Study of radial profiles of the Ar metastable atom population in a dc glow discharge by means of spectrometric measurements and 1D kinetic model

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Radial profiles of the Ar metastable atom density in a dc glow discharge in argon were studied both experimentally and theoretically in a wide range of gas pressures and discharge currents. In the experiments the dc discharge was maintained in cylindrical tubes fabricated from Pyrex and molybdenum glass for two cases: clean inner tube surface and inner surface preliminary covered with carbonitride or carbonic film. The calculations were performed using the self-consistent 1D axial-symmetric discharge model, boundary condition for the equation of metastable atom number density was varied by changing the value of the reflection coefficient.

1. Introduction

To the best of our knowledge the radial profiles of the argon metastable atom density in dc glow discharge were studied mainly theoretically. In the present paper the radial profiles were studied both experimentally and theoretically in cylindrical discharge tubes with a radius of R = 2 cm in a wide range of gas pressures (P = 0.1 Torr – 10 Torr) and discharge currents (I = 10 mA - 50 mA).

The aim of the present work was twofold: (1) to study variation of radial profiles with gas pressure; (2) to evaluate the reflection coefficient of argon metastable atoms from clean tube surface and the surface covered with carbonitride or carbonic film.

2. Experimental setup and procedures

The population of the metastable states was measured using optical absorption technic. The experimental setup consisted of two aligned identical discharge tubes filled with argon at equal pressures, the discharge currents in the tubes were set equal. Discharge tubes with a discharge zone of 40 cm made of molybdenum-glass or Pyrex were utilized. The cylindrical electrodes were installed in the side arms of the tubes. Plasma radiation emitted from the first tube was modulated by a chopper and separated in the longitudinal direction at different radii by thick opaque screen with a set of ~0.7-mm-diameter apertures arranged along the tube radius. Then, the radiation was directed to the second tube, where the density of metastable atoms was determined from the coefficient of radiation absorption. To obtain the required spatial resolution (~ 1 mm), a thin screen with apertures placed coaxially with those of the first screen was installed after the second discharge tube. Then, the radiation passed through a chosen aperture was focused onto the spectrometer slit. The signal from the spectrometer arrived at the input of a narrowband amplifier, which made it possible to improve the signal-to-noise ratio and separate radiations emitted by the first and second tubes. The density of metastable atoms was determined from the coefficient of radiation absorption in the second tube measured for the most intense transitions with wavelengths in the range of 697–811 nm (4p – 4s transitions).

The magnitude of the electric field in the positive column of discharge was calculated from the measured voltage drop across the discharge gap and the electrode voltage falls. Additional experiments were performed to determine the gas temperature in the tube. In this case, a small admixture (<0.01%) of CO (which did not affect the electric parameters of discharge), was added to argon and the rotational temperature of CO molecules measured by using the unresolved rotational structure of the bands of the Angstrom system.

To study how the state of the tube wall affects the radial profiles of metastable atoms, experiments with discharge tubes whose inner walls were covered with carbonitride (CNx) film or amorphous carbon were also performed. Note that the presence of a film on the tube wall did not affect the electric parameters of the discharge.

To deposit the carbonitride film a discharge in a molybdenum-glass tube was ignited in the flow of a He–N_2–CH_4 gas mixture [1]. To cover the tube wall with a carbon layer, a discharge in a He–5%CO mixture was used. The thickness of the deposited films was about 1-μm.

3. Kinetic model

The plasma parameters in the positive column of a glow discharge in argon were calculated using the one-dimensional (along the radius of the tube) kinetic model [2]. The model includes balance equations for charged species, a system of kinetic equations for populations of electronic states, an equation for the gas temperature and an equation for the electric circuit. Rate coefficients for electron-induced processes and electron transport coefficients were calculated by solving the electron Boltzmann equation.

In the model the four lower levels ($1s_5$ and $1s_3$ metastable levels and $1s_2$ and $1s_4$ resonance levels in the Paschen notation) were taken into account separately, and the higher states were combined into three effective levels.

In paper [2], the density of metastable atoms near the wall surface was assumed to be zero. In the present work, the model was modified so as to take into account the reflection of excited atoms from the wall. This was done by imposing appropriate boundary conditions obtained on the basis of the kinetic theory of gases (see, e.g., [3]),

$$R\left(\frac{\partial M(r)}{\partial r}\right)_{r=R} = \alpha M(R), \quad \alpha = \frac{R v_{\mathrm{th}}}{2D}\frac{1-K}{1+K},$$

where M is the density of metastable atoms, r is the coordinate along the radius of the tube, D is the diffusion coefficient of metastable atoms, v_{th} is their thermal velocity, and K is the coefficient of the reflection from the wall without loss of excitation.

4. Results and discussion

The measured radial distributions of the density of metastable atoms for molybdenum-glass and Pyrex tubes coincided within measurement errors. It was found that at higher pressures (5-10 Torr) the results of modelling (the value of the electric field in the positive column, the gas temperature on the tube axis and the populations of metastable states) agree well with the experimental data. It is illustrated by fig. 1 where the measured and calculated radial profiles of $Ar(1s_5)$ atom density are shown. One can see that, at $P = 7$ Torr, the measured density profiles of metastable atoms for the clean tube and the tube whose wall is covered with a film are nearly the same within experimental errors. The calculated profiles are changed negligibly with variation of reflection coefficient.

At low pressures the difference between measured and calculated parameters becomes more substantial. For example, at $P = 0.1$ Torr and $I = 12$ mA the calculated density of $Ar(1s_5)$ atoms on the tube axis is 3.7 10^{11} cm^{-3}, while the measured density is 1.7 10^{11} cm^{-3}. At $P = 0.1$ Torr the use of tube whose inner wall is covered with a film leads to reduction (as compared to the case of a clean tube) in the density of $Ar(1s_5)$ atoms near the wall. In simulations the density of $Ar(1s_5)$ atoms near the wall depends on the used reflection coefficient. These facts are illustrated by fig. 2, where normalized measured and calculated profiles are shown. By comparing the calculated and experimental results shown in fig. 2 the value of the reflection coefficient can be roughly evaluated. Taking into account the measurement errors, $K = 0.4\pm0.2$ (clean glass surface) and $K < 0.2$ (tube wall covered with a film). The value of K for a clean glass wall agrees with the data from [3].

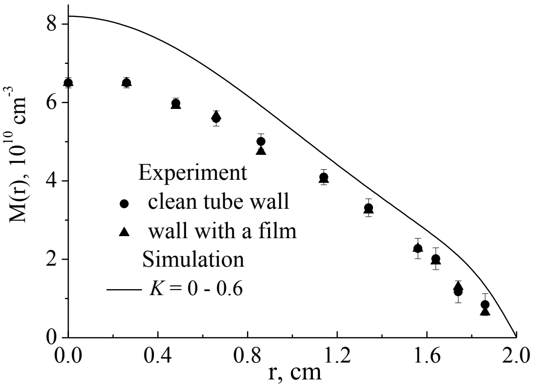

Fig. 1. Measured and calculated radial profiles of $Ar(1s_5)$ atom density. $P = 7$ Torr, $I = 12$ mA.

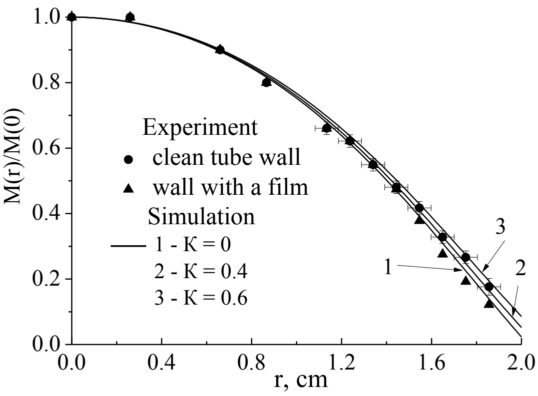

Fig. 2. Measured and calculated normalized profiles of $Ar(1s_5)$ atom density. $P = 0.1$ Torr, $I = 12$ mA.

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5. References

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