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Numerical Investigation on $Ar/CH_4/H_2$ Induction Thermal Plasma Field with Arbitrary Power Modulation at Reduced Pressures for Diamond Film Growth

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The authors have been investigating the application of RF modulated induction thermal plasma (MITP) to diamond film growth. This MITP offers time-controlled heat and radical particle fluxes on the substrate holder. Our previous research shows that irradiation of $Ar/CH_4/H_2$ plasma at reduced pressures increases the growth rate of diamond film in the experiments [1]. In the present study, we numerically calculated the temperature, gas flow velocity fields, and mole fraction distributions of CH_4/H_2 with different modulated input power waveforms. The radical particle fluxes above the substrate holder were also calculated to consider suitable modulated input power waveforms for diamond growth at reduced pressures.

Figure 1 shows a schematic cross-sectional view of the plasma torch ($z < 330$ mm) and the chamber ($z > 330$ mm). The wall temperature was fixed at 300 K. Argon was supplied from the end of the torch ($z = 0$ mm) at 20 slpm each in the axial and swirl directions. The water-cooled tube was inserted from the top of the torch to the axial position $z = 160$ mm. Through this tube, the feedstock CH_4/H_2 gas was supplied with a flow rate of 0.02/2 slpm as a feedstock gas. The pressure in the plasma torch and chamber was set to 20 torr. Input coil power was modulated to 4 waveforms as shown in Fig. 2. Waveform (a) 7.9→7.9 kW has the rectangular waveform whose duty factor is 25%, and waveforms (b)7.9→5.6 kW, (c)6.9→4.6 kW, (d)5.9→3.6 kW have different maximum power P_{max} and minimum powers P_{min1} and P_{min2} in Fig.2. Table 1 lists the different P_{max}, P_{min1} and P_{min2}. First, the temperature, flow velocity, and mole fraction of CH_4/H_2 fields of thermal plasma were obtained by solving the coupled equations of conservation of mass, momentum, and energy, Maxwell's equation, and the transport equation of CH_4/H_2 gas on the local thermal equilibrium assumption. Then, the particle flux on the substrate ($z = 386$ mm) was calculated using the calculated temperature, flow velocity, and mole fraction of CH_4/H_2 fields, and the calculated thermal equilibrium particle composition [2].

Figure 3 shows the calculated results for temperature above the substrate holder ($z = 386$ mm). Compared to waveform (a), the temperature for waveforms (b)-(d) become kept around 3000-4000 K during lower power duration at which the high carbon radical fluxes are present according to the calculated thermal equilibrium composition [2]. Figure 4 shows that time-averaged fluxes of neutral particle above the substrate holder ($z = 386$ mm). C_2, C_2H and CH_3 are known as key species for diamond growth. Compared to waveform (a), C_2, C_2H and CH_3 fluxes were high in waveform (b)-(d) during the lower power duration.

This result shows possibility that the radical particle flux on the substrate holder contributing diamond film growth increases by decreasing input power gently from falling to rising on pulse wave whose duty factor is 25%.

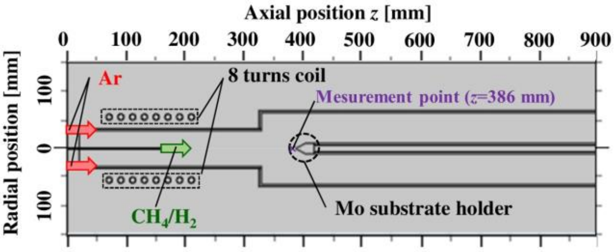

Fig.1 Calculation space.

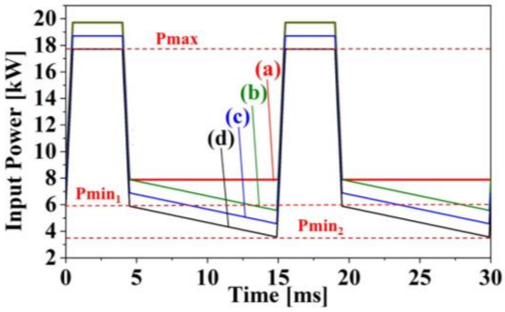

Fig.2. Modulated input power waveforms.

Table 1. Waveform condition.

	Pmax [kW]	$\mathrm{Pmin_1}$ [kW]	$\mathrm{Pmin_2}$ [kW]
(a)	19.7	7.9	7.9
(b)	19.7	7.9	5.6
(c)	18.7	6.9	4.6
(d)	17.7	5.9	3.6

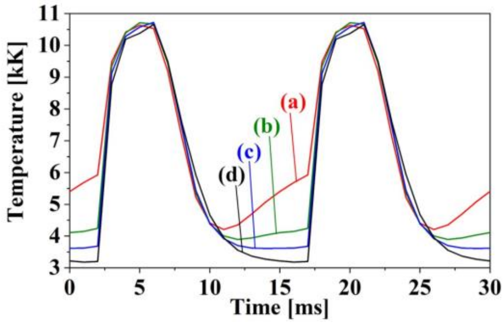

Fig.3. Temperature above the substrate holder ($z = 386$ mm) versus time.

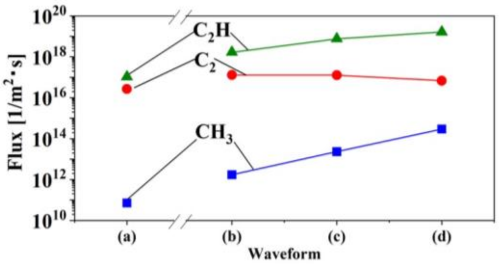

Fig.4. Time-averaged fluxes of neutral particle above the substrate holder ($z = 386$ mm).

References
[1] K. Hata, *et al.*: *J.Appl.Phys.*, **126**, 223302 (2019)
[2] K. Hata, *et al.*: *J.Phys.D:Appl.Phys.*, **54**, 195105 (2021)