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Development of Pulse-Modulated RF Induction Plasma Reactor for Advanced Materials Processing on the Basis of *CONCERTED AMPLIFICATION*

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In order to apply the pulse-modulated RF induction plasma to the materials processing, the condition of controlled generation was tried to extend. Typically, when the Ar-H_2 plasma was generated at 750 Torr and a high power level of 17 kW, the low power level went down to about 4 kW, i.e. below 1/4 of the higher level, at which the power level of 4kW, the continuous plasma generation was unable to be sustained. The kind and concentration of chemical species in the plasma changes with time in every cycle. The increased difference between the high and lower levels was large enough to give rise to the non-equilibrium situation at the instance of pulse-on and off and the increase of chemically reactive radical species, as well as the time-dependent change of plasma temperature. Such unique condition is expected to offer the unique physico-chemical condition for materials processing. The range of stable generation was determined for Ar-H_2 and Ar-N_2 plasmas.
Key words: concerted amplification, thermal plasma processing, pulse-modulation, non-equilibrium effect.

1. Introduction

Thermal plasma is characterized by its high enthalpy and chemical reactivity, and has been used for the various kinds of materials processing. However, some disadvantages, such as radiation loss in powder processing, the damage on substrates and the grown films, come from the high enthalpy. Actually, it is too high. Some methods have been tried to reduce the influence of the high enthalpy in materials processing. The time dependent control of this work is one of the methods for controlling precisely the energy level and the kind and concentration of chemical species in plasma. The RF induction plasma of a pulse-modulated mode has been successfully generated, for the first time, with a sufficiently high electric power for materials processing[1,2]. An important thing was that the plasma temperature in the pulse-on time was almost the same as that of continuous generation. The total energy of plasma decreased, while the maximum temperature remained unchanged.

At the first stage, the steep overshoot and undershoot of the coil current wave form were recognized at the time instance of pulse on and off, giving an abnormally large current flow in the electric circuit, and some of transistors were broken. The shimmer level was introduced for decreasing the magnitude of such overshooting, and the low power level in the pulse-off period was almost 1/3 of the higher one in the pulse-on period.

In this work, the rise and decay times of RF current were made a little longer, with the intention of suppressing the overshoot and undershoot, and of lowering further the low power level.

2. Experimental

The pulsed-plasma generation and data acquisition of plasma emission is described elsewhere[1-3]. The solid state amplifier [MP-22CY, Denki Kogyo Co., Ltd.] was employed for the pulsing plasma generation. The invertor-type power source supplies the electric power of 22 kW continuously with nominal frequency of 1 MHz, and has a high electric energy efficiency up to 90%. The electric matching with a load is attained by the phase locked loop [PLL] with variable frequency and an LC matching circuit. The RF power was pulse-modulated by imposing the external pulsed signal to switch a static induction transistor[SIT]. The pulsing rise time of power source is less than 1 μs. The external signal was generated by a pulse generator [HP 8116A] with a response time of 6 ns.

The plasma torch consists of two co-axial quartz tubes[1]. Between the tubes, cooling water flows. The inner diameter of inner tube is 55 mm. The induction coil consists of thirteen turns. The large number of turn comes from the restriction of electrical matching with

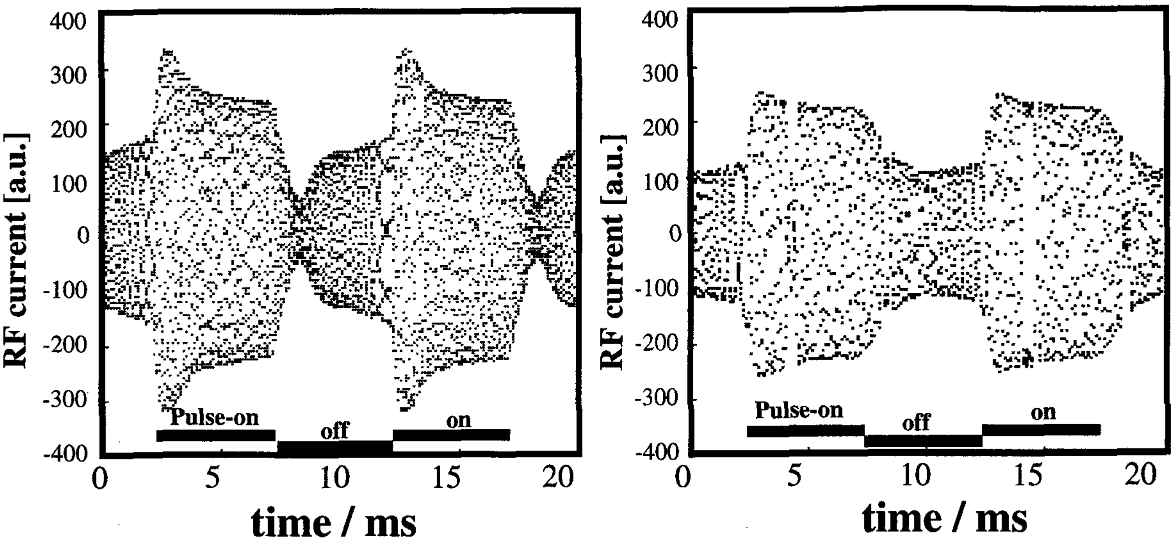

Fig. 1 Temporal change of RF current for Ar-H_2 plasma with rapid(left) and slow(right) pulse signals.

the solid state power supply. Operation conditions are as follows. The sheath gas is composed of Ar and H_2(or N_2) at the flow rate of 98 l/min and 6 l/min, respectively. The plasma was firstly generated at the continuous power level of 17 kW and the reactor pressure was controlled at 750±3 Torr. As the power source here has a high energy efficiency of 90%, the power of 17 kW corresponds equivalently to the power over 30 kW introduced by the ordinal plate-type power source, which has a relatively low energy efficiency below 50%.

The emission was taken at two positions, at the middle of RF coil and 10 mm below the bottom of the RF coil, by an optical system with a spatial resolution of 1 mm and transmitted through an optical fiber. The emission intensity monochromated by a JOBIN YVON HR-320 was detected by a photomultiplier [Hamamatsu, R1104] with a response time of 70 ns. The detected signal was stored through a digitizer [Autonics, APC 510] with a minimum sampling time of 50 ns per address.

3. Results and discussion

Figure 1 shows temporal change of RF current for the 5-ms pulse-on time and 5-ms pulse off time, that is, for the pulse duty factor (100 × [on-time] / [on-time + off-time]) of 50% with the pulsing frequency of 100 Hz. In the left-hand figure of RF current, the steep overshoot and undershoot are recognized at the time instance of pulse on and off, which gave an abnormally large current flow in the electric circuit and some of transistors were broken in the preliminary experiments[1]. In order to avoid the breakdown of transistors, the shimmer level was introduced for decreasing the magnitude of overshooting and this was set to be the current ratio as 0.6, that is, the lower power level is almost 1/3 of the higher one. For the present condition, the rise time and the decay time of RF current are 0.4 and 1.1 ms, respectively. The plasma remained stable until the pulse duty factor went down to 30 %, below which the plasma fluctuated strongly and then diminished.

In order to solve the problem of over and under shoots, the response of imposed pulse signal was made slower. The electric circuit was modified to give the relatively slow change of signal of time constant 940 μsec. By this way, it takes about 1.5 ms to go up to the higher level. In the right-hand figure, the slow response led to a little over shoot and no undershoot. Consequently, in the right-hand figure, both the rise time, 0.7 ms, and decay time, 2.4, became a little longer than those in the left-hand figure. And, the lower shimmer level went down to 48%, i.e., the power of lower level is 23%(~4kW) of higher level. Below this shimmer level, the discharges between the turns of RF coil began to occur and the plasma could not sustained. In the case of Ar-N_2 plasma, almost no overshoot was observed, and the shimmer current level was lowered to about 40%, i.e. 16%(~3kW) of the lower power level. It should be noted that, at the power level of 3 or 4kW, the continuous plasma generation was unable to be sustained.

Figure 2 shows the optical emission from atomic argon at 751 nm detected at the middle of RF coil for the relatively slow switching of the left-hand of Figure 1. The temporal change is for the case of the 10-ms pulse-on time and 5-ms pulse off time. The emission from argon atoms at the middle of RF coil showed the non-equilibrium situation induced by the rapidly increasing intensity and the sudden interruption of electromagnetic field. After the time instance of pulse-on, there is short incubation time, less than 0.5 ms, before the optical emission begins to rise up. The incubation time and the rise time became longer, when SCL is lowered and the minimum of emission became lower. The increasing emission intensity exceeded the intensity level of continuous generation, which indicates the elevated electron temperature, and the maximum of the overshoot is the higher for the lower SCL. It took another 1.5 ms for the emission to relax into the plateau, where the emission intensity was same as that of the continuous generation. During the period of plateau, the plasma would be under the quasi-equilibrated state. The exited temperature of Ar atom through a Boltzman's plot was determined only for the plateau region as 8,000-10,000 K, which was equivalent to that for the continuos generation. However, the temperature was unable to be determined in the other region due to the more scattered

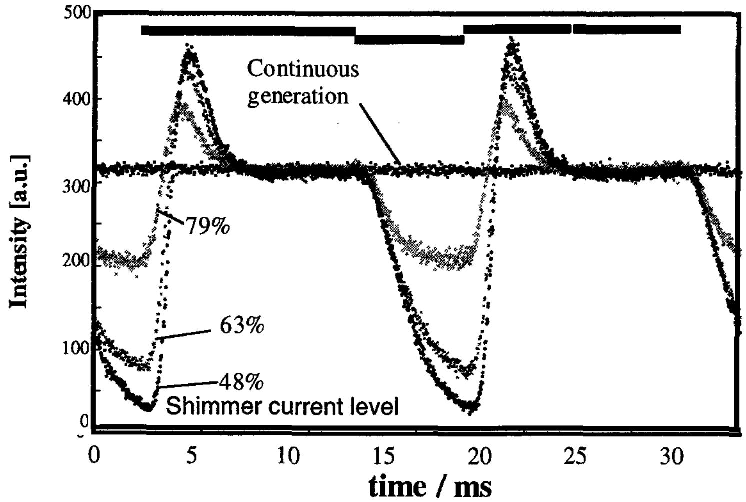

Fig. 2 Temporal change of Ar line(751 nm) emission intensity from Ar-H_2 plasma taken at the middle of RF coil for various shimmer current levels.

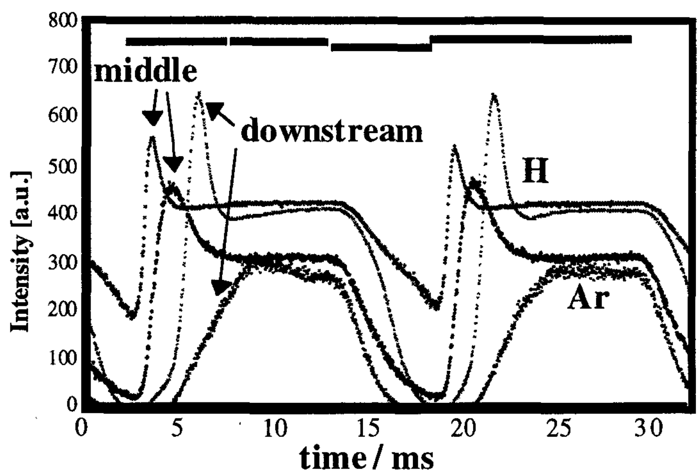

Fig. 3 Temporal change of emission intensity of Ar(751 nm) and H_α lines from Ar-H_2 plasma taken at the middle of RF coil and 1 mm below the bottom of RF coil. Shimmer current level was at 48%.

Boltzman's plot. The decay time, ~3 ms, of emission was longer than the rise time, which agrees with the theoretical prediction [4]. For the lower SCL, it is shown that the cooling rate of plasma is higher, and that the emission went down to the lower minimum. Regt et al. suggested that the interruption of magnetic field followed by the rapid cooling of plasma induced non-equilibrium condition, in temperature (T_e>T_h, where T_e and T_h indicate the temperatures of electrons and heavy particles, respectively.) and electron density[5]. All the variations, that is, the longer incubation time, the higher maximum, and the longer rise time, are probably related to the enhanced non-equilibrium condition on heating up the colder plasma.

As shown in Fig. 3, the emission from hydrogen atom also shows the overshoot with the shorter rise time, ~1 ms. It should be noted that hydrogen emission shows the overshoot even at the downstream, while the emission from Ar atoms shows no overshoot. When the plasma flow leaves from the high-temperature coil region, the temperature drops very rapidly to deviate from equilibrated concentration of chemical species. In the pulsed-plasma, the quenching effect is multiplied by the induced condition following switching-on and off. The overshoot of hydrogen emission at the downstream is higher than that at the middle of coil, which could be the evidence of overpopulated chemically reactive hydrogen atoms.

Figure 4 shows the range of stable generation for the pulsed-plasma, when the pulse-on time changes. As was predicted by numerical analysis[4], for the same length of pulse-on time, when the pulse-off time increases beyond a critical value, the plasma becomes unstable and at last diminishes. Experimentally, the plasma cannot be sustained because of the vigorous vibration and the abnormal discharges.

When the shimmer level was 60%, for the longer pulse-on time than 5ms, the plasma was stable until the pulse-off time went up to 10 ms irrespective of pulse-on time. However, in the case of short pulse-on time of 2 ms, the plasma became unstable with the relatively short

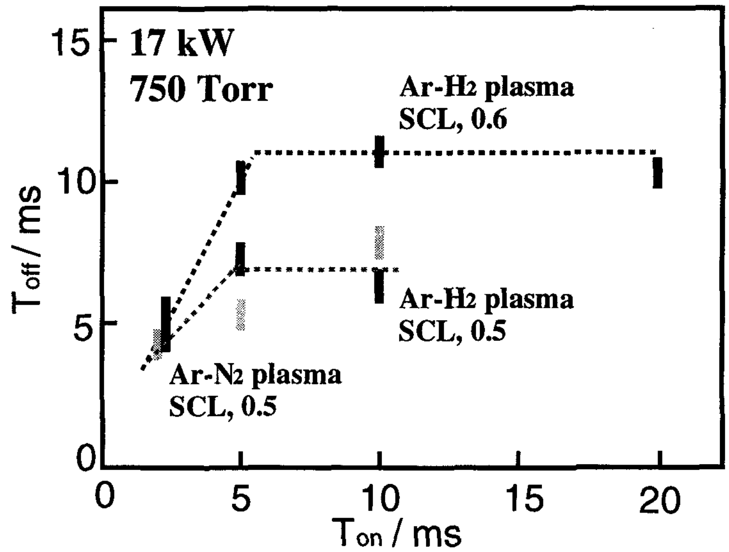

Fig.4 Stable generation range for pulse-modulated RF induction plasmas. SCL means the shimmer current level.

pulse-off time of 4 ms. In the case of the short pulse-on time, the plasma is not heated sufficiently and the stable region is limited. When the shimmer level went down to 50%, the critical pulse-off time was 6-7 ms for the longer pulse-on time(more than 5 ms) and ~4 ms for the short pulse-on time(2 ms). The shorter critical pulse-off times than those for the SCL of 50% is due to the more cooled and deviated non-equilibrium condition. Depending on the duration of pulse-on and -off times, the time dependence of optical emission changed variously. It was recognized that the duration of pulse-on and -off times as well as the shimmer current level are the important parameters, which determine the degree of deviation from equilibrated condition in thermal plasma. Because of induced non-equilibrium condition and difference in the necessary sustain power and response of plasma, controlled generation range for Ar-H_2 and Ar-N_2 plasmas varied complicatedly depending on the generation conditions.

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