Improved Uniformity of Photoresist Ashing for a Half-Inch Wafer with Double U-shaped Antenna Structure in a Microwave-Excited Water Vapor Plasma

Takeshi Aizawa¹, ²*, Taishin Shimada¹, Tasuku Sakurai¹, Yusuke Nakano¹
Yasunori Tanaka¹, Yoshikico Uesugi¹ and Tatsuo Ishijima¹

¹ Electrical Engineering and Computer Science, Graduate School of Natural Science & Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan
² Yonekura MFG Co., Ltd. 2-11-5 Shin-yokohama, Kohoku, Yokohama 222-0033, Japan
*t-aizawa@stu.kanazawa-u.ac.jp, ishijima@ec.t.kanazawa-u.ac.jp

In this study, the uniformity of a photoresist ashing for a half-inch wafer was improved by a developed antenna structure, a double U-shaped antenna, in microwave-excited water vapor plasma. The optimized double U-shaped antenna structure, obtained by simulating an electric field, generated a spread distribution microwave plasma. Experimentally obtained results demonstrate that the observed optical emission distribution image from the microwave plasma resembles the electric field distribution obtained from the simulation under the present water vapor plasma generation condition. The double U-shaped antenna showed a higher ashing rate and better uniformity than the conventional slot antenna.

Keywords: Double U-shaped antenna, Electromagnetic field simulation, Microwave-excited plasma, Water vapor

1. Introduction

Lithography processes of semiconductor manufacturing commonly use a photoresist. It functions as a mask on the substrate surface during ion implantation or etching. It must be removed after these processes. For photoresist removal, chemical solution treatment (sulfuric acid hydrogen peroxide mixture, SPM) [1] or oxygen plasma treatment [2–4] is generally used. Actually, SPM processing requires transportation and chemical storage, which entails operational costs. Furthermore, sulfuric acid recycling is difficult. It is not environmentally friendly. However, oxygen plasma treatment requires a higher substrate temperature for a higher ashing rate, which can exacerbate oxidation of metal wiring. Moreover, earlier reports have described that the device performance is degraded by damage on to a dielectric material with low-k during the oxygen plasma ashing process. Therefore, several ashing techniques have been studied for this purpose [5–9]. These ashing techniques are expected to reduce damage, but at with a reduced ashing rate, which is approximately 1 μm/min.

Among the various ashing techniques, water–plasma–asher (WPA) is expected to realize a very effective process that produces little damage. Microwave excited plasma is generated with a slot antenna using only ultrapure water as the material gas [10]. Moreover, WPA has a higher ashing rate. It is effective for photoresists hardened by ion implantation [11]. Furthermore, the substrate can be cooled directly with ultrapure water. Actually, slot antennas are often used with microwave-excited plasmas [12]. However, microwave plasma processes using a slot antenna often have difficulties such as poor uniformity and small processing size. Therefore, various antennas and microwave plasma-generation methods such as the spoke antenna [13], ring slot antenna [14], multislotted planar antenna [15], radial-line antenna [16,17], slotted waveguide antennas [18], long-line shaped antenna [19–21], using a dielectric material embedded multi-hollow structures under a slot antenna [22], among others [23–30] have been proposed to improve uniformity and to increase the
process size. The approaches associated with these antennas for improving the uniformity and increasing the processing size include changing the antenna arrangement and the shape. For instance, arranging many slots radially in a radial-line slot antenna increases the processing area considerably. Minimal Fab [31], which uses a half-inch wafer, has been developed to provide an optimal system for semiconductor devices having low and medium volume markets. Because placing multiple slots in a small area is difficult, this study specifically examines the antenna shape. Our earlier work assessed an antenna used in the WPA: a slot antenna with a single slit [10]. Plasma was generated in an elliptical shape along this slit. Therefore, the photoresist removal shape in WPA was observed as an elliptical shape resembling the plasma emission shape. Previous studies show that the ashing rate of a photoresist of OFPR5000 at the center of a half-inch wafer was 12 µm/min, but the rate outside of the wafer was only 4 µm/min when the wafer was placed on a stage at 3.5 mm below the antenna. Plasma irradiation is performed excessively on the substrate surface at the wafer center. Therefore, the ashing rate uniformity on the wafer surface must be improved.

For this study, we simulated the electric field distribution of antenna with various shapes using electromagnetic simulation to investigate the ashing rate uniformity of the substrate. The experimental study was also conducted to confirm improvement of the uniformity with the new type of antenna developed for this study.

2. Antenna Model Simulation
2.1. Calculation model
The slot antenna structure was modified to generate uniform plasma and thereby improve the ashing rate uniformity. The antenna structure was designed using commercially available electromagnetic wave simulation software: CST Microwave Studio© [10,32]. Figure 1 presents a simplified model based on which the simulation was performed. Simulation was conducted at frequencies of 2.2–2.7 GHz using a time domain solver. The electric field distribution was evaluated assuming that the microwave input power was 1 W because the plasma was not considered in this simulation. Microwaves were applied to the antenna through quartz with relative permittivity $\varepsilon_r$ of 3.75 inserted into the R22 standard rectangular waveguide with size set to 56 × 28 mm². The quartz was loss-free. Free space boundary conditions were applied at the top of the quartz waveguide. The chamber was assumed to be a polytetrafluoroethylene. The waveguide was assumed to be a perfect conductor. The antenna material, low-resistance Si, had electrical conductivity of 1000 S/m in electric field calculations. The chamber interior space was regarded as vacuum. Water was not introduced into the chamber because the calculation time was higher with water even though the calculation result underwent no significant change. The antenna surface on the chamber side was set as $z = 0$ mm. The electric field distribution was evaluated at $z = 0$ mm and $z = 6.0$ mm.

Fig. 2 portrays the antenna structure in this simulation model. This simulation investigated a slot antenna with a single slit (Fig. 2(a)), an H-
shaped antenna used in our earlier study with rectangular space at both ends of the slit (Fig. 2(b)), and a double U-shaped antenna with a separated H-shaped structure (Fig. 2(c)).

2.2. Simulation of Electric Field Distribution

Fig. 3 presents the electric field intensity at the center of the antenna surface $z = 0$ mm as a function of vertical length $L$ for the H-shaped antenna presented in Fig. 2(b). The electric field intensity increases with length $L$. It takes the maximum value at $L = 13$ mm after which it decreases as $L$ increases further. The antenna is considered to have a resonant structure when the outer circumference length of the slit approaches the microwave wavelength in the quartz $\lambda_c$. We experimentally applied the TE$_{10}$ mode in the R22 standard waveguide at 2.45 GHz excitation. Therefore, the guided microwave wavelength in the quartz $\lambda_q$ is equal to $\lambda_q/\sqrt{\varepsilon_r} \approx 76$ mm, where $\lambda_q$ represents the guided microwave wavelength in vacuum. For this study, an H-shaped antenna with vertical length $L = 12$ mm was chosen. The outer circumference length was 79 mm, which approaches the calculated value of $\lambda_c$. For the double U-shaped antenna, the outer circumference length of a single slit was set to 71 mm, which is also close to the value of $\lambda_c$. For the slot antenna, the antenna with slot length $L_W = 37$ mm has maximum electric field intensity at total circumference of 75 mm. However, the slot antenna was manufactured with $L_W = 20$ mm for an earlier study because of device size restrictions.

Fig. 4 presents simulation results of the electric field distribution at $z = 6.0$ mm. The electric field distribution of the slot antenna in Fig. 4(a) is elliptical. This distribution matches well with the appearance of the plasma light emission and the ashing shape of the photoresist in an earlier study. Moreover, results show that the electric field intensity decreased greatly as the distance increased from the center of the slot antenna, where the electric field intensity had a maximum value of about 100 V/m. Uniformity of the electric field intensity was defined as $(E_{\text{max}} - E_{\text{min}})/2 \times E_{\text{avg}}$, where $E_{\text{max}}$, $E_{\text{min}}$, and $E_{\text{avg}}$ respectively represent the maximum, minimum, and average electric field intensity at 14,641 points in a $\pm 6$ mm square area at 0.1 mm intervals. The slot antenna uniformity was 34.2%. However, for the H-shaped antenna presented in Fig. 4(b), the electric field distribution is circular instead of an elliptical shape. Also, $E_{\text{max}}$ increased by one digit compared to the slot antenna. The H-shaped antenna uniformity was 36.4%. It is expected that the ashing uniformity will not differ much, but the ashing rate is expected to be higher because plasma is generated easily in a high electric field. For the double U-shaped antenna presented in Fig. 4(c), the electric field distribution was much greater over the 0.5 inch wafer size. The uniformity
was 13.7%. The uniformity is expected to be improved considerably.

3. Experiment Results and Discussion

3.1. Experiment setup

Fig. 5 presents a schematic diagram of the experimental apparatus for WPA. Ultrapure water was introduced into the chamber up to 30 mm height under the antenna. The chamber pressure was reduced using a scroll pump. It was fixed at about 1.8 kPa. Consequently, the chamber was filled with saturated vapor of ultrapure water. Microwaves were guided along the TE$_{10}$ mode of a quartz-filled rectangular waveguide, and propagated to the antenna installed at the waveguide end. This experiment used the slot antenna, the H-shaped antenna with $L = 12$ mm, and the double U-shaped antenna. These antenna were cut out from a Si wafer with a resistivity of less than $1.2 \times 10^{-3}$ Ω·cm. The input microwave was modulated using a 100 Hz square wave. The peak power was 200 W. The on-time duty factor was 30%. Plasma emission images were obtained from the chamber bottom using a digital camera. Ashing was performed on the photoresist using these antennas to assess the ashing rate uniformity. The ashing target was an image reversal photoresist (AZ5214) spin-coated onto a half-inch p-type Si wafer. After the wafer was placed on an alumina stage at 6.3 mm below the antenna, the plasma was irradiated for 1 min. The film thickness before and after ashing was measured using an interference thickness meter (HORIBA STEC). The film thickness before ashing was about 1.4 μm. The ashing rate and its uniformity were evaluated by measuring the film thickness before and after ashing at 81 points in a circular area of 10 mm diameter.

3.2. Results and Discussion

Fig. 6 portrays emission images of plasma observed using the antennas of three types. Elliptical plasma was observed with the slot antenna. For the H-shaped antenna, an enlarged plasma was observed in the vertical direction of the slit. For the double U-shaped antenna, results showed that the plasma was generated in each slit. These plasmas mutually interfered and became one large plasma body. This interference was observed only with high peak power based on high-speed camera observations (emission images are not shown here). These findings suggest that the antenna structure and modulated microwave power can enlarge the plasma shape.

Fig. 6. Emission images of microwave excited plasma at $P_{\text{avg}} = 60$ W, $p = 1.8$ kPa: (a) slot antenna, (b) H-shaped antenna, and (c) double U-shaped antenna.

Fig. 7 shows the ashing rate distribution found for each antenna. The maximum value of the color map is the same as the maximum value of the ashing rate. For the slot antenna, the photoresist was removed with an elliptical shape under influence by the elliptical plasma shape. However, with the H-shaped antenna, the photoresist was removed with a circular shape influenced by the circular plasma shape. These distribution results are similar to the electric field distribution but the maximum ashing rate did not correlate with the electric field intensity. By the double U-shaped antenna, the photoresist was removed more uniformly over the entire wafer surface than other antennas, indicating improved uniformity. However, the ashing rate was highest at the wafer center, which was slightly different from the electric field distribution. The electron density at the center of the antenna increased, probably because of integration of the two plasmas generated at the double U-shaped antenna. When uniformity is
It was fixed at about 6.3 mm below the antenna. The chamber pressure was monitored using a vacuum gauge (Gastec, Model V-2000). The chamber pressure was kept at a constant value during the experiment.

These antenna were cut out from a Si wafer with a diameter of 100 mm and thickness of 500 μm. The antenna was installed at the waveguide end. This antenna revealed that the OH radical density at d = 5.5 mm was about 2 × 10^{14} cm^{-3}[33], so the double U-shaped antenna is also regarded as having density near the substrate. Laser-induced fluorescence measurement of the H-shaped antenna revealed that the OH radical density at d = 5.5 mm was about 2 × 10^{14} cm^{-3} or more. The OH radical density as well as electron density measurements are the future work to understand the ashing rate difference between the H-shaped antenna and double U-shaped antenna.

**4. Conclusion**

Electromagnetic field simulation of the antenna structure was performed to improve the ashing rate and the uniformity. The H-shaped antenna changed the plasma spread from elliptical to circular. The ashed photoresist shape also became circular, but the uniformity was the same as that for the slot antenna. However, for the double U-shaped antenna, the uniformity was improved greatly. The maximum ashing rate was increased. The ashing rate distribution result was similar to the distribution of the electric field intensity at 6 mm from the antenna, suggesting that the ashing shape can be estimated from the simulation. The double U-shaped antenna can not only improve the uniformity; it can also increase the electric field intensity. The electric field intensity obtained using the antenna with the optimal shape parameter was 10 times greater than that obtained using a conventional slot antenna. Results show that the microwave-excited plasma was generated efficiently and that the ashing rate was higher when using the double U-shaped antenna.

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**References**

1. W. Kern, *J. Electrochem. Soc.*, **137** (1990) 1887.
2. S. Fujimura, J. Konno, K. Hikazutani, and H. Yano, *Jpn. J. Appl. Phys.*, **28** (1989) 2130.
3. K. Taniguchi, K. Tanaka, T. Inomata, and M. Kogoma, *J. Photopolym. Sci. Technol.*, **10** (1997) 113.
4. S. Fujimura, K. Shinagawa, M.T. Suzuki, and M. Nakamura, J. Vac. Sci. Technol. B Microelectron. Nanom. Struct., 9 (1991) 357.
5. Y. Susa, H. Ohtake, Z. Jianping, L. Chen, and T. Nozawa, J. Vac. Sci. Technol. A Vacuum, Surfaces, Film, 33 (2015) 061307.
6. H. Horibe, M. Yamamoto, T. Maruoka, Y. Goto, A. Kono, I. Nishiyama, and S. Tagawa, Thin Solid Films, 519 (2011) 4578.
7. M. Yamamoto, Y. Goto, T. Maruoka, H. Horibe, T. Miura, E. Kusano, and S. Tagawa, J. Electrochem. Soc., 156 (2009) H505.
8. H. Horibe, M. Yamamoto, E. Kusano, T. Ichikawa, and S. Tagawa, J. Photopolym. Sci. Technol., 21 (2008) 293.
9. T. Miura, M. Kekura, H. Horibe, and M. Yamamoto, J. Photopolym. Sci. Technol., 21 (2008) 311.
10. T. Ishijima, H. Sugiuara, R. Saito, H. Toyoda, and H. Sugai, Plasma Sources Sci. Technol., 19 (2010) 6.
11. T. Ishijima, K. Nosaka, Y. Tanaka, Y. Uesugi, Y. Goto, and H. Horibe, Appl. Phys. Lett., 103 (2013) 142101.
12. F. Werner, D. Korzec, and J. Engemann, Plasma Sources Sci. Technol., 3 (1994) 473.
13. H. Shirai, K. Yoshino, G. Ohkawara, and H. Ueyama, Jpn. J. Appl. Phys., 40 (2001) L701.
14. K. Shimatani, T. Okamoto, and Y. Okamoto, Vacuum, 66 (2002) 359.
15. Y. Yasaka, D. Nozaki, K. Koga, M. Ando, T. Yamamoto, N. Goto, N. Ishii, and T. Morimoto, Jpn. J. Appl. Phys., 38 (1999) 4309.
16. C. Tian, T. Nozawa, K. Ishibashi, H. Kameyama, and T. Morimoto, J. Vac. Sci. Technol. A Vacuum, Surfaces, Film, 24 (2006) 1421.
17. T. Goto, M. Hirayama, H. Yamauchi, M. Moriguchi, S. Sugawa, and T. Ohmi, Jpn. J. Appl. Phys., 42 (2003) 1887.