Investigation of Light Source Wall Cleaning Methods by Means of HF Plasma[1]

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Abstract – This work is devoted to the investigation of different glass cleaning methods by means of a high-frequency (about 100 MHz) electrodeless discharge plasma mainly for the light source technology needs. For experiments the helium discharge was used in the pressure range $0.2 < p < 7$ Torr. The lamp vessel training efficiency was investigated using emission spectroscopy. The spectra of pollution elements and helium lines were registered using different cleaning methods in dependence on the helium pressure and the discharge power. In addition, a stationary collisional-radiative model for helium high frequency electrodeless discharge was developed. Results of the calculations are compared with experimental results. Important plasma parameters, such as electron temperature, absorbed power, spectral line intensity versus discharge current, are estimated.

1. Introduction

An interaction of the plasma with surrounding glass or quartz walls is a very important problem in a vast of applications, especially in the light source industry. Very different fillings were used in the lamps and the problem of interaction of discharge plasma with the walls as well as a penetrating of atoms through the lamp wall is very important Electrodeless discharge plasma sources are well suited for investigations of this interaction because of the luck of electrodes, which are an additional source of the impurities in the plasma. Our research is concerned with the high-frequency (HF) electrodeless plasma source preparation for different applications [1, 2]. The interaction of different type of plasma with a glass or quartz surfaces has been investigated. In this work, the helium high-frequency discharge sources were prepared and investigated using different glass wall cleaning methods.

2. Experimental Results

For the diagnostics of interaction between filling element and glass walls of the discharge source, we have prepared cylindrical high-frequency electrodeless light sources, filled with pure helium. Helium pressure was changed in the range of 0.2–7 Torr. The lamps were placed into the coil of a high-frequency generator and an inductively coupled discharge was exited by means of a HF field of about 100 MHz frequency. Emission spectra in the spectral range from 300–800 nm, emitted from the cylindrical discharge lamps were registered. An example of registered spectrum, emitted from a helium high-frequency electrodeless discharge is shown in Fig. 1.

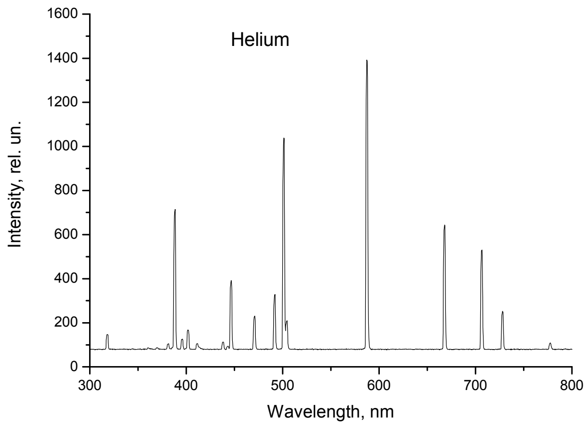

Fig. 1. A spectrum example of Helium high-frequency electrodeless discharge

For efficiency control of the concrete glass wall cleaning technique, we used intensity measurements several helium spectral lines. The spectral line intensities were registered in dependence on both, the helium pressure in the light source and discharge power, controlled by the discharge current. Three different light source-cleaning methods were compared: 1) vacuum-thermal cleaning; 2) source cleaning by means of a helium discharge; 3) by means of a krypton discharge.

We can see that in the cleaned light sources, using a discharge, helium spectral line intensities are about two orders higher as in light sources, prepared without cleaning. The higher He line intensities in Fig. 2 show that the cleaning by means of krypton discharge is more effective as the cleaning method by means of helium. The intensity dependence on discharge current without training shows only a little change (Fig. 2,

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line 1). In this case, the concentration of admixtures, coming out from the walls of source, is to high and therefore helium line intensities show only a slow decrease.

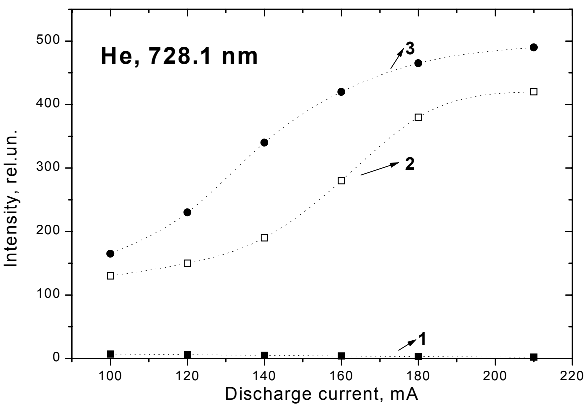

Fig. 2. Helium 728.1 nm spectral line intensity, emitted from pure He light source, as a function of discharge current for 1 – source cleaned by vacuum-thermal method, 2 – source cleaned using He-discharge, 3 – source cleaned using Kr-discharge

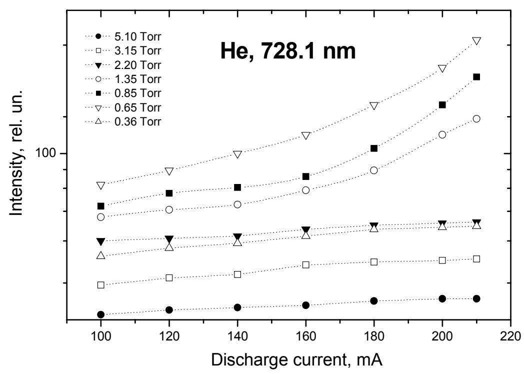

Fig. 3. Helium 728.1 nm spectral line intensity versus discharge current for He HF light source by different He pressures

In Fig. 3 is shown the helium 728.1 nm line intensity as a function of the discharge current by different helium pressures. The significant changes of spectral line intensities for He, we can observe in the light sources within quit small He pressure range of 0.65–1.35 Torr only. For the commercial application of light sources, most important is H-discharge. In our case, the necessary conditions for H-discharge are fulfilled when the discharge current is higher as 160 mA and He pressure in the light source is in the range of 0.65–1.35 Torr. This is just the region, in which the sharp changes of the spectral line intensities of helium are observed.

3. Theoretical High-Frequency Electrodeless Plasma Modeling and Validation

A stationary collisional-radiative model for helium high-frequency electrodeless discharge is developed by coupling transport equations for the electrons, atomic and molecular ions, the electron energy balance equation, the rate balance equations for the excited states and the electromagnetic field equations [3]. It is assumed that the discharge is supported in a tube of radius $R \sim 1$ cm and is represented by an infinitely long cylinder placed inside a solenoid. The plasma is assumed to be homogeneous along the z axis and the parameters are assumed to depend on the radial coordinate r. The basic system of equations can be written as follows:

1. The electron transport equation

$$\frac{\partial n_e}{\partial t} = D_{am}\nabla^2 n_e + S_e n_e + S_a n_a n^* - \beta n_i n_e^2 - \alpha n_M^+ n_e. \quad (1)$$

Equation (1) describes the process of ambipolar diffusion, the term ∇^2 is the Laplace operator; D_{am} being an appropriate diffusion coefficient; n_e, n_a, n^* and n_M^+ are the electron, ground state atom and metastable atom densities and n_M^+ is the molecular ion density. S_e is the total collisional rate coefficient for ionization, S_a is the associative ionization rate coefficient, β is the three-body recombination coefficient and α is the dissociative recombination rate coefficient. The total electron ionization rate coefficient is presented in the form

$$S_e = \sum_m n_m WI_m, \quad (2)$$

where n_m is the population density of the m-th excited state; $WI_m = <\sigma_m v_e>$ is the electron collision rate coefficient for ionization of the state m; σ_m is the ionization cross-section for level m and $<\ldots>$ stands for averaging over the Maxwellian electron velocity v_e distribution. Other parameters such as WI_m, S_a, β, α were taken from [4–7]. The assumption of the Maxwellian distribution function is justified in the situation with the distinct skin effect, since the high-frequency field is located in the narrow skin depth δ, $\delta << R$ and electron-electron elastic collisions promote the Maxwellian distribution.

2. The electron energy balance

$$\frac{3}{2}\frac{\partial}{\partial t}(n_e k T_e) = div(q_T) + S^+ - S^-. \quad (3)$$

In Eq. (3) q_T defines the total: conductive and convective fluxes of electron heat; S^+ is the term corresponding to joule heating; S^- is the sink term for cooling of the electron gas due to inelastic collisions with atoms. Our estimations and previous numerical calculations have shown that electron temperature T_e is almost constant over the whole tube cross-section.

3. The population density balance equations

The rate equations for given excited states account for the production and destruction of that states as a result of collisional and radiative processes

$$n_m\{\sum_{k\neq m} W_{mk}n_e + WI_m n_e + \sum_{k<m} A_{mk}\theta_{mk}\} -$$
$$-\{\sum_{k\neq m} W_{km}n_k n_e + \sum_{k>m} A_{km}\theta_{km}n_k\} = 0. \qquad (4)$$

The Einstein coefficients A_{mk} and electron collision rate coefficients W_{mk} and WI_m were adapted to the "block" structure of the atom model. θ_{mk} is an escape factor which takes into account the effect of radiation imprisonment and is mainly dependent on the optical thickness.

4. The molecular ions transport equations

$$\frac{\partial n_M^+}{\partial t} = D\nabla^2 n_M^+ + S_a n_a n^* + \eta n_e n_a^2 - \alpha n_M^+ n_e, \qquad (5)$$

where n_M^+ is the molecular ion density, D is the corresponding diffusion coefficient; η is the three body ionic conversion rate coefficient; α is the dissociative recombination rate coefficient.

5. The Maxwell equations were presented in the form

$$\Delta H_z - iH_z/\delta^2 = 0; \qquad (6)$$

$$\mathrm{rot}H_z = 4\pi\sigma_c E_\varphi / c. \qquad (7)$$

Here Δ is the Laplace operator in a cylindrical coordinates; δ is the skin-depth length; σ_c is the conductivity of plasma. Eq. (6) was solved numerically by matrix sweep procedure.

Iterative algorithms were used for solving the complete equation system. Several calculations were performed to test the model. For experimental validation the helium HF EDL was used. The typical operating conditions were the following: the gas pressure $0.1 < p < 10$ Torr, the frequency of the applied electromagnetic field of app. 100 MHz, the tube radius $0.3 < R < 1.5$ cm.

The electron temperature reaches rather high values in the low-pressure region and decreases at increasing pressure. This is in a good coincidence with the experimental data that higher levels are better exited by lower He pressures. Good agreement between experimental results and calculations were obtained for the dependence of spectral line intensity as a function of the discharge pressure and power.

In Fig. 4 is plotted the calculated intensity of the 728.1 nm line versus the magnetic field amplitude for different values of the gas pressure.

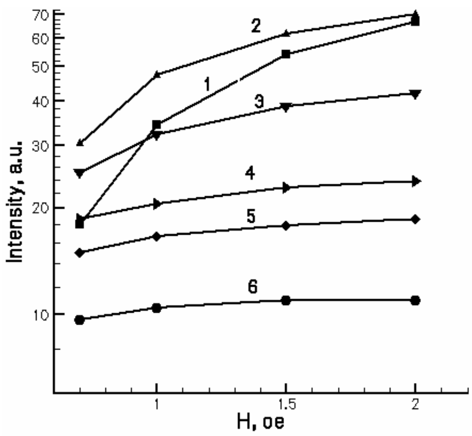

Fig. 4. Calculated intensity of the 728.1 nm line versus the external magnetic field amplitude for different values of the gas pressure p: (1) $p = 0.4$ Torr, (2) $p = 0.6$ Torr, (3) $p = 1$ Torr, (4) $p = 2$ Torr, (5) $p = 3$ Torr, (6) $p = 5$ Torr

Comparing Figs. 3 and 4, one can say that there is qualitative agreement in the behavior of theoretical and experimental curves.

5. Conclusions

Our work shows that the light source glass vessel cleaning by means of krypton HF-discharge is more effective as the cleaning method in helium discharge. The best discharge conditions and pressure range of helium were estimated, showing the maximum increase for emitted helium line intensities.

An improved self-consistent model of the high-frequency electrodeless discharge is presented in the paper. Iterative algorithms were used for solving the complete system. Rather good agreement between experimental results and calculations were obtained.

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