New Inductively Coupled Plasma Source for uGmni Etching Module - "ISM-duo"

Kenta DOI[*1], Toshiyuki NAKAMURA[*1], Keiichiro ASAKAWA[*1], Katsuaki TOCHIBAYASHI[*2], Mitsuyasu ASANO[*2], and Ryuichiro KAMIMURA[*2]

[*1]Institute of Advanced Technology, ULVAC, Inc., 1220-1 Suyama, Susono, Shizuoka 410-1231, Japan

[*2]Advanced Electronics Equipment Division, ULVAC, Inc., 2500 Hagisono, Chigasaki, Kanagawa 253-8543, Japan

Our new plasma source "ISM-duo" enables the across-wafer etching rate uniformity of our uGmni etching module to be controlled. ISM-duo consists of an RF current distribution unit and two separate ICP antennas placed coaxially so as to control the spatial distribution of plasma generated in the process chamber. The RF current distribution to each antenna is performed at an arbitrary ratio without depending on process parameters such as gas type, and changing the distribution ratio does not disturb impedance matching. These features enable a stable operation of the etching rate uniformity control through the optimization of the RF current distribution ratio for various processes. ISM-duo delivers a new process tuning knob that enlarges the process window in our etching module.

1. Introduction

Since before the launch of our uGmni etching module, our NE series etching systems have been widely used in etching applications, including compound semiconductors such as GaAs, InP, GaN, and SiC; metal thin films for SAW/BAW, power devices, etc.; and piezoelectric films such as PZT and Sc-doped AlN for piezo-MEMS. As we progress towards Society 5.0[1-3], a future society based on ICT/IoT, the demand for these electronic devices is expected to increase, which means larger diameter substrates and mass production will be needed. Meeting the processing requirements will also become more difficult, as exemplified by the miniaturization of the processing dimensions of radio-frequency devices[5, 6] due to the broadening of communication frequencies[4, 5]. As a result, there is a strong need to expand the process window to improve the yield rate.

In the dry etching process, across-wafer uniformity depends on process parameters such as gas type, process pressure, and input power. The etching rate, selectivity, and fabrication shape also depend on the process parameters, and trade-offs are likely to occur between the across-wafer etching distribution and the other process requirements mentioned above. To address this issue, in order to enlarge the process window, we developed a new plasma source "ISM-duo" that enables the across-wafer etching distribution to be controlled without depending on process parameters (ISM: ICP with Static Magnetic field, duo: distribution uniformity optimizable).

Inductively coupled plasma (ICP) is generated by passing an RF current through a coil. The ICP equivalent circuit can be represented as a transformer. A fluctuating magnetic field generated by passing an RF current through an ICP antenna causes an eddy current to flow through the plasma. As a result of the eddy current generation, radio-frequency power is transmitted to the plasma, sustaining the discharge. In other words, the spatial distribution of the plasma can be controlled by adjusting the spatial distribution of the intensity of the radio-frequency fluctuating magnetic field in the process chamber. The ISM-duo plasma source consists of an RF current distribution unit and two ICP antenna networks, where antennas are placed concentrically at the top of the process chamber. By distributing RF current to the inner and outer ICP antennas at the desired ratios, it is possible to control the spatial distribution of the intensity of the high-frequency fluctuating magnetic field, and thus the spatial distribution of the plasma. This makes it possible to control the across-wafer etching distribution simply by adjusting the RF current distribution ratio, while keeping the process parameters such as gas type, process pressure, and input power fixed. In this paper, we explain the design philosophy and electrical operation of the RF current distribution unit[7], which is the core technology of ISM-duo, and introduce the controllability of the across-wafer distribution based on actual etching process data.

*1 Institute of Advanced Technology, ULVAC, Inc.
1220-1 Suyama, Susono, Shizuoka 410-1231, Japan
*2 Advanced Electronics Equipment Division, ULVAC, Inc.
2500 Hagisono, Chigasaki, Kanagawa 253-8543, Japan

2. Design considerations

Changes in the RF current distribution ratios to multiple networks connected in parallel can be made by adjusting the impedance of each network. As shown in Fig. 1(a), a variable impedance element (e.g., a variable capacitor) is introduced into each parallel network, and the RF current is distributed on the basis of the difference in impedance of each network. Here, L_A, L_B are the inductances and R_A, R_B are the resistive components of the respective ICP antennas. In the case of the circuit in Fig. 1(a), for example, the capacitances of the variable capacitors C1, C2 connected in series to each ICP antenna are negatively proportional to each other as shown in Fig. 1(b). As a result, the relationship between the impedances of each network changes in such a way that they intersect as a function of C1 capacitance, as shown in Fig. 1(c). Since the RF current flowing through each network is distributed in accordance with the relationship between the impedances of each network, the RF current as a function of C1 capacitance results in the characteristics shown in Fig. 1(d). The above is the basic principle of variable distribution of RF current to multiple networks.

In an actual plasma processing system that discharges under various process conditions, the impedance of each network changes from the unloaded state by coupling with the plasma. This can result in an unexpected situation where the distribution ratio deviates from the value set in light of the theoretical impedance under no load. Below we describe in detail the phenomenon of impedance change during plasma generation.

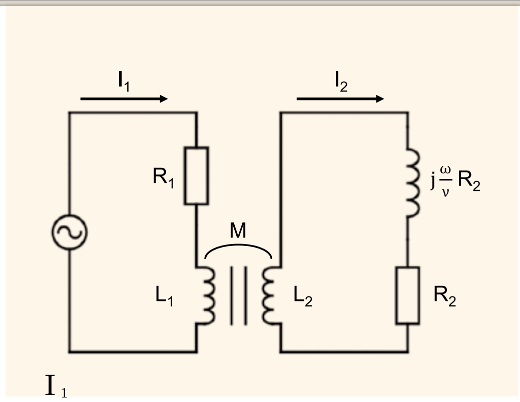

Fig. 2 Electrical circuit model of inductively coupled plasma[8)]

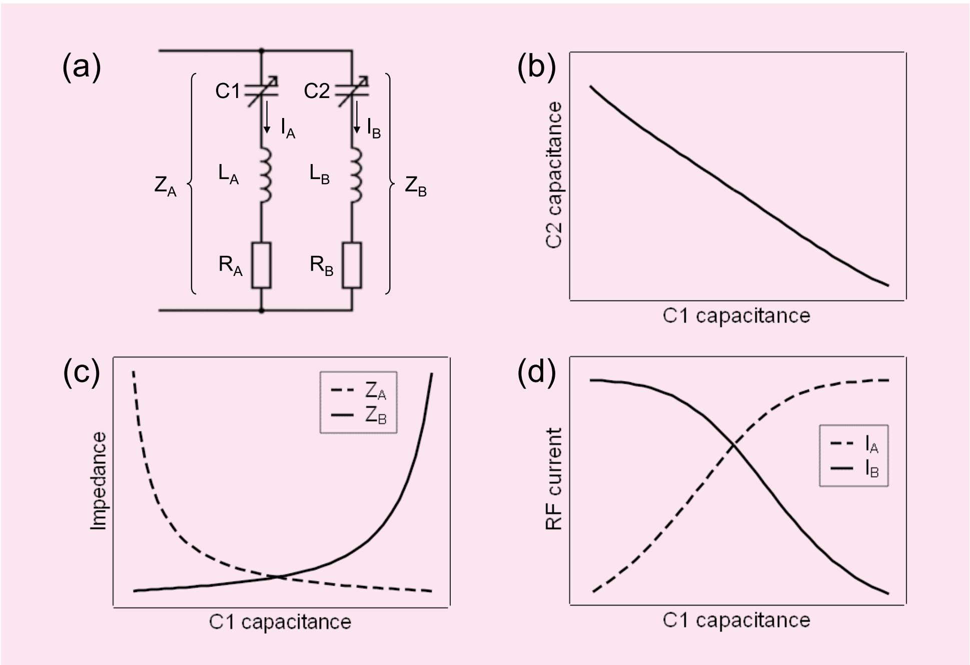

Fig. 1 Example of (a) an RF current distribution circuit comprised of two antenna networks, where the impedance and RF current distribution ratio of each network is determined by the C1 and C2 capacitance, and (b-d) electrical characteristics thereof: (b) the relationship between C1 and C2 capacitance; (c) the impedance characteristics of each current-distributed network Z_A and Z_B as functions of C1 capacitance; and (d) the RF current of each current-distributed network as functions of C1 capacitance

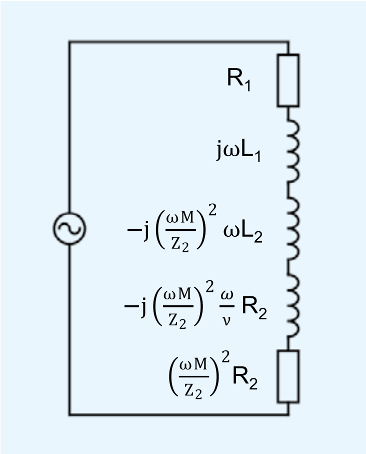

Fig. 3 Equivalent circuit of inductively coupled plasma[8]

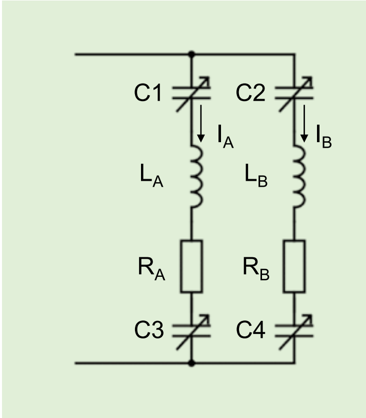

Fig. 4 Electrical circuit diagram of the RF current distribution unit of ISM-duo. The capacitances C1 and C2 determine the impedance and RF current distribution ratio of each network, while C3 and C4 are employed to minimize the impedance change of each network due to coupling to plasma and mutual induction

When considering the electrical circuit diagram of an RF circuit for ICP generation, as in Fig. 2, the ICP antenna can be regarded as the primary coil of a transformer with a resistive component R_1 and an inductance L_1, and the discharge can be regarded as the secondary coil with inductance L_2[8]. Here, R_2 is the resistive component of the plasma load impedance. Note that for simplicity, the matching box and the RF current distribution mechanism are not included in the schematic. When an RF current I_1 with angular frequency ω flows through the ICP antenna, an RF magnetic field is generated in the discharge space. As a result, eddy current I_2 flows into the plasma, which is the secondary circuit. The system can therefore be understood as a composition in which plasma is generated and maintained by transmitting RF power. The circuit model of the ICP represented by the transformer in Fig. 2 can be represented by the series equivalent circuit in Fig. 3[8]. Thus, it can be seen that the resistive component R_2 and the inductance L_2 due to the coupling to the plasma are added as constants to the impedance of the RF circuit including the ICP. In addition, it should be noted that when two ICP antenna networks are placed in the vicinity of each other, apparent reactance changes occur due to mutual induction. During discharge, these impedance changes invalidate the distribution ratio setting determined from the theoretical impedance value under no load. Moreover, the impedance change depends on the discharge conditions, including the type of gas. Therefore, in order to guarantee stable distribution operation, i.e., similar distribution characteristics and impedance matching under various discharge conditions, what is needed is a structure that incorporates dynamic control to offset the constant impedance change.

3. Structure of the RF current distribution unit and its electrical operation[7]

The ISM-duo's RF current distribution unit is designed to operate stably without the distribution ratio and total impedance depending significantly on the process conditions. To ensure similar distribution performance under all process conditions, we developed the RF current distribution unit as a C (L) C series connection. The circuit structure is shown in Fig. 4. Variable capacitors C1, C2 are provided on the power input side (matching box side) to adjust the impedance of each network and determine the distribution ratio, and variable capacitors C3, C4 are provided on the return (GND) side to offset the impedance change of the ICP antenna caused by the coupling to the plasma. Similar to the circuit in Fig. 1, the capacitances of C1 and C2 have a negative proportional relationship, as shown in Fig. 1(b). The position (capacitance) of C3 and C4 is automatically controlled dynamically so as to be in LC series resonance with the concentrically arranged inner annular ICP antenna L_A and the outer annular ICP antenna L_B, respectively. This ensures that the impedance of the series of ICP antenna and return capacitor (C3 or C4) in each network is always only the resistive component R_A or R_B. As a result, it is possible to minimize the difference in impedance due to differences in the discharge state. This dynamic and automatic LC series resonance control has the advantage of minimizing changes in impedance even when the distribution ratio is changed in the entire circuit, improving the stability of impedance matching. Resistive components R_A and R_B are not large, and the circuit can be regarded as effectively a parallel circuit of C1 and C2. In other words, only C1 and C2 contribute to overall impedance as main elements. Since C1 and C2 are in a negative proportional relationship, the combined capacitance is always constant. Therefore, even when the distribution ratio is changed, no significant change in impedance occurs. In addition, since C2 automatically operates in a negatively proportional relationship to C1, and C3 and C4 are automatically controlled as described above, the distribution operation can be easily handled by setting only the capacitance or position of C1. The user can perform the desired current distribution by setting only the position (capacitance) of C1 while referring to a distribution characteristic graph (for example, Fig. 1-d) prepared in advance.

We performed discharge operation testing of ISM-duo after installing it in the uGmni-200E etching module (Fig. 5).

Fig. 6 shows the test results of the RF current distribution characteristics and the total impedance (c) of the inner annular ICP antenna (a) and the outer annular ICP antenna (b) at the time of discharge. Fig. 6(c) compares the results when the star electrode, which is described in the next section, is turned ON and OFF. Fig. 6(a) and (b) show that the RF current flowing to the inner and outer annular ICP

Fig.5 uGmni-200 system with a single etch module

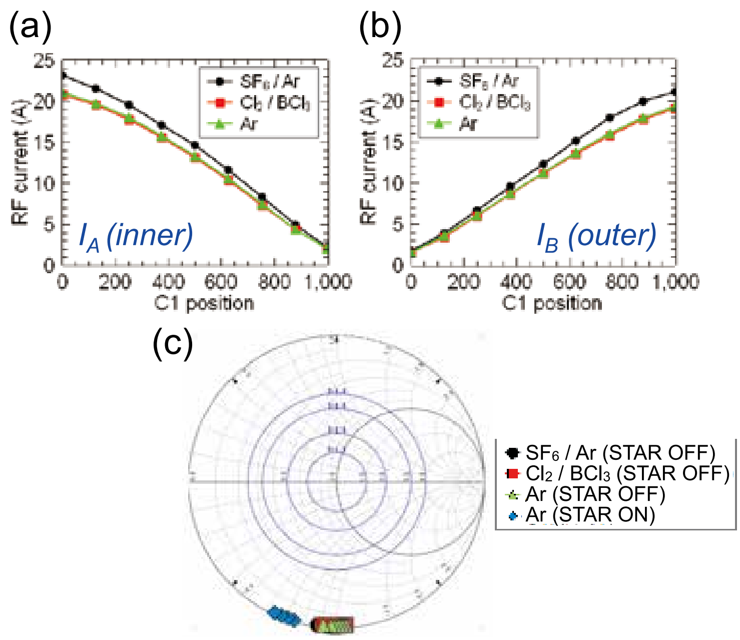

Fig.6 Electrical characteristics of our RF current distribution unit: RF current distributed to the (a) inner and (b) outer annular antennas, respectively, as functions of the C1 position for discharges of several process gases; and (c) a corresponding impedance chart of the entire load including the RF current distribution circuit and both inner and outer antennas

antennas can be distributed at the desired ratio by using the C1 position (capacitance) as the input (variable), and that the current distribution to the inner and outer ICP antennas can be performed with similar characteristics, even with different gas types. In addition, Fig. 6(c) shows that the total impedance did not change significantly even when the distribution ratio was changed, confirming the operational stability of ISM-duo. Here, the total impedance is the impedance of the actual load, including the distribution unit, the ICP antenna, and the plasma, as seen from the output terminal of the matching box. In other words, the results show that it is the impedance itself that is matched and controlled to 50 Ω, and that high matching stability was obtained without much dependence on the gas type or distribution ratio. As noted earlier, the LC series resonance control of C3 and C4 always offsets the reactance component of the corresponding ICP antenna, which depends on the discharge conditions, thus suppressing the overall impedance change.

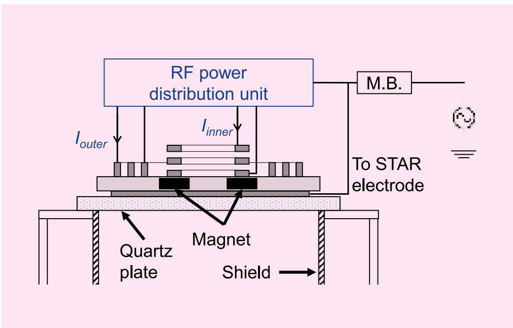

Fig. 7 ISM-duo (ICP with Static Magnetic field – distribution uniformity optimizable) plasma source

4. ICP antenna designed specifically for ISM-duo

The ICP antenna that we designed specifically for ISM-duo is designed to be able to control the across-wafer etching distribution while maintaining the magnetic field ICP characteristics of conventional ISM plasma sources[9] (Fig. 7). To control the spatial distribution of the plasma, we arranged the inner annular ICP antenna and the outer annular ICP antenna concentrically at the top of the atmosphere side of the process chamber. We then connected those two independent ICP antennas to the RF current distribution, as illustrated by L_A and L_B in Fig. 4, which enabled spatial distribution control of the plasma by changing the RF current distribution ratio. The magnetic field assist can generate plasmas with lower pressure, lower electron temperature, and higher density than other ICP methods, enabling a wide range of plasma control from ionic etching to radical etching.

The adhesion of conductive deposits to the RF input window reduces the RF power transmittance, causing process shifts such as a drop in the etching rate. We therefore equipped ISM-duo with a "star electrode[10]" for preventing this adhesion of conductive deposits to the RF input window so that the system can continue to support etching processes that produce a lot of residue in the chamber, such as PZT and Pt, in which deposit adhesion to the RF input window is a concern. Fig. 6(c) shows the total impedance when the distribution ratio is changed when the star electrode is turned ON and OFF. The results show that the impedance change due to turning the star electrode ON or OFF is small, and that high matching stability was obtained without much dependence on the distribution ratio even when it was ON. In this way,

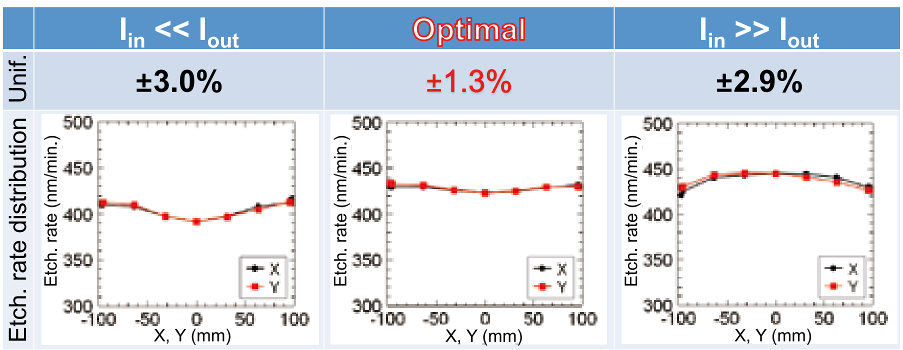

Fig. 8 Etching rate distributions of polysilicon across a Ø200-mm wafer obtained at several RF current distribution ratios to the inner and outer annular antennas

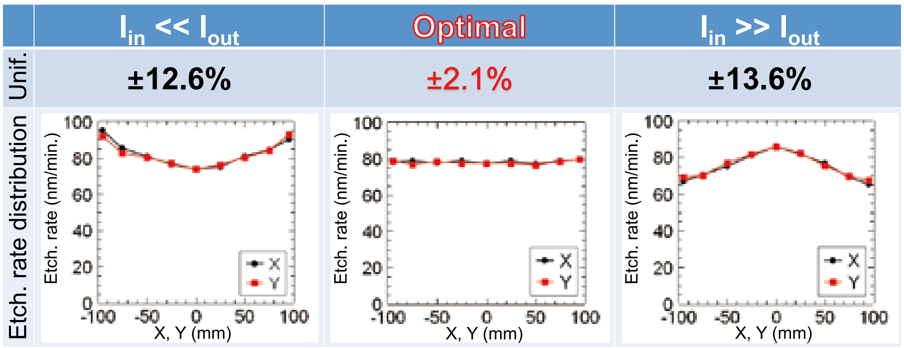

Fig. 9 Etching rate distributions of aluminum across a Ø200-mm wafer obtained at several RF current distribution ratios to the inner and outer annular antennas

we have added a function to control the across-wafer etching distribution while maintaining the conventional technology represented by ISM and the star electrode.

5. Process case study; Across-wafer etching distribution control

We installed ISM-duo in the uGmni-200E etching module and evaluated its control of the across-wafer etching rate distribution. Fig. 8 shows the across-wafer etching distribution of polysilicon obtained at several RF current distribution ratios. This is the result of etching a Ø200 mm wafer with chlorine plasma. The figure shows that it is possible to control the unevenness of the across-wafer etching rate distribution by changing the distribution ratio. It is possible to optimize the across-wafer etching rate distribution simply by changing the distribution ratio without adjusting the process parameters such as pressure and input power. In this example of polysilicon etching, an across-wafer etching distribution with a concave shape can be obtained by increasing the RF current distribution ratio to the outer annular ICP antenna, while a convex shape can be obtained by increasing the distribution ratio to the inner annular ICP antenna. By optimizing the distribution ratio, an across-wafer uniformity of ±1.3% was obtained at an edge cut of 3 mm.

Next, we conducted actual process tests of Al etching to verify the controllability of the across-wafer distribution in various processes. Fig. 9 shows the resulting across-wafer etching distribution. As in the case of polysilicon, the across-wafer uniformity of Al could be optimized simply by adjusting the distribution ratio, without changing the process parameters such as pressure and power input. For this result, we used a 5 mm edge cut for the sake of pattern convenience.

6. Conclusion

In this paper we reported on the features of our new "ISM-duo" plasma source, which is equipped with a mechanism for adjusting the across-wafer etching distribution, and its ability to control the across-wafer distribution. The ISM-duo is equipped with an RF current distribution unit capable of distributing the RF current to the two ICP antenna networks with high impedance matching stability without relying on process conditions such as gas type. Combining the distribution unit with an ICP antenna designed specifically for ISM-duo allows the spatial distribution of the plasma to be controlled under all process conditions. As a result, we were able to demonstrate that the across-wafer etching distribution could be controlled over a wide range of processes. The controllability of the across-wafer etching distribution obtained by the introduction of ISM-duo contributes to the enlargement of the process window, helping users deal with increasing process complexity due to smaller device processing dimensions and larger substrate diameters. By supporting the electronics industry with our technology, we hope to help realize a more prosperous, safe, and secure future.

References

1) Cabinet Office, Government of Japan (2016) "5th Science and Technology Basic Plan," URL: https://www8.cao.go.jp/cstp/kihonkeikaku/index5.html.
2) Ministry of Education, Culture, Sports, Science and Technology (2021), "White Paper on Science, Technology, and Innovation 2021: Toward Realizing Society 5.0," URL: https://www.mext.go.jp/b_menu/hakusho/html/hpaa202101/1421221_00023.html.
3) A. Deguchi, C. Hirai, H. Matsuoka, T. Nakano, K. Oshima, M. Tai, and S. Tani: "What Is Society 5.0? In: Hitachi-UTokyo Laboratory (H-UTokyo Lab.) (eds) Society 5.0" (Springer, Singapore, 2020).
4) H.-J Song and T. Nagatsuma: IEEE Trans. Terahertz Sci. Technol., **1**, 256 (2011).
5) Osamu Kagami, "Research and development of basic technology for terahertz wave devices" (Materials for the 9th Results Presentation Meeting for Expanding Radio Resources, Ministry of Internal Affairs and Communications, 2016).
6) A. K. Sarin Kumar, P. Paruch, J.-M. Triscone, W. Daniau, S. Ballandras, L. Pellegrino, D. Marré, and T. Tybell.: Appl. Phys. Lett., **85**, 1757 (2004).
7) Kenta Doi and Toshiyuki Nakamura: Patent 7052162 (2022).
8) R.B. Piejak, V.A. Godyak, and B.M. Alexandrovich: Plasma Sources Sci. Technol., **1**, 179 (1992).
9) Kazuhiro Watanabe, Mie Ikuta, and Mitsuhiro Endo: Patent JP-A-07-161488 (1995).
10) Kazuhiro Watanabe, Mie Ikuta, and Mitsuhiro Endo: Patent JP-A-08-316210 (1996).