Improved controllability of high frequency inductively coupled plasma generation by series resonant metamaterial structures

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Abstract: In this study, resonator of series ring capacitance and wire inductance was used as the metamaterial structure, aligned in line as a unit structure. The operating frequency for plasma generation is around 68.6 MHz, and the resonant frequency of the metamaterial is in the range of 60 MHz to 70 MHz. The experimental results showed that the plasma emission was concentrated around the metamaterial, indicating the possibility of controlling the plasma energy by the metamaterial installation in inductively-coupled plasma.

Keywords: Plasma generation, metamaterial, high frequency

1. Introduction

In plasma sources for semiconductor manufacturing, plasma generation is performed with microwave or radio-frequency power. It is known that at these frequencies, e.g., 50-60 MHz, electrons are captured in the discharge space, resulting in highly efficient plasma generation [1]. Frequently, a method called inductively coupled plasma generation is used for this plasma generation. In the method proposed here, plasma generation is performed using a spiral antenna as usual, but unlike typical communication antennas, metamaterials are additively installed, since the energy radiation of several 100 W output power must be homogeneous for the purpose of plasma material processing. This is expected to enable both homogeneous consumption of energy and high density of plasma by locally controlling the plasma energy at the metamaterials. At present, our group has succeeded in achieving high density and high uniformity of microwave plasma [2][3]. In this study, plasma generation using metamaterials in the high-frequency (several 10 MHz) band was performed and this attempt was made to control the plasma around the metamaterials.

2. Experimental setup

The metamaterials were evaluated by measuring the received intensity (S_{21}) of the metamaterial with a series resonance frequency of 68.6 MHz using Vector Network Analyzer (VNA, Anritsu, MS2028B).

Plasma generation was controlled using this metamaterial. The frequency of plasma generation is 60, 68, 70, 75 MHz. Inductively coupled plasma (ICP) was generated in a vacuum chamber (Ar gas 7.0 Pa) (Fig.1). In this configuration, a high-frequency (60-70 MHz) magnetic field is generated from the antenna, and the electrons are accelerated by the induced electric field from the magnetic field to generate plasma [4]. In this study, a spiral-shaped copper wire was used as an antenna, and it is held by 2 Teflon plates in a chamber. We set up the metamaterial inside the Teflon plate on the chamber side (Fig. 2).

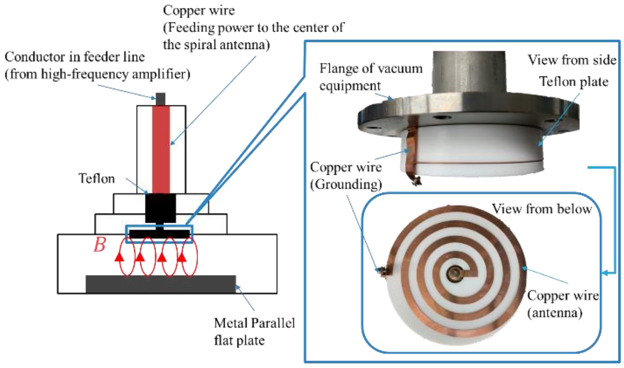
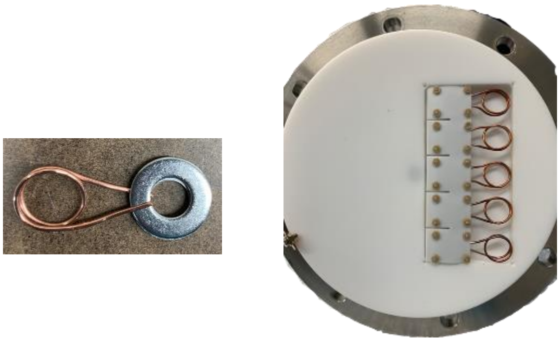


Fig. 1. Configuration of ICP generator.



(a) (b)

Fig. 2. Photo image of metamaterial. (a) The unit structure of the metamaterial (meta-atom). (b) Installed the metamaterial in a Teflon.

3. Result and Discussion

First, the metamaterial was evaluated using a Vector Network Analyzer (VNA). The result in Fig.3 shows a decrease in the received intensity at 68.6 MHz, indicating that the metamaterial is functioning in this region. This metamaterial structure can be regarded the copper wire as a coil and the metallic rings as a capacitor, and thus the equivalent circuit of this metamaterial structure is a series LC circuit (Fig.4,5). Therefore, at the resonant frequency, instant fields are intensified, stored between the coil-ring resonators, and dissipated as energy radiation. In this measurement, since we are observing transmitted waves of electromagnetic waves, it is thought that energy is stored at the resonant frequency, temporarily decreasing the reception intensity.

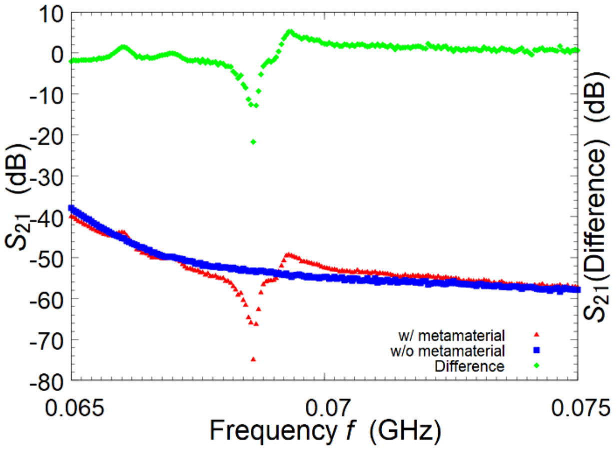


Fig. 3. The measurement result of transmitted wave spectrum.

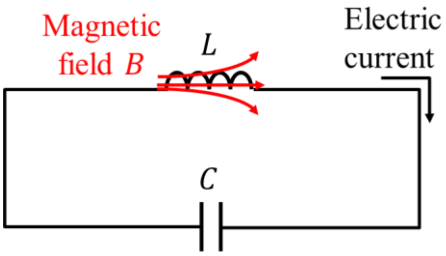


Fig. 4. Equivalent circuit of the meta-atom.

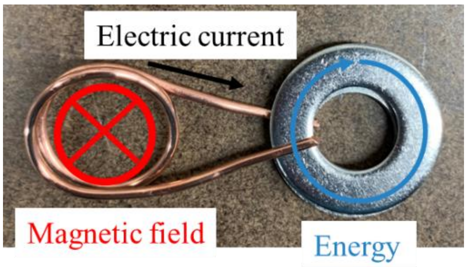
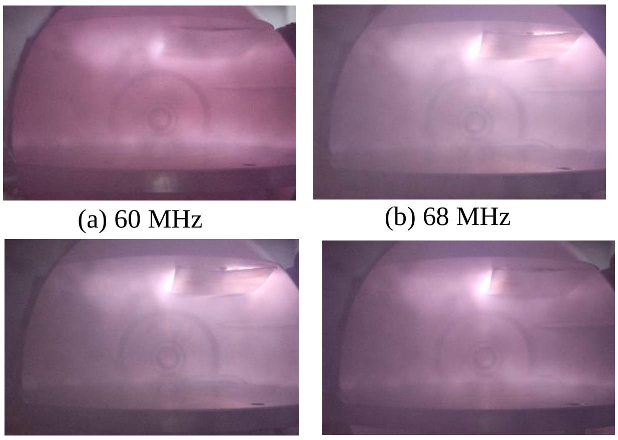


Fig. 5. Theoretical diagram of the meta-atom.

Next, plasma was generated using this metamaterial (Fig.6.) and the starting electric (ignition) power for discharge was as shown in Fig. 7. From Fig. 6, we confirmed the phenomenon that plasma emission is concentrated around the metamaterial. At 60 MHz, the plasma spreads over the vicinity of the metamaterial, while at 68-75 MHz, the plasma is concentrated near the metamaterial. Also, it was found from Fig.7 that starting electric power of discharge was the highest at 68 MHz and the lowest at 60 MHz.



(a) 60 MHz (b) 68 MHz

(c) 70 MHz (d) 75 MHz

Fig. 6. Visible images of Ar plasma.

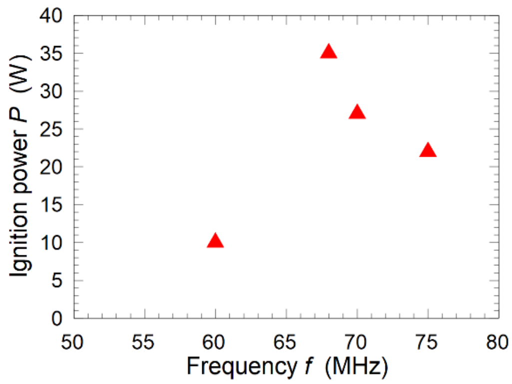


Fig. 7. The relationship between starting electric power of discharge and frequency.

According to these results, it is thought that energy was stored between the sprit-ring resonators and more power for plasma generation around the resonant frequency of the metamaterial was required. This stored energy is transferred to the plasma as energy radiation, producing a high-density plasma.

4. Conclusion

In this study, plasma generation was performed using a series resonant metamaterial, and the possibility of locally controlling the plasma energy around the metamaterial was confirmed. Conventionally, in case of semiconductor processes in the frequency band of several 10 MHz, heterogeneity with plasma generation has been a problem when processing wafers were about size of 12 inches. However, it is thought that wafers can be processed homogeneous by using metamaterials in heterogeneous areas. In the future, we will examine the possibility of applying metamaterials to semiconductor fabrication equipment while diagnosing the plasma density using the metamaterial effect.

5. Acknowledgements

This work was partially supported by Tokyo Electron and a Grant-in-Aid for Scientific Research from the

Japanese Ministry of Education, Culture, Sports Science and Technology (JSPS KAKENHI Grant Numbers JP18H03690 and JP22K18704).

6. References

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