Simulation Study of Microwave Microplasmas based on Microstrip Technology

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Abstract: This paper presents a three-dimensional fluid model for a low-power microwave-excited argon microstrip plasma source operated at 2.45 GHz. The gas pressures in the gas channel are 50 and 100 Torr and the input power is 2 W. Simulations are performed by the Plasma Module of COMSOL Multiphysics@. The resonance zone at which the electron density is equal to the critical density is solved by adding an effective collision frequency to the momentum collision frequency. Results show that the governed ions are atomic argon ions (Ar^+) and molecular argon ions (Ar_2^+) and the latter has a wider distribution. The electric field induced by the electromagnetic wave is concentrated in the neighborhood of the inner surface of gas channel under the microstrip line.

Keywords: Microwave plasma, Microstrip technology, Critical plasma density, 3D model.

1. Introduction

The generation of stable plasmas can be easily done using microwave generators. A large number of chemical processes make use of such plasma sources. The microstrip technology can provide a low-power electrodeless microwave-excited plasma source [1], in which the microwave power can be directed to the target area precisely, so as to allow the generation of high-density plasmas and reduce the contamination of the plasma source by sputtering electrodes. Since the microstrip technology uses a metallic wave-guiding structure on the substrate surface to transmit the microwave power to the underlying gas channel, a three-dimensional modeling will be needed, which would be computationally intensive.

In this work, a three-dimensional model is developed based on COMSOL Multiphysics@ [2]. An effective collision frequency is used to smooth the resonance zone at which the electron density is equal to the critical density. The discharge properties of argon microstrip plasmas at high gas pressures are obtained and analyzed.

2. Numerical Model

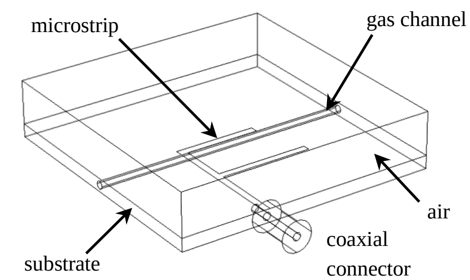


Figure 1.Schematic of a low-power microwave-excited argon microstrip plasma source.

The schematic of a low-power microwave-excited argon microstrip plasma source used in this work is shown in Fig. 1, which has been described in earlier literature [3]. A gas channel of 0.9 mm diameter and 30 mm length is embedded into the square Al_2O_3 substrate of 30 mm long and 1.5 mm height. The model also includes an air area of $30\times30\times5$ mm size. The microstrip line has a width of 0.8 mm, which is connected to a coaxial microwave connector.

The simulations for a 2.45 GHz microwave-excited argon plasma source applied by an input power of 2 W are carried out. The gas pressures are 50 and 100 Torr and the gas temperature is assumed to be 300 K. The species taken into account are electrons, atomic argon ions (Ar^+), molecular argon ions (Ar_2^+), electronically excited atoms (Ar^*), electronically excited molecules (Ar_2^*), and the background argon atoms (Ar). Dimer species are included because of the relatively high operating pressures [4]. 15 kinds of chemical reactions comprised of electron elastic scattering, electron impact ionization and excitation reactions, Penning ionization reactions, three-body reactions for dimer excited species and ion formation, quenching and de-excitation reactions are considered in this work, as listed in Table 1. The basic equations of the plasma simulations used in this research include a pair of drift–diffusion equations for the electrons, a modified Maxwell–Stefan equation for the ion and neutral species, a Poisson's equation for the space charge electric field, as well as an electro-

Table 1: The reactions included in the model.

No.	Reaction	Ref.
1	$e^- + \mathrm{Ar} \rightarrow e^- + \mathrm{Ar}$	2
2	$e^- + \mathrm{Ar} \rightarrow e^- + \mathrm{Ar}^*$	2
3	$e^- + \mathrm{Ar} \rightarrow 2e^- + \mathrm{Ar}^+$	2
4	$e^- + \mathrm{Ar}^* \rightarrow 2e^- + \mathrm{Ar}^+$	2
5	$e^- + \mathrm{Ar}^* \rightarrow e^- + \mathrm{Ar}$	2
6	$e^- + \mathrm{Ar}^+ \rightarrow \mathrm{Ar}^*$	4,5
7	$2e^- + \mathrm{Ar}^+ \rightarrow \mathrm{Ar}^* + e^-$	4,5
8	$e^- + \mathrm{Ar}_2^+ \rightarrow \mathrm{Ar}^* + \mathrm{Ar}$	4,5
9	$2\mathrm{Ar}^* \rightarrow \mathrm{Ar}^+ + \mathrm{Ar} + e^-$	4,5
10	$2\mathrm{Ar}_2^* \rightarrow \mathrm{Ar}_2^+ + 2\mathrm{Ar} + e^-$	4,5
11	$\mathrm{Ar}^* + 2\mathrm{Ar} \rightarrow \mathrm{Ar}_2^* + \mathrm{Ar}$	4,5
12	$\mathrm{Ar}^+ + 2\mathrm{Ar} \rightarrow \mathrm{Ar}_2^+ + \mathrm{Ar}$	4,5
13	$\mathrm{Ar}_2^* \rightarrow 2\mathrm{Ar}$	4,5
14	$e^- + \mathrm{Ar}_2^* \rightarrow 2e^- + \mathrm{Ar}_2^+$	4,5
15	$e^- + \mathrm{Ar}_2^* \rightarrow e^- + 2\mathrm{Ar}$	4,5

magnetic field equation for microwave heating. The detailed information for the model can be found in our previous work [6,7].

It is known that the electromagnetic wave cannot penetrate into the regions of the plasma where the electron density exceeds the critical density

$$n_e = \frac{\epsilon_0 m_e \omega^2}{e^2}, \quad (1)$$

where ϵ_0 is the permittivity of free space, m_e is the electron mass, ω is the angular frequency of the electromagnetic wave, e is the unit charge. For $\omega/2\pi$ =2.45 GHz, $n_e = 7.6 \times 10^{16}\mathrm{m}^{-3}$ [8]. A resonance zone at which the electron density is equal to the critical density is formed, *i.e.*, the electromagnetic wave transits from being propagating to evanescent in the zone. This is a non-local kinetic effect, which is difficult to be approximated with a fluid model. In this work, in order to solve the problem, an effective collision frequency is added to the momentum collision frequency ν_m:

$$\nu_m = \nu_e + \nu_{\mathrm{eff}}, \quad (2)$$

where ν_e is the collision frequency between the electrons and neutrals. $\nu_{\mathrm{eff}} = \omega/\delta$ is the effective collision frequency, in which δ is a parameter, considered as a compromise between accuracy and numerical stability.

The resonance zone is smoothed by activating the *Compute tensor plasma conductivity* function

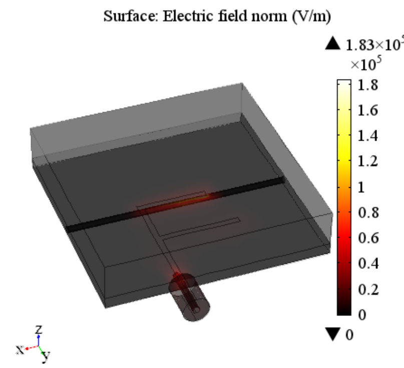
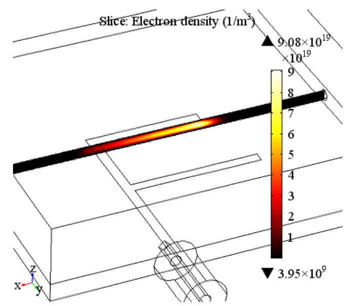
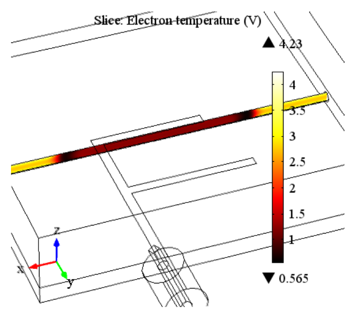


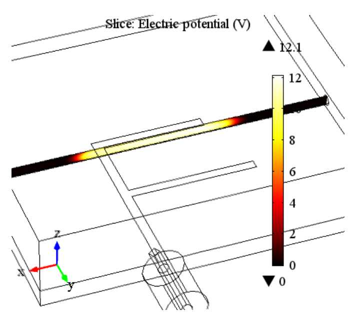
Figure 2. Electric field induced by the electromagnetic wave in a microwave-excited microstrip plasma source.



(a) Electron density



(b) Electron temperature



(c) Electric potential

Figure 3. Electron density, electron temperature and electric potential in the plasma channel of microstrip plasma source at 50 Torr.

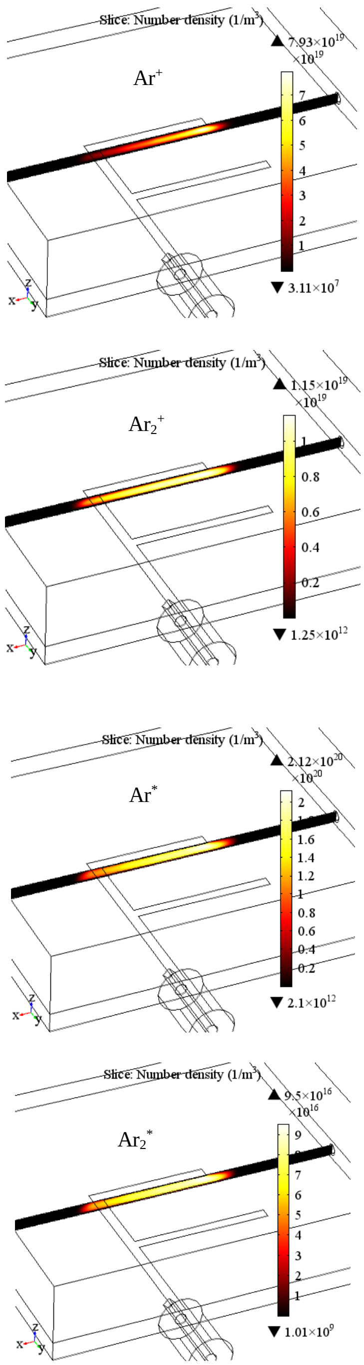


Figure 4. Densities of Ar^+, Ar_2^+, Ar^* and Ar_2^* in the plasma channel of microstrip plasma source at 50 Torr.

in the Plasma Module of COMSOL [2]. $\delta = 20$ is used as a Doppler broadening parameter in this work.

3. Simulation results

Figures 2-5 show the calculated results for a 2.45 GHz microwave-excited argon microstrip plasma source at the gas pressure of 50 Torr applied by an input power of 2 W. The number of elements of computational mesh is 122485, which is composed of 64333 tetrahedral elements and 58152 prism elements. The computational time is 35 hours and 24 minutes. The calculation is performed by means of a high performance desktop computer with an Intel(R) Xeon(R) CPU E5-1600 of 3.7 GHz and 128 GB RAM memory.

Figure 2 show the high electric field induced by the electromagnetic wave is concentrated the inlet of microwave and the area below the microstrip line. It is obvious that the microwave power is directed to the gas channel. As shown in Fig. 3, the maximum electron density arrives at 9.08×10^{19} m^{-3}, distributed below the microstrip line. The governed ions are found to be atomic argon ions (Ar^+) and molecular argon ions (Ar_2^+). It is known that Ar^+ ions are the governed ions at low gas pressures, but at high gas pressures, the three-body reaction ($Ar^+ + 2Ar \rightarrow Ar_2^+ + Ar$) becomes important [9]. Because of high argon atom density uniformly distributed in the whole gas channel, the three-body reactions cause the distribution of Ar_2^+ be much wider than that of Ar^+ (Fig. 4). Ar^* atoms are main electronically excited species, which density is much higher than Ar_2^* density. The resonance zone at which the electron density is equal to the critical density of 7.6×10^6 m^{-3}, is found to cover a large central area in the gas channel and is very close to the inner surface of the gas channel (Fig. 5). Although the electromagnetic wave transits from being propagating to evanescent in the zone, the thickness of the zone is negligible. The maximum electrical conductivity arrives at 33.5 S/m.

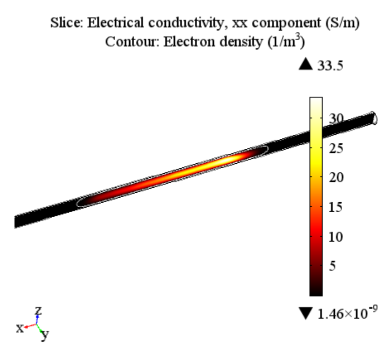
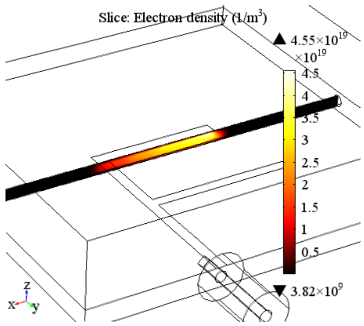
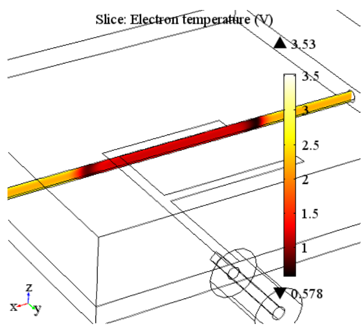


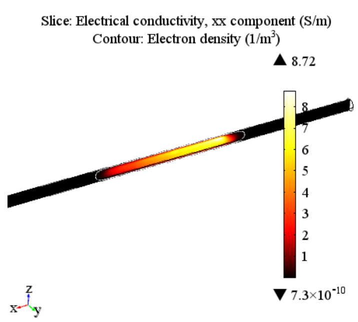
Figure 5. Electrical conductivity and critical electron density (contour) in the plasma channel of microstrip plasma source at 50 Torr.



(a) Electron density



(b) Electron temperature



(c) Electrical conductivity

Figure 6. Electron density, electron temperature, electrical conductivity (critical electron density) in the plasma channel of microstrip plasma source at 100 Torr.

The simulations for a 2.45 GHz microwave-excited argon microstrip plasma source at the gas pressure of 100 Torr are also performed. The applied input power is sustained to be 2 W. The typical calculated results are given in Fig. 6. Due to the increase of the collisions between electrons and neutrals, the electron temperature is decreased and the maximum electron density reduces down to 4.55×10^{19} m^{-3}. It is noted that the electrical conductivity at 100 Torr is much smaller than that at 50 Torr. The maximum electrical conductivity is only 8.72 S/m.

4. Conclusions

This paper presents the simulation results of a low-power microwave-excited argon microstrip plasma source. It is shown that the microwave power is directed to the gas channel. The governed ions are comprised of atomic argon ions (Ar^+) and molecular argon ions (Ar_2^+). The three-body reactions to produce Ar_2^+ ions become important at high gas pressures. A resonance zone in which the electromagnetic wave transits from being propagating to evanescent is formed. For the higher gas pressure, the electron density, electron temperature and electrical conductivity are reduced due to the increase of electron-neutral collisions.

5. References

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