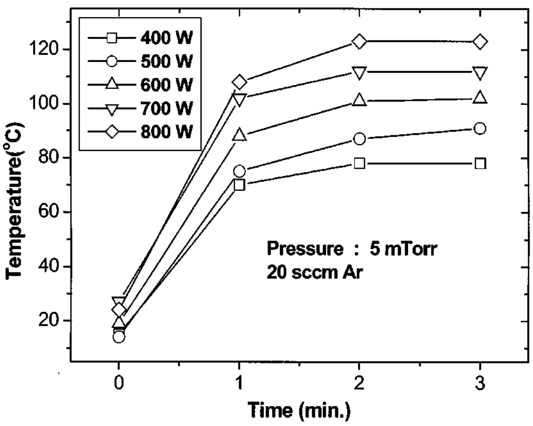

Fig. 8. Wafer temperature as a function of time in Ar plasma.

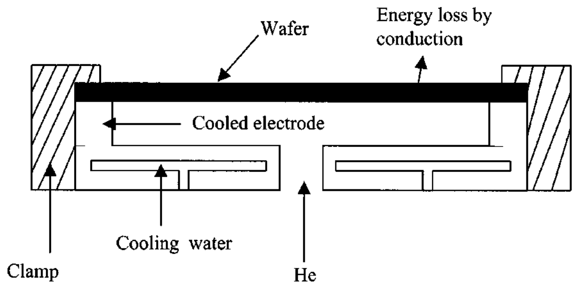

Fig. 9. Schematic diagram of a high thermal conductivity gas cooling system in a plasma etcher.

plasma. The wafer temperature increases with time and maintains relatively constant temperature after 1 min. This result indicates that to obtain an average etch rate, etching has to last at least for two minutes, especially in the backside-water-cooled electrode system.

Based on this work, it is concluded that an electrode having a water-cooled-backside geometry gains heat from the plasma and may enhance an etch reaction. This may be critical for etching hard materials, whose etch products are less volatile (for example, dry etching of strong bond-energy materials such as III-nitrides, magnetic materials, and ferroelectric materials). However, the wafer-heating phenomenon may not be good for photoresist materials that have to stand long enough for pattern transfer. To avoid wafer heating, it would be a promising geometry to fill the gap between the wafer and the electrode with a gas of a high thermal conductivity, such as helium, in addition to cooling the electrode backside with cold water (see Fig. 9). This is attributed to an increased heat transfer coefficient and an increased number of gas molecules available to transfer energy from the wafer to the backside-cooled electrode.

SUMMARY AND CONCLUSIONS

Heat transfer between the wafer and the electrode was studied experimentally in a planar-type inductively coupled plasma reactor. The wafer heating effect was dependent on the reactor pressure, the ICP source, and the rf chuck power. A substantial increase in the temperature of wafer was observed mainly due to heat transfer from the bulk plasma to the electrode. The decrease in the wafer temperature at a higher pressure was also observed and it was attributed to two reasons: the decrease in plasma density (or electron density) at a higher pressure and a resistance to heat transfer in a micro gap formed between the wafer and the electrode. Compared to the case of no rf-chuck power applied, the wafer temperature when the chuck was biased with 13.56 MHz rf power showed a greater increase in temperature mainly due to an increased bombardment energy of ions. Based on this work, it is concluded that an electrode having a water-cooled-backside geometry gains heat from the bulk plasma and thus enhances an etch reaction, leading to a fast dry etching of strong bond-energy materials.

ACKNOWLEDGMENTS

This work was supported in part by grant No. R01-2000-00330 from the Basic Research Program of the Korea Science & Engineering Foundation (KOSEF) through the Chonbuk National University.

REFERENCES

Cho, B.-C., Im, Y. H. and Hahn, Y. B., "Fast Dry Etching of Doped GaN Films in Cl_2-Based Inductively Coupled High density Plasmas," *J. Kor. Phys. Soc.*, **37**, 23 (2000).

Givens, J., Lee, J., Cain, O., Marks, J., Keswick, P. and Cunningham, C., "Selective Dry Etching in a High Density Plasma for 0.5 μm Complementary Metal-Oxide-Semiconductor Technology," *J. Vac. Sci. Technol. B*, **12**, 427 (1994).

Hahn, Y. B. and Pearton, S. J., "Global Self-Consistent Model of an Inductively Coupled Plasma Etching System," *Korean J. Chem. Eng.*, **17**, 304 (2000).

Hahn, Y. B., Hays, D. C., Cho, H., Jung, K. B., Lambers, E. S., Abernathy, C. R., Pearton, S. J., Hobson, W. S. and Shul, R. J., "Inductively Coupled Plasma Etching in ICl- and IBr-Based Chemistries: Part I. GaAs, GaSb and AlGaAs," *Plasma Chem. Plasma Proc.*, **20**(3), 405 (2000).

Hahn, Y. B., Hays, D. C., Cho, H., Jung, K. B., Lambers, E. S., Abernathy, C. R., Pearton, S. J., Hobson, W. S. and Shul, R. J., "Inductively Coupled Plasma Etching in ICl- and IBr-Based Chemistries: Part II. InP, InSb, InGaP and InGaAs," *Plasma Chem. Plasma Proc.*, **20**(3), 417 (2000).

Park, J. S., Kim, T. H., Choi, C. S. and Hahn, Y.-B., "Dry Etching of $SrBi_2Ta_2O_9$: Comparison of Inductively Coupled Plasma Chemistries," accepted, *Korean J. Chem. Eng*. (2001).

Hahn, Y. B. and Kim, D. O., "Structural and Electrical Properties of $SrTiO_3$ Thin Films Prepared by Plasma Enhanced Metal Organic Chemical Vapor Deposition," *J. Vac. Sci. Technol. A*, **17**(4), 1982 (1999).

Kim, D. O., Choi, R. J., Nahm, K. S. and Hahn, Y. B., "Growth Characteristics and Deposition Mechanism of $SrTiO_3$ Thin Films by Plasma Enhanced MOCVD," *J. Vac. Sci. Technol. A*, **18**(2), 361 (2000)

Hahn, Y. B., Lee, J. W., Vawter, G. A., Shul, R. J., Abernathy, C. R., Hays, D., Lambers, E. S. and Pearton, S. J., "Reactive Ion Beam Etching of GaAs and Related Compounds in an Inductively Coupled Plasma of Cl_2-Ar Mixture," *J. Vac. Sci. Technol. B*, **17**(2), 366 (1999).

Hahn, Y. B., Hays, D. C., Donovan, S. M., Abernathy, C. R., Han, J., Shul, R. J., Cho, H., Jung, K. B. and Pearton, S. J., "Effect of Additive Noble Gases in Chlorine-Based Inductively Coupled Plasma Etching of GaN, InN and AlN," *J. Vac. Sci. Technol. A*, **17**(3), 763 (1999).

Kiihanmaki, J. and Franssila, S., "Deep Silicon Etching in Inductively Coupled Plasma Reactor for MEMS," *Physica Scripta.*, T79 (1999).

Lee, J. W., Mackenzie, K. D., Johnson, D., Shul, R. J., Hahn, Y. B., Hays, D. C., Abernathy, C. R., Ren, F. and Pearton, S. J., "Damage to III-V Devices During Electron Cyclotron Resonance Chemical Vapor Deposition," *J. Vac. Sci. Technol. A*, **17**(4), 2183 (1999).

Liberman, M. A. and Lichtenberg, A. J., "Principles of Plasma Discharges and Materials Processing," John Wiley & Sons, Inc., N. Y. (1994).

Ono, K. and Tuda, M., "Profile Evolution during Cold Plasma Beam Etching of Silicon," *Jpn. J. Appl. Phys.*, **36**, 4854 (1997).

Pearton, S. J., Emerson, A. B., Chakrabarti, U. K., Lane, E., Jones, K. S., Short, K. T., White, Alice E. and Fullowan, T. R., "Temperature Dependence of Reactive Ion Etching of GaAs with $CCl_2F_2 : O_2$," *J. Appl. Phys.*, **66**, 3839 (1989).

Tretheway, D. and Aydil, E. S., "Modeling of Heat Transfer and Wafer Heating Effects during Plasma Etching," *J. Electrochem. Soc.*, **143**, 3674 (1996).