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Measurement of Dynamic Response Time in Pulse Modulated Thermal Plasma

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A novel system was developed of an inductively coupled thermal plasma with a fundamental frequency of 450 kHz. This system can modulate the amplitude of the coil current periodically with a cycle of the order of 10 ms by switching MOSFET inverter power supply. The pulse modulated Ar thermal plasma was successfully generated at a power of 30 kW under the atmospheric condition. Shimmer current level(SCL) , which means the ratio of lower to higher level of the coil current could be reduced from 100 to 40 % to sustain the pulse modulated Ar ICP. Spectroscopic measurements of radiation intensity of an Ar spectral line was carried out to estimate the dynamic response time of the pulse modulated plasma. It was found that the dynamic response time has a magnitude of about 1.5 ms at 10mm below the coil end on the center axis. The effect of SCL on the plasma response time was also investigated. It was revealed that the on-delay time increased with decreasing the lower level of the coil current, while rising and falling times had the magnitude around 1.5 ms almost independent of it.
Key words: thermal plasma, pulse modulation, Ar spectral line, temperature, shimmer current level(SCL)

1. INTRODUCTION

The thermal plasma under the atmospheric pressure has widely been used for many technologies such as the production of new materials, material processing and destruction of the wastes because of its high reaction activity and high temperature. Recently, the inductively coupled thermal plasma is being paid much attention in many industrial fields, especially in materials processing, since the inductively coupled plasma (ICP) is free from any contamination owing to unnecessity of any electrodes[1-6].

For the purpose of using ICP in the materials processing fields, much effort has been made to sustain the ICP statically under the steady condition. On the other hand, we have developed a new system for sustaining ICP with a function of AM modulating the coil current using MOSFET inverter power supply. The intentional modulation of the coil current may induce the ICP to be under the transient and dynamic state and chemically non-equilibrium condition. This has a probability of introducing new materials processing. In addition, the use of this "pulse modulated plasma" allowed us to investigate transient state of the pure plasma free from any contamination fundamentally. This means that this plasma may be adopted to elucidate the circuit breaker arc interruption phenomena in an electric system.

In the present paper, the dynamic response time including rising time, falling time, on-delay time and off-delay time of the pulse modulated Ar plasma was estimated from measured radiation intensity of Ar spectral line to investigate the thermal inertia of the plasma. The influence of SCL(Shimmer current level) , which means the ratio of lower to higher level of the coil current, on the response time of the plasma was measured. It was found that the lower temperature state in the plasma could be produced with remaining high temperature state by controlling the lower level of the coil current, and that the on-delay time increased with a reduction of the lower coil current, while the rising and falling time was almost independent of it.

2. CONCEPT OF PULSE MODULATION OF THE COIL CURRENT

Fig. 1 illustrates the general concept of pulse amplitude modulation of the coil current. In a conventional steady operation, the coil current has a fixed peak value with a fundamental frequency like 450 kHz, as indicated in Fig.1 (a). On the other hand, the pulse modulated coil current, introduced in the present paper, has a periodically changed peak value with a cycle of 100 Hz for example, as demonstrated in Fig.1(b). Such a modulation of the coil current can make the ICP be disturbed and fluctuated intentionally. We defined the ratio c/d of the lower to the higher levels of the coil current as "SCL(Shimmer Current Level)", the time period a with a higher level of the coil current as "On-time", the time period b with a lower level of the coil current as "Off-time". These parameters are greatly important for the pulse modulated plasma to be controlled.

3. PLASMA TORCH AND POWER SUPPLY

Fig.2 shows a schematic diagram of the plasma torch used in the experiment. The torch was composed of two coaxial quartz tubes with a length of 370 mm. The inner quartz tube has a inside diameter of 70 mmϕ, and the outer one has a outside diameter of 95 mmϕ. Between

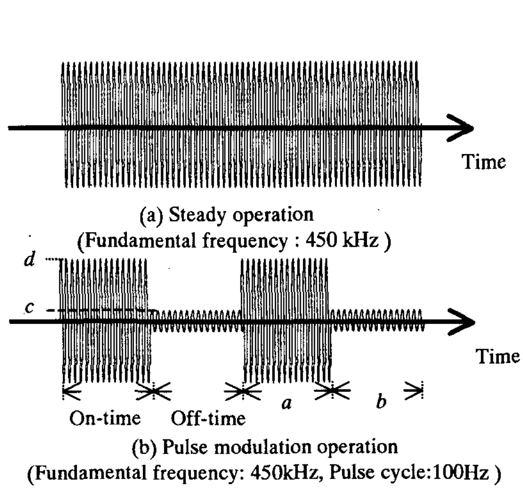

Fig.1 General concept of pulse modulation of coil current.

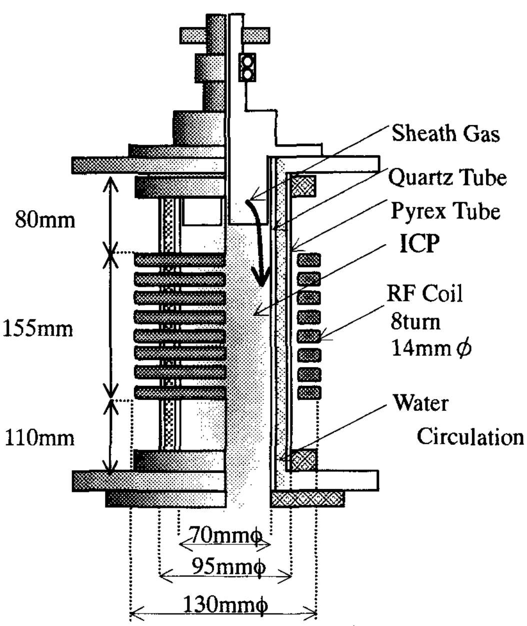

Fig.2 Plasma torch.

these tubes, the water flowed from downer to upper side in order to keep the wall-temperatures around 300 K. Argon gas was supplied as a sheath gas along the tube wall with a swirl to prevent the plasma from contacting to damage the wall. The flow rate was set to 100 liters/min (=1.67×10^{-3} m^3/s). A 10-turn coil with 153 mm long was used. The use of such a long coil permitted us to produce long plasma space. The coil was connected with a MOSFET (Metal Oxide Semiconductor Field Effect Transistor) inverter power supply with a rating power of 50 kW and a rating frequency of 450 kHz through the impedance matching LC series circuit. This power supply has a much higher power-conversion efficiency around 85 % during dc/ac inverter performance than a conventional vacuum tube[7]. Moreover, this power supply can make AM

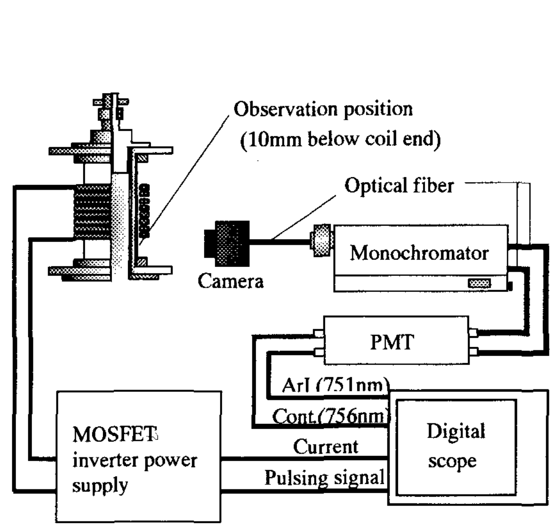

Fig.3 Optical system for spectroscopic observation.

modulation of the coil current with a cycle of several milli-seconds as indicated in Fig.1(b) by switching MOSFET.

4. SPECTROSCOPIC OBSERVATION SYSTEM

Fig.3 indicates the optical system for spectroscopic observation. The observation position was set at 10 mm below the coil end on the torch center axis. The light from the observation position was transmitted through a camera lens and a fiber bindle to the slit of a monochromator. At the focal plane of the monochromator, other two optical fiber bundles were installed to measure light intensities at two specified wavelengths simultaneously. These fibers had two photomultiplier tubes to convert light intensities into electrical signals. The measurement range of this system for one channel was 1.0 nm. In the experiment, we chose 751 and 756 nm as the two specified wavelengths to measure the radiation intensities of Ar atom spectral line at 751.465 nm and that of the continuum. The Ar atom spectral line is emitted through a much large transition probability of 0.43×10^{8} s^{-1}[8], and therefore the time variation in its intensity directly corresponds to that in the internal state of the plasma. Subtracting the intensity of the continuum from that at 751 nm after a calibration yields a net intensity of Ar line at 751.465 nm. The relative spectral sensitivity of the overall optical system including the monochromator , the fiber bundles and the photomultiplier tubes was calibrated using a standard tungsten-hailide lamp.

5. RESULTS AND DISCUSSIONS

5.1 Pulse modulation of coil current

Fig.4 shows time variation in the pulsing signal and that in the peak value of the coil current of the pulse modulated Ar plasma for the 10 ms on-time and 5 ms off-time under the atmospheric pressure condition for different SCL. The higher levels of the coil current was fixed to about 250 A_{peak}(=177 A_{rms}), and the input power was 30 kW for SCL=100%. As seen in Fig.4 we successfully established a pulse modulated Ar plasma

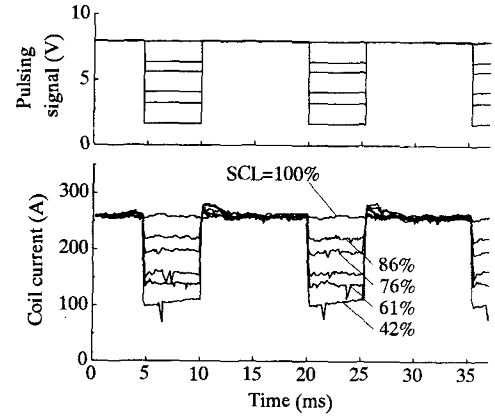

Fig.4 Coil current.

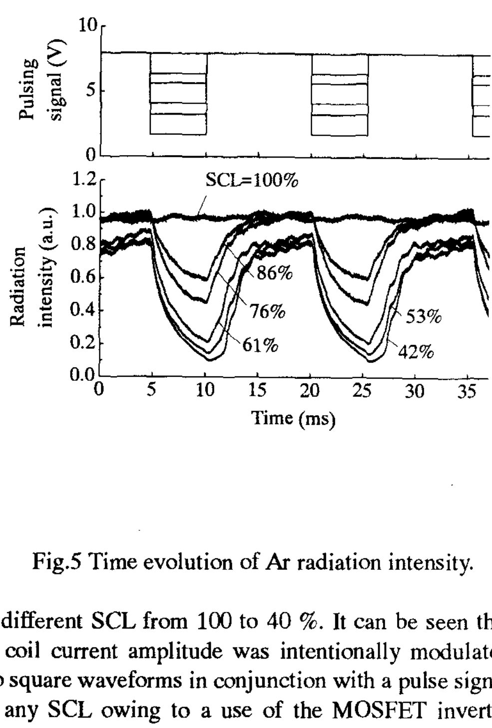

Fig.5 Time evolution of Ar radiation intensity.

for different SCL from 100 to 40 %. It can be seen that the coil current amplitude was intentionally modulated into square waveforms in conjunction with a pulse signal for any SCL owing to a use of the MOSFET inverter power supply. In addition, the transition from lower to higher levels of the coil current only took 0.2 ms which was much faster than a plasma response time described later.

5.2 Time variation in Ar atom spectral line

Fig.5 demonstrates time evolution of the radiation intensity of the Ar spectral line for different SCL. As found in this figure, the intensity also periodically changed with the pulse signal. However, it was not a square waveform like that of the coil current but a blunt waveform. This means that the number density of Ar atom excited to the upper energy level 106054 cm^{-1} (13.1 eV=2.10 $\times$ 10^{-18} J) changed with such a waveform[9]. This bluntness is considered to be ascribed to a thermal inertia of the plasma itself, and therefore the

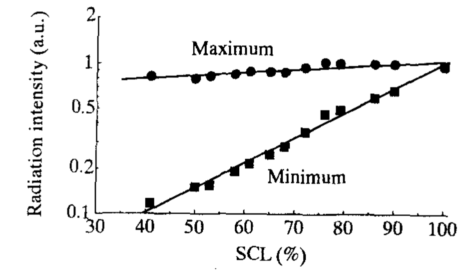

Fig.6 Dependence of maximum and minimum radiation intensities on SCL.

characteristic time of this waveform can be considered to the response time of the plasma because it was much longer than a transition period 0.2 ms of the AM coil current peak. Further spectroscopic observation was carried out for other five Ar spectral lines at 727.3, 738.4, 763.5, 772.4 and 794.8 nm, and these spectral lines were found to have similar time variations in radiation intensity to that of 751 nm. This indicates that the excitation equilibrium may be established, whilst ionization reaction might not reach the equilibrium state. Accordingly we used the radiation variation at 751 nm for understanding the dynamic behavior of the plasma.

In addition, decreasing SCL reduced its radiation intensity especially just before the on-operation. Fig.6 indicates the maximum and minimum values of the radiation intensity during a pulse modulation cycle with a logarithm vertical axis. The intensity had a similar maximum value roughly irrespective of SCL. However, its minimum value decreased exponentially with a reduction of SCL. This indicates that we can control a low temperature state or a low excited state by a reduction of the low level of the coil current remaining a high temperature state with a stable high level of the current.

5.3 Characteristic time of Ar spectral line

For the purpose of investigating a plasma response feature, the characteristic times including "rising time", "falling time", "on-delay time" and "off-delay time" were estimated using the waveform of the measured radiation intensities of Ar spectral line. These characteristic times means the response speed which is determined by the thermal inertia of the plasma. The rising and falling times correspond to the transient response speed in on- or off- operations, respectively, while the on-delay and off-delay times are the stability of the lower and higher states, respectively. Fig.7 shows the definition of these characteristic times used in the present paper. For example, the rising time was defined as the time from 10 to 60 % in radiation intensity during rising period to avoid the effect of noise above 60%.

Fig.8 indicates the characteristic times at 10 mm below coil end on the center axis versus SCL. The rising time, falling time and off-delay time has a magnitude

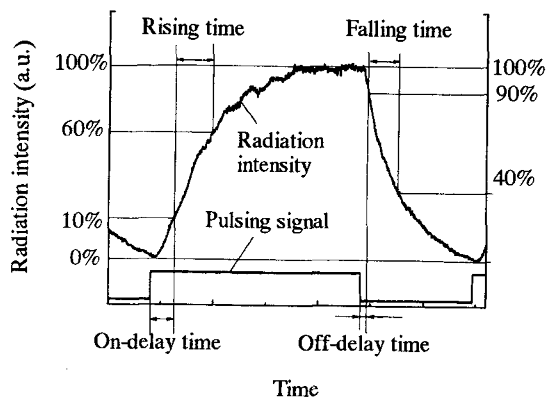

Fig.7 Definition of the characteristic times.

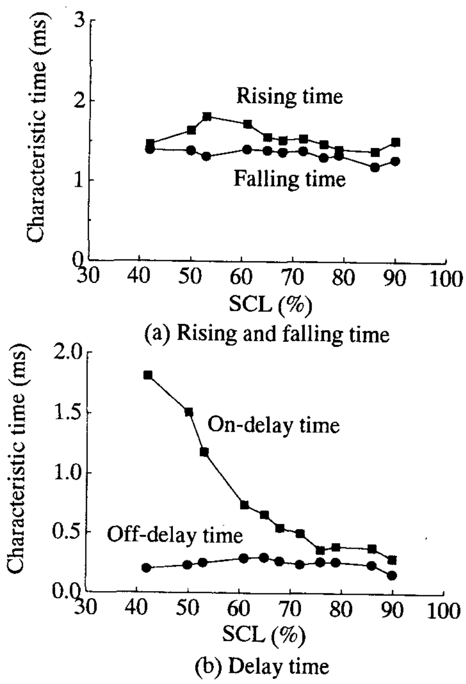

Fig.8 The effect of SCL on the characteristic times of Ar ICP at 10mm below coil end.

around 1.5 ms, 1.5 ms and 0.3 ms, respectively, almost independent of SCL. However, the on-delay time increased remarkably with reducing SCL. For example, for SCL=90 %, on-delay time is 0.2 ms while it is around 1.8 ms for SCL=45 %. This dependence on SCL is considered to arise from the following fact: Just before the on-operation, the gas temperature has lowest value during a pulse modulation cycle. On the other hand, specific heat at constant pressure per unit volume ρC_p of Ar plasma increases with a decay of temperature in the range 7000 to 3000 K[10]. This ρC_p will determine the response time of temperature variation at the observation point as seen in the energy conservation equation. Therefore, a lower SCL produces lower gas temperature just before the on-operation, and a larger on-delay time due to high specific heat. Just before the off-operation, the plasma was nearly under a steady state and has a similar gas temperature. As the result, the off-delay and falling times was unconcerned with SCL.

6. CONCLUSIONS

We have newly developed an ICP system with a MOSFET power supply, which has a function of AM modulation of the coil current. The modulation of the coil current leads the plasma to the under the transient state intentionally.

The influence of SCL(Shimmer current level), which means the ratio of the lower to higher level of the coil current, on the internal state of the pulse modulated Ar plasma was investigated. The dynamic response time including rising time, falling time, on-delay time and off-delay time of the plasma was estimated from measured radiation intensity of Ar spectral line. It was found that the lower temperature state in the plasma could be produced with remaining high temperature state by controlling the lower level of the coil current, and that the on-delay time increased with a reduction of lower current, while the rising and falling time was almost independent of it.

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