Heavy particles and rate coefficients in HF and MW discharges in Argon at atmospheric pressure

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Density profiles of the plasma constituents – excited species and ions as well as the rate coefficients of the main elementary processes in the gas discharge are obtained on the base of a self-consistent numerical model of Argon surface-wave-sustained discharge. Their dependence on the gas discharge conditions is also shown.

1. General

Surface-wave-sustained discharges (SWDs) have been studied both theoretically and experimentally in the last 40 years. They have the ability to work in wide range of discharge conditions: frequencies from MHz to GHz, gas pressure from mTorr to several atm, discharge radius from µm to several cm, discharge length from mm to several m, working gas – rare, molecular gasses and arbitrary mixtures. The wide interest in SWDs results from the increasing number of applications they have found in various fields, like technology [1], medicine [2,3], etc. The latest applications demand the plasma sources to be small, inexpensive and to have sufficiently high concentration of charged particles and chemically active species. Moreover applications like medical plasmas need to be sustained in open air, and to have considerably low gas temperature. Adequate solution to the above requirements is offered by the atmospheric pressure SWDs. In these kind of discharges the plasma is sustained by travelling electromagnetic wave excited by a wave launcher situated at one end of a plasma column. The wave propagates along the plasma–dielectric interface and heats the electrons. Absorbing the wave energy the electrons are able to create and sustain plasma by collisions.

However practical applications require detailed knowledge of the discharge characteristics on the discharge conditions, more precisely density profiles of the plasma constituents – electrons, excited species and ions as well as the rate coefficients of the main elementary processes in the gas discharge. Such knowledge can be provided in economical and reliable way by a self-consistent model. The model consists of two parts – electrodynamics of the wave sustaining the discharge coupled to plasma kinetics [4]. Basis of the kinetic model are Boltzmann's equation, particles balance equations and energy balance equations. The model is applied to Argon plasma at atmospheric pressure.

At atmospheric pressure complicated argon energy level diagram should be considered and a lot of elementary processes should be taken under consideration. The following species are included in the argon energy level diagram at atmospheric pressure model: Ar, Ar(4*s*), Ar(4*p*), Ar(3*d*), Ar(5*s*), Ar(5*p*), Ar(4*d*), Ar(6*s*), Ar_2^*, Ar^+, Ar_2^+, and Ar_3^+ (Fig. 1). All these excited states are considered as blocks of levels with effective energy $u_k = \sum_{j=1}^{m} u_{k,j} / m$ where $u_{k,j}$ is the energy of each level in the block k and m is their number. In all calculations the averaged population is used.

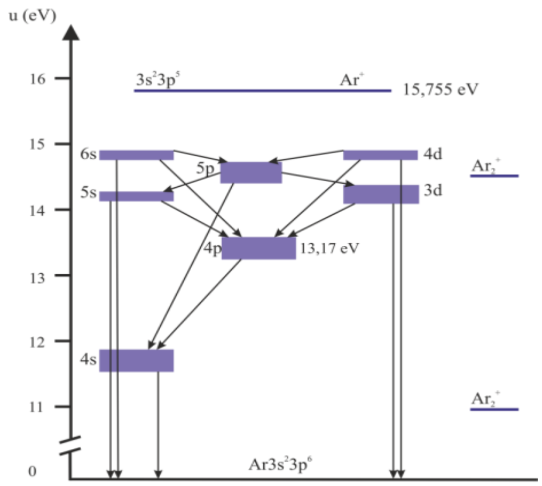

Fig. 1. Argon energy levels diagram

The electron energy distribution function (EEDF) obtained from Boltzmann equation is not-Maxwellian in wide range of discharge conditions. It is used for obtaining the electron transport parameters, the rates of elementary processes, and several other key quantities such as the effective electron-neutral collision frequency for momentum transfer ν_{eff} and the mean power θ.

2. Results

In this work results for the rate coefficients for direct and stepwise ionization and excitation, the electron-neutral collision frequency, the excited atoms population and the ions densities are presented. The numerical calculations are conducted at the following discharge conditions: plasma with radii 0.05 cm, 0.1 cm and 0.2 cm sustained by surface wave of frequencies 2 GHz, 1.5 GHz, 1 GHz and 0.5 GHz.

In Fig. 2 the energy dependence of the rate coefficients for direct and stepwise ionization are presented. The ionization from 4d Argon level has highest rate coefficient while the direct ionization coefficient is four orders lower and is the smallest one.

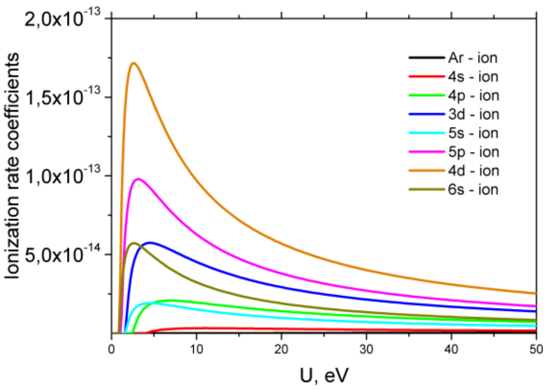

Fig. 2. Rate coefficients for direct and stepwise ionization

At high energy the rate coefficients for ionization decrease because intensive excitation processes occur at these energies. The rate coefficients for direct excitation (Fig. 3) are lower than those for stepwise excitation (Fig. 4). As one can expect the highest rate coefficient for direct excitation is for 4s level and the lowest is for 6s level.

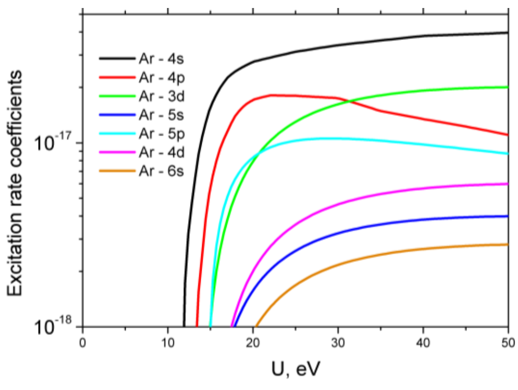

Fig. 3. Rate coefficients for direct excitation

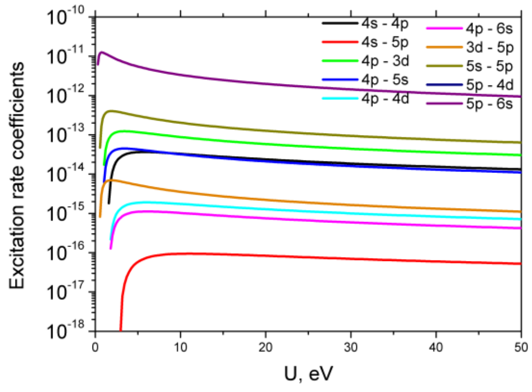

Fig. 4. Rate coefficients for stepwise excitation

The behaviour of the rate coefficients for direct excitation with the energy increasing is different for the 4p and 5p levels in comparison to the group of s and d levels. The rate coefficients for stepwise excitation (Fig. 4) are almost constant (slightly decreasing) with the energy. The highest rate coefficient is 5p to 6s excitation and the lowest rate coefficient is 4s to 5p excitation.

Electron—neutral collision frequency for momentum transfer is obtained from the model at various wave frequencies and plasma radii. Its dependence on the electron number density is presented in Fig. 5. One can see from Fig. 5 that with wave frequency increasing electron—the neutral collision frequency increases at higher plasma density. The observed dependence is better defined at low wave frequency and abates with the increasing of the wave frequency. The effect of the plasma radius on the electron—neutral collision frequency is shown on Fig. 6. The results indicate insignificant influence of the plasma radius on the investigated plasma parameter.

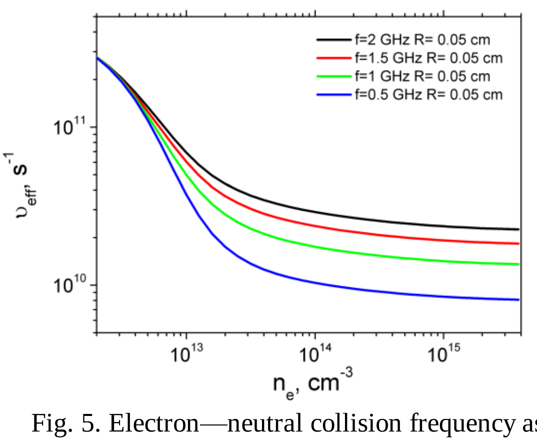

Fig. 5. Electron—neutral collision frequency as a function of plasma density for different wave frequency and radius 0.05 cm.

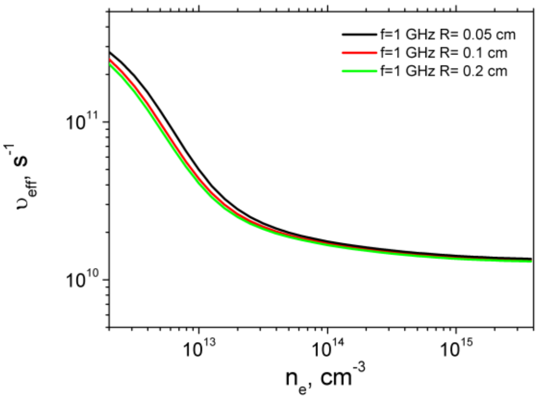

Fig. 6. Electron—neutral collision frequency as a function of plasma density for different radius and wave frequency 1 GHz.

In Fig. 7 the behaviour of Argon excited states population as function of plasma density is preserved. The solid lines correspond to wave frequency 1 GHz and plasma radius 0.05 cm and the dashed lines to wave frequency 1 GHz and plasma radius 0.2 cm. The effect of plasma radius is very small and mainly at low plasma density. The most populated is Ar 4s state followed by Ar 4p while the less populated state is 6s. The population of all levels increases with the plasma density.

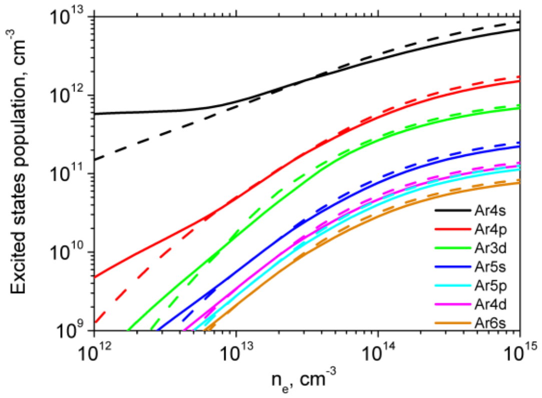

Fig. 7. Argon energy excited states population.

The Argon ions included in the model are Ar^+, Ar_2^+ and Ar_3^+. The argon molecule Ar_2 is also taken into account. The concentrations of Ar ions and the molecule are presented in Fig. 8. The solid lines correspond to plasma radius 0.05 cm, the dashed lines to plasma radius 0.1 cm and the dotted lines to plasma radius 0.2 cm. At high plasma density the highest concentration has the Ar^+ ion while at low plasma density the Ar_2^+ is the most important ion. a A maximum of the Ar_3^+ ion concentration can be observed at 10^{14} cm^{-3} plasma density. The concentration of argon molecule decreases with the plasma density increasing. The effect of the plasma radius is significant for Ar_2 and Ar^+ concentration at low plasma densities while no influence can be observed on Ar_2^+ and Ar_3^+ densities. (Fig. 8).

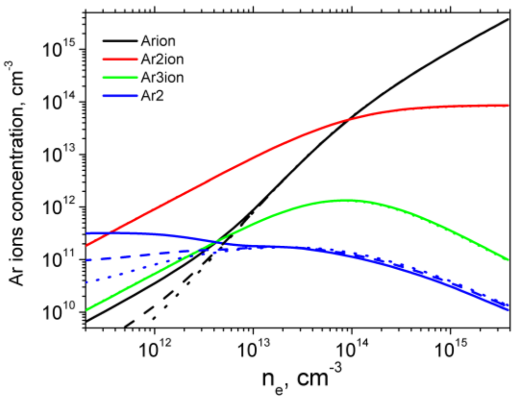

Fig. 8. Argon ions and Ar molecule concentration.

3. Conclusion

Argon plasma column at atmospheric pressure sustained by travelling electromagnetic surface wave is theoretically studied by means of a self-consistent model.

The kinetic part of the model gives the plasma characteristics: electron—neutral collision frequency, the rate coefficients of the main elementary processes in the gas discharge, excited species concentrations and ions concentrations. The influence of the plasma parameters on the argon ions density, excited argon atoms density and electron–neutral collision frequency has been studied.

In the argon energy levels population the influence of the plasma radius is observed at low plasma densities. For the electron neutral collision frequency strong influence on the wave frequency at high plasma density and no dependence of plasma radius are obtained.

4. References

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