Generation of high-power arbitrary-wave-form modulated inductively coupled plasmas for materials processing

著者	Tanaka Yasunori, Morishita Yu, Fushie Shunsuke, Okunaga Kyota, Uesugi Yoshihiko
journal or publication title	Applied Physics Letters
volume	90
number	7
year	2007-01-01
URL	http://hdl.handle.net/2297/6752

doi: 10.1063/1.2696885

APPLIED PHYSICS LETTERS **90**, 071502 (2007)

Generation of high-power arbitrary-wave-form modulated inductively coupled plasmas for materials processing

Yasunori Tanaka,[a] Yu Morishita, Shunsuke Fushie, Kyota Okunaga, and Yoshihiko Uesugi
Division of Electrical Engineering and Computer Science, Kanazawa University, Kakuma, Kanazawa, Ishikawa, 920-1192, Japan

(Received 9 December 2006; accepted 20 January 2007; published online 15 February 2007)

An arbitrary-wave-form modulated induction thermal plasma (AMITP) system was developed using a high-power semiconductor high-frequency power supply. The modulated high-power plasma is a breakthrough technique for controlling the temperature and the radical density in high-density plasmas. The arbitrary-wave-form modulation of the coil current enables more detailed control of the temperature of the high-density plasmas than the pulse-amplitude modulation that has already been developed. The Ar AMITP with intentionally modulated coil current could be generated at a power of 10–15 kW. Results showed that the Ar excitation temperature between the specified excitation levels was changed intentionally according to the modulation control signal. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2696885]

Recently, high-pressure high-power inductively coupled plasmas have become effective heat and chemical species sources for various materials processing such as syntheses of nanopowders[1–4] diamond films,[5] and thermal barrier coatings.[6] This has occurred because they can provide advantages of remarkably higher enthalpy and higher radical density than cold plasmas. They also cause little contamination because they use no electrodes. Nevertheless, their overly high enthalpy is difficult to control using only conventional settings of gas flow and electrical input power for thermal plasmas under steady state conditions. This uncontrollable high enthalpy is indicated as a cause of thermal damage to substrates and grown films.

To control this high enthalpy and temperature, Ishigaki *et al.* first developed the pulse-modulated induction thermal plasma (PMITP) system with static induction transistors.[7] We have also developed a PMITP system that uses metal-oxide-semiconductor field-effect transistors (MOSFETs).[8–10] These two systems can modulate the amplitude of the coil current sustaining thermal plasmas in a square wave form. This square-wave-form modulation enables us to control the temperature, chemical reaction, and gas flow fields in thermal plasmas in time domain.[11,12] Such a PMITP has attracted much attention recently as a power source for advanced materials processing. For example, Ohashi *et al.* applied a PMITP to hydrogen doping on ZnO.[13,14] Their results showed that irradiation of the Ar–H_2 PMITP can dope hydrogen atoms into ZnO and thereby improve its photoluminescence. In addition, we have continued fundamental investigations to elucidate the unique dynamic behaviors of the PMITP using experimental and numerical approaches.[12,15] These investigations revealed that coil current modulation can promote chemical and thermal nonequilibrium states, even in high-power atmospheric pressure plasmas.[12] Another important effect related to PMITP is that the modulation of the coil current can increase the nitrogen excited atom density and simultaneously decrease the heat flux, which is attributable to chemically nonequilibrium effects.[15] This fact implies that the time-domain-controlled plasma still has some potential for advanced materials processing. Therefore, we have been investigating detailed control of the temperature and densities of chemical species using a unique time-domain control technique.

In this letter, we report a developed arbitrary-wave-form modulated induction thermal plasma (AMITP) system with a fundamental frequency of 400 kHz at a rated power of 30 kW. The arbitrary-wave-form modulation of the coil current enables more precise control of the thermal plasma temperature. Actually, the Ar AMITP induced by an intentionally modulated coil current was generated at a power of 10 kW. Time evolutions in the radiation intensities of Ar spectral lines were measured to study the dynamic behavior of the AMITP. Furthermore, the Ar excitation temperatures between the specified excitation levels were simply estimated and were found to change according to the modulation control signal. There are few examples of such a high-power arbitrary-wave-form modulated inductively coupled plasma that is sustained for materials processing.

Figure 1 shows the electric circuit of a rf power supply for AMITPs. The power supply comprises four main parts: a rectifier circuit, an insulated gate bipolar transistor (IGBT) dc-dc converter (chopper) circuit, a MOSFET full-bridge inverter circuit, and an impedance-matching circuit with a

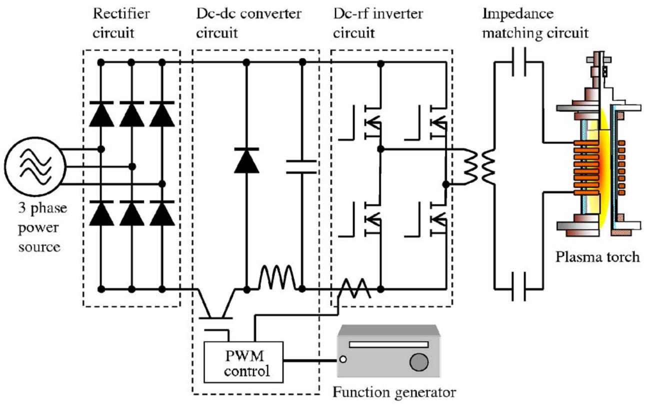
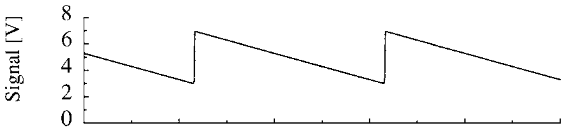


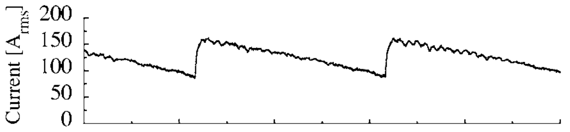
FIG. 1. (Color online) Electric circuit of rf power supply for AMITP.

---

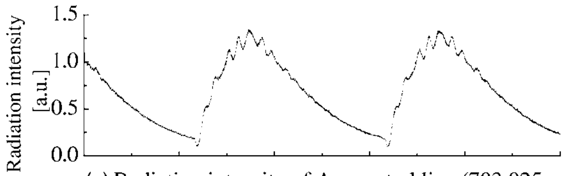
[a] Author to whom correspondence should be addressed; electronic mail: tanaka@ec.t.kanazawa-u.ac.jp



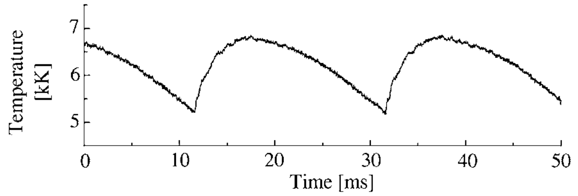
(a) Modulation control signal.



(b) Inverter output current in rms.



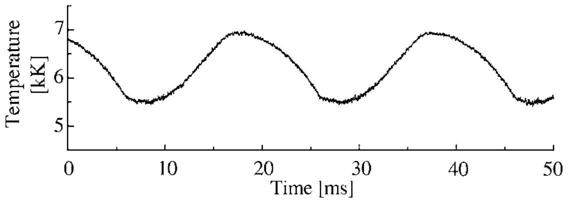
(c) Radiation intensity of Ar spectral line (703.025nm)



(d) Ar excitation temperature

FIG. 2. Time evolution in (a) modulation control signal, (b) inverter output current as a root-mean-square value, (c) radiation intensity of argon atomic line at a wavelength of 703 nm, and (d) Ar excitation temperature between levels $3p^5(^2P^0_{3/2})6s$ and $3p^5(^2P^0_{1/2})4p$ for the Ar AMITP. The modulation is made in a sawtooth wave form. The observation position of the radiation intensity and the Ar excitation temperature is 10 mm below the coil end at the center axis of the torch. The input power is 10 kW, pressure is 40 torr, and Ar gas flow rate is 80 SLPM.

(a) Modulation control signal.

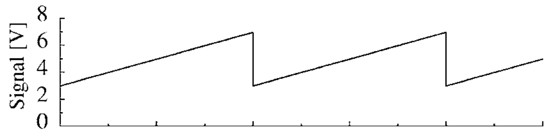


(b) Ar excitation temperature

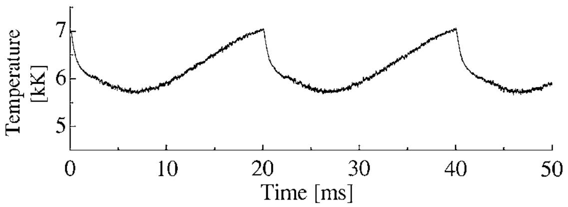
FIG. 3. Time evolution in (a) modulation control signal and (b) Ar excitation temperature between levels $3p^5(^2P^0_{3/2})6s$ and $3p^5(^2P^0_{1/2})4p$ for the Ar AMITP. Modulation is made in a triangle wave form. The observation position of the radiation intensity and the Ar excitation temperature is 10 mm below the coil end at the center axis of the torch. The input power is 10 kW, pressure is 40 torr, and Ar gas flow rate is 80 SLPM.

matching transformer and an *LC* series circuit. The frequency of the MOSFET inverter is controlled to around 350−450 kHz by a phase-locked-loop control to obtain load-impedance matching. This driving frequency around 350−450 kHz is much lower than those used in the conventional rf plasma devices. The lower frequency electromagnetic field realizes higher skin depth in the plasma, which helps to sustain a large volume plasma. In addition, the adoption of this lower frequency enables us to use the power MOSFET at low cost. The output current of the IGBT dc-dc converter circuit and therefore the amplitude of the MOSFET output rf current are controlled to fit the wave form of the modulation control signal using the pulse width modulation control method to the IGBT. The modulation control signal was made with a programmable function generator. It was confirmed through those experiments that the total energy conversion efficiency of this power supply was greater than 95% for all cases. This higher energy conversion efficiency is an advantage of using such a semiconductor power element for sustaining high-power rf plasmas.

The plasma torch has an identical configuration to that used in our previous work; its details are available in Ref. 11. The plasma torch has two coaxial quartz tubes. The inner diameter of the interior quartz tube is 70 mm, and its length is 370 mm. An argon gas was supplied as a sheath gas along the inside wall of the interior quartz tube from the top of the plasma torch. The total gas flow rate was fixed at 80.0 slpm (standard liters per minute) ($=1.33\times10^{-3}$ m^3 s^{-1}). The pressure inside the chamber was fixed at 40 torr (=5.3 kPa). This pressure is lower than atmospheric pressure, but it is similar to those adopted, for example, in plasma-spraying processing. The dc input power was fixed at 10 kW in all modulation cases. Spectroscopic observation was carried out to measure the time evolution in radiation intensities of two argon atomic spectral lines at wavelengths of 703.0 and 714.7 nm, and of the continuum at 709 nm. Subtracting the radiation intensity of the continuum at 709 nm from the measured radiation intensities at 703.0 and 714.7 nm shows the net radiation intensities of the argon atomic lines. The observation position was 10 mm below the coil end at the center axis of the plasma torch. Consequently, in this case, we measure it from the hot region of the thermal plasmas. We also estimated the Ar excitation temperature between levels as $3p^5(^2P^0_{3/2})6s$ and $3p^5(^2P^0_{1/2})4p$ from the radiation intensity of the above two argon lines using the two-line method. In general, the Ar excitation temperature can be defined if the population of the excited atoms follows the Boltzmann distribution. The Ar excitation temperature estimated in the present work is one index to express the relative population of the specified excitation levels. The electron impact exci-

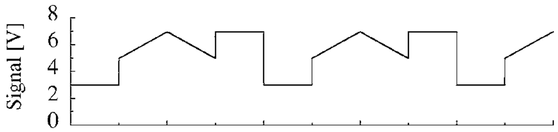


(a) Modulation control signal.

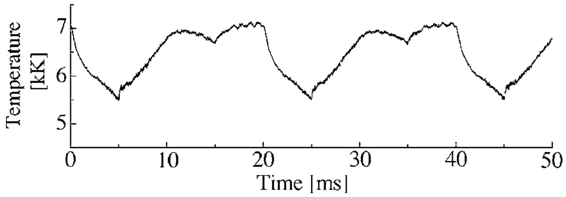


(b) Ar excitation temperature

FIG. 4. Time evolution in (a) modulation control signal and (b) Ar excitation temperature between levels $3p^5(^2P^0_{3/2})6s$ and $3p^5(^2P^0_{1/2})4p$ for the Ar AMITP. The modulation is made in a sawtooth wave form. The observation position of the radiation intensity and the Ar excitation temperature is 10 mm below the coil end at the center axis of the torch. The input power is 10 kW, pressure is 40 torr, and Ar gas flow rate is 80 SLPM.



(a) Modulation control signal.



(b) Ar excitation temperature

FIG. 5. Time evolution in (a) modulation control signal and (b) Ar excitation temperature between levels $3p^5(^2P^0_{3/2})6s$ and $3p^5(^2P^0_{1/2})4p$ for the Ar AMITP. The modulation is made in an originally made wave form. The observation position of the radiation intensity and the Ar excitation temperature is 10 mm below the coil end at the center axis of the torch. The input power is 10 kW, pressure is 40 torr, and Ar gas flow rate is 80 SLPM.

tation response time for Ar is of the order of 10^{-5} s from a simple estimation, $(\langle\sigma_{\mathrm{ex}}(v_e)v_e\rangle n_e)^{-1}$, if the electron temperature T_e is 0.5 eV and the electron density $n_e = 10^{17}\ \mathrm{m}^{-3}$, where σ_{ex} is the total cross section for electron impact excitations and v_e is the thermal velocity of the electron. The estimated excitation time is much shorter than the millisecond order of the modulation cycle that will be described later.

Figure 2 shows (a) the modulation control signal, (b) the inverter output current in root-mean-square (rms) value, (c) the radiation intensity of the argon atomic line at a wavelength of 703.0 nm, and (d) the Ar excitation temperature between the specified levels for the pure Ar AMITP. In this case, the modulation signal is an inverted sawtooth wave form. As illustrated in Figs. 2(a) and 2(b), the inverter output current with 100 A can be modulated according to the modulation control signal. This current modulation can also change the radiation intensity of the argon line, as indicated in Fig. 2(c). This change in the radiation intensity is considered to arise mainly from the following two phenomena: (i) it is caused by the change in the population of the excited atoms and (ii) it is caused by the expansion of light emitted region in the plasma, i.e., the increase in the plasma radius. A check can be made for the change in the population of the excited atoms from the estimated Ar excitation temperature in Fig. 2(d). In that figure, it is apparent that the Ar excitation temperature between the specified levels also changes consistently with the modulation control signal. The Ar excitation temperature increases rapidly from 5200 to 6700 K immediately after a rapid increase in the rms value of the rf current. After that, the Ar excitation temperature decreases gradually with time.

Similar experiments were made for other modulation wave forms to examine the temperature control of the plasmas. Figures 3–5, respectively, represent (a) the modulation control signal and (b) the Ar excitation temperature between the specified levels for the pure Ar AMITP in the cases of the triangle wave form, the sawtooth wave form, and the intentionally made wave form with the programmable function generator. Results showed that the Ar excitation temperature can be changed between 5500 and 7000 K with the modulation control signal for nearly all cases. In other words, we can control the Ar excitation temperature in time domain on the order of milliseconds. This implies that for future advanced processing, it will be possible to control the temperature of the plasma intentionally by monitoring the temperature and feeding it back to the power source.

In summary, the arbitrary-wave-form modulated induction plasmas can fine control the temperature of high-power plasmas. Furthermore, it is expected that various chemically nonequilibrium conditions can be established in the AMITP with reactive gases if the plasma has some reactions with different reaction rates. Note, for example, that reactions with only heavy particles have much lower reaction rates than reactions involving electrons. In this case, the AMITP might enhance the specified reactions with the electrons. These unique features of the AMITP can be useful for some advanced materials processing.

[1] L. Tong and R. G. Reddy, Mater. Res. Bull. **41**, 2303 (2006).
[2] J. E. Lee, S. M. Oh, and D. W. Park, Thin Solid Films **457**, 230 (2004).
[3] T. Ishigaki, S. M. Oh, J. G. Ji, and D. W. Park, Sci. Technol. Adv. Mater. **6**, 111 (2005).
[4] M. Shigeta, T. Watanabe, and H. Nishiyama, Thin Solid Films **457**, 192 (2004).
[5] J. O. Berghaus, J.-L. Meunier, and F. Gitzhofer, Meas. Sci. Technol. **15**, 161 (2004).
[6] H. Huang, K. Eguchi, and T. Yoshida, Sci. Technol. Adv. Mater. **4**, 617 (2003).
[7] T. Ishigaki, F. Xiaobao, T. Sakuta, T. Banjo, and Y. Shibuya, Appl. Phys. Lett. **71**, 3787 (1997).
[8] T. Sakuta, Y. Tanaka, Y. Hashimoto, and M. Katsuki, Electr. Eng. Jpn. **138**, 26 (2002).
[9] T. Sakuta, Y. Tanaka, K. C. Paul, M. M. Hossain, and T. Ishigaki, Trans. Mater. Res. Soc. Jpn. **25**, 35 (2000).
[10] Y. Tanaka and T. Sakuta, Trans. Mater. Res. Soc. Jpn. **25**, 293 (2000).
[11] Y. Tanaka and T. Sakuta, Plasma Sources Sci. Technol. **12**, 69 (2003).
[12] Y. Tanaka, J. Phys. D **39**, 307 (2006).
[13] N. Ohashi, T. Ishigaki, N. Okada, T. Sekiguchi, I. Sakaguchi, and H. Haneda, Appl. Phys. Lett. **80**, 2869 (2002).
[14] N. Ohashi, T. Ishigaki, N. Okada, H. Taguchi, I. Sakaguchi, S. Hishita, T. Sekiguchi, and H. Haneda, J. Appl. Phys. **93**, 6386 (2003).
[15] Y. Tanaka, T. Muroya, K. Hayashi, and Y. Uesugi, Appl. Phys. Lett. **89**, 031501 (2006).