Study on the formation of thin films using an rf non-thermal plasma jet at atmospheric pressure

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The deposition of thin silicon-organic films using an atmospheric plasma jet is investigated theoretically and experimentally. The interaction of gas heating and flow, generation of argon plasma in the active volume, the transport of active plasma particles into the effluent and the generation and transport of precursor fragments towards the target surface is analysed by a twodimensional axisymmetric fluid model. The calculated radial profiles of precursor reactants at the target surface are compared with measured film profiles.

The plasma in a miniaturized atmospheric pressure plasma jet (APPJ) has been investigated by a self-consistent fluid model. The APPJ is configured as a capacitively coupled capillary jet discharge [1], which is illustrated in Fig. 1. Between the outer and the inner quarz capillary, argon gas flows in the indicated direction with flow rates between 0.1 and 2 slm. A precursor mixture flows through the inner capillary, gets activated in the effluent and feeds the deposition of a layer at the substrate. Two ring-shaped electrodes are attached to the outer capillary in a distance of $d = 4.5$ mm. Between the upper electrode, driven by an rf voltage at 27.12 MHz, and the lower grounded electrode standing or rotating discharge filaments have been observed which occur as a single or multiple filaments depending on the power and flow rate [1]. The argon plasma in a single filament has previously been characterized by measurements and a fluid model [2].

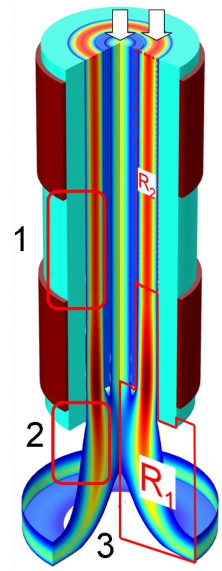

Fig. 1: APPJ with solution regions.

The present investigation is devoted to the interplay between the plasma generation in the active zone (1) where the RF power is supplied to the filament(s), the transport of active plasma particles due to the gas flow into the effluent (2), their reaction with the precursor and the transport of precursor fragments towards the target (3). In the effluent, the precursor is dissociated due to collisions with active species of the argon plasma into various fragments which undergo further reactions. Here, for simplicity, only a lumped reaction of the precursor with active argon species has been taken into account and the transport of the reaction products to the target has been investigated.

To determine the density of active species a plasma model is solved in region R_1. The model includes particle balance equations for electrons, atomic and molecular argon ions, argon atoms excited into a lumped metastable, a lumped resonant and higher states as well as excimer molecules in triplet and singlet states. Furthermore, the electron energy balance equation, Poisson equation and balance equations for charges on the dielectric interfaces have been solved. The rate coefficients of 19 collisions between electrons and heavy particles as well as the electron transport coefficients were determined by solving the 0d Boltzmann equation and used as functions of the mean electron energy. In addition, 15 heavy particle reactions are included. The heating of the electrons is described by a source term in their energy balance equation with a spatial profile limited to the position of the filaments. The gas flow and gas temperature in region R_1+R_2 has been determined by solving the Navier Stokes and the heat balance equations taking into account the gas heating by the filament.

Figures 2a-f show some results obtained with average velocities of 0.5 m/s in the inner and 1.0 m/s in the outer capillary. The electrostatic potential (Fig. 2a) constitutes a confinement of the charge carriers in the filament of about 14 V with an opening in downstream direction. Ground potential was assumed at z=12 mm and the surface charge density was used to specify the electric field at the dielectric surfaces of the capillaries and the target. The particle density of Ar_2^+ (Fig. 2b), which is similar to the electron density, exceeds $10^{18}m^{-3}$ in the filament and reaches values of about $10^{16}m^{-3}$ at the outlet of the outer capillary (z=6 mm). Figures 2d and 2e show axial and radial profiles of the charge carriers and of excited species. Due to the rapid conversion reaction $Ar^+ + 2Ar \rightarrow Ar_2^+ + Ar$ the dominant ion is Ar_2^+ everywhere. The excimer $Ar_2(^3\Sigma_u^+)$ and metastable atoms are strongly excited in the filament region but get strongly depleted in downstream direction due to rapid loss processes. The decrease of the densities of electrons and molecular ions, which are obviously the dominant active species in the effluent, is much less pronounced. Consequently, the reaction $Pc + Ar_2^+ \rightarrow RP + Ar$ of the precursor Pc with molecular argon ions was considered as source of the reaction products RP. These products are generated in the mixing zone and flow towards the target as shown in Fig. 2c. Their radial density profile at the target, as shown in Fig. 2f, qualitatively agrees with the measured thickness profile of footprints [3].

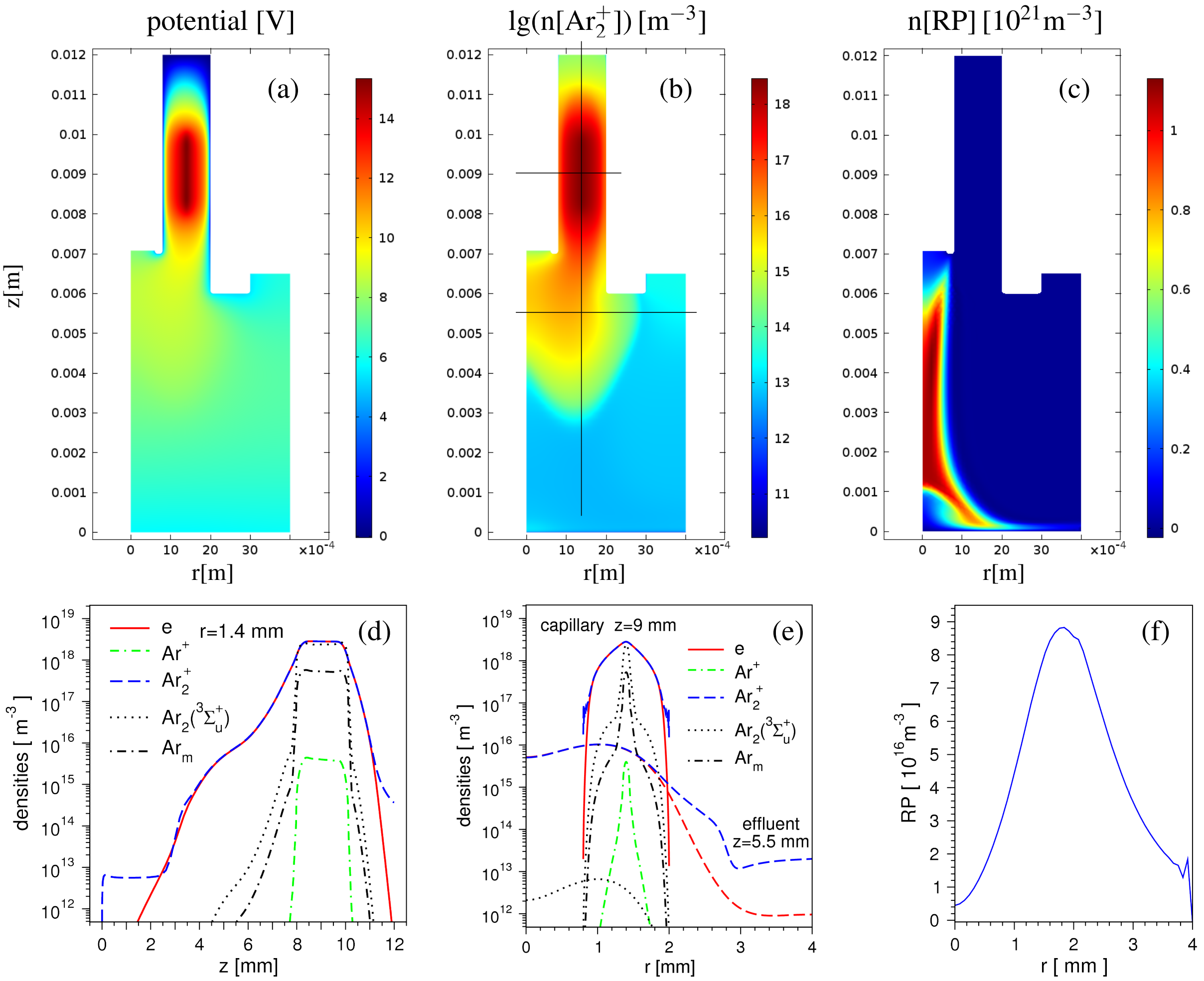

Fig. 2: Top: electric potential (a) and densities of Ar_2^+ (b) and precursor fragments RP (c); Bottom: particle densities along the indicated line in axial (d) and radial (e) direction, densities of the precursor fragments RP at the target surface (f).

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References

[1] J. Schäfer, R. Foest, A. Ohl, K. Weltmann, *Plasma Phys. Control. Fusion* **51** (2009) 124045

[2] J. Schäfer, F. Sigeneger, R. Foest, D. Loffhagen, K. Weltmann, *Eur. Phys. J. D* **60** (2010) 531

[3] J. Schäfer, R. Foest, A. Quade, K. Weltmann, *J. Phys. D* **41** (2008) 194010