Plasma Temperature and Surface Studies of Argon-Hydrogen Containing Low-Temperature Dumbbell form Light Sources

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Abstract: In the current study we present the plasma temperature and surface topography measurement results for dumbbell-form lamps before and after the additional training at 2.4 GHz frequency. The plasma temperature was determined from the OH emission in all three parts of the lamp (spherical, capillary and cylindrical), exciting the discharge at 100 MHz field frequency. The SiO₂ glass surface topography measurements were performed with Atomic Force Microscope. The surface is much smoother when gigahertz field had been used, however no significant differences between plasma temperatures before and after the training at 2.4 GHz could be observed. It was observed that in the capillary part of the lamp the plasma temperature is lowest and the inner surface is roughest, contrary to the other parts of the lamp, where temperature is much higher and the surface smoother, showing that the plasma temperature affects surface topography as well.

Key words: Plasma, plasma temperature, plasma-surface interactions, spectroscopic diagnostics.

1. Introduction

Our work is concerned with the preparation and investigation of high-frequency electrodeless light sources (HFELS). The HFELS are widely used as bright radiators of narrow and intensive spectral lines covering spectral region from VUV to IR. The HFELS vessels are mostly made of SiO₂ glasses and filled with different metal vapors and rare gases at low pressure. High frequency electromagnetic field is applied to induce an inductively coupled discharge. The excitation frequency of the applied high-frequency field is 100 MHz. Such lamps are well suited for the investigation of plasma interaction with the lamp bulb, due to the absence of electrodes. During the electrodeless lamp operation plasma interacts with the

bulb wall material, causing nanoscale modifications of this material. The surface topography influences some important properties of the lamp, for example, the operating lifetime. The surface characteristics become especially important when decreasing the dimensions of the light source. Plasma-surface interaction studies are of great interest in the surface treatment technologies [1-3]. For instance, authors of Ref. [1] studied the surface modification dependence upon the pressure of RF plasma used to treat surface, and authors of Ref. [2] investigated the properties of surface before and after the treatment with oxygen plasma.

In our previous works, we investigated the temperatures of helium HFELS SiO₂ glass wall [4], showing that the oxygen is emitted exactly from the glass walls of the bulb, and we also studied the inner surfaces and spectra of HFELS of different forms (spherical, cylindrical and dumbbell) filled with Ar+H₂ [5]. The results reported in Ref. [5] showed that in the

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case of dumbbell-form lamp the oxygen combines with hydrogen producing OH, which is a very active particle and can be responsible for surface modifications.

In the current study, we present plasma temperature and surface topography measurement results for dumbbell-form lamps (Fig. 1) before and after the training at 2.4 GHz frequency. Such dumbbell-form lamps consist of three parts: (1) spherical; (2) capillary; and (3) cylindrical. The excitation coil was placed around the part that was investigated and the applied field was of 100 MHz frequency. The investigated HFELS samples were filled with argon and hydrogen of total pressure of 1 Torr (Ar/H₂ mixing ratio was 9:1).

2. Experiment

2.1 Determination of Plasma Temperature

It is known that one of the main parameters describing plasma is temperature of plasma particles. For hydrogen-containing plasmas it is convenient to use the Q-branches of Fulcher-transition system ($d^3\Pi_u^- \rightarrow a^3\Sigma_g^+$) of hydrogen to determine the plasma (neutral particle) temperature [6-8]. However, as it was shown in one of our previous works [5], in the spectra of dumbbell-form lamps we cannot observe the molecular lines of H₂. At the same time, we can register strong OH emission in UV region.

The intensity distribution over the rotational lines of OH ($A^2\Sigma^+ \rightarrow X^2\Pi$; $v = v' = 0$, Q₁-branch at 306.4 nm) can be used to determine the plasma (gas) temperature [9, 10]. This method is described in details elsewhere [11]. Briefly, measured relative intensity of the spectral line (I), wavelength (λ), transition probability (A), energy of the rotational level (E) and rotational temperature (T) are connected via the following formula:

$$\text{Log} \left(\frac{I \cdot \lambda}{A} \right) = \text{const} - \frac{E}{T} \times 0.625 \quad (1)$$

If the population distribution over the rotational levels corresponds to Boltzmann distribution, then the plot of $\text{Log}(I \cdot \lambda / A)$ versus energy E is a linear function and the rotational temperature T (equal to plasma

Fig. 1 Example of the dumbbell-form lamp with indicated (1) spherical, (2) capillary and (3) cylindrical parts.

Table 1 Transition parameters for the lines of (A-X) (0-0) Q₁ branch of OH radical [11].

Line	λ (nm)	E (cm ⁻¹)	A (10 ⁸ s ⁻¹)
Q ₁ (4)	308.328	32,779	33.7
Q ₁ (5)	308.517	32,948	42.2
Q ₁ (6)	308.734	33,150	50.6
Q ₁ (8)	309.239	33,652	67.5
Q ₁ (9)	309.534	33,952	75.8
Q ₁ (10)	309.859	34,283	84.1

temperature) is obtained from the slope of the linear fit ($-0.625/T$). Line assignments, wavelengths λ , energies E and transition probabilities A are given in Table 1.

The gas temperature dependence from the current in the induction coil was investigated for all three parts of the dumbbell-form lamp before and after the training at 2.4 GHz frequency. The light from the lamp was imaged on the entrance slit of the spectrometer (JobinYvon SPEX 1000M, grating 1200 l·mm⁻¹, focal length 1 m) and detected by the means of a charge-coupled device matrix detector (2048 × 512 Thermoelectric Front Illuminated UV Sensitive CCD Detector, Symphony). The emission spectra of the discharge under study have been recorded in the wavelength range $\lambda = 306$ –312 nm, containing the $A^2\Sigma^+ \rightarrow X^2\Pi$; $v = v' = 0$ transition of OH radical. An example of the registered spectra with some identified lines is shown in Fig. 2.

2.2 Lamp Inner Surface Studies by Means of an Atomic Force Microscope

Topography of the light source wall was studied by means of an atomic force microscope (AFM) in a

Fig. 2 Example of the registered OH ($A^2\Sigma^+ \rightarrow X^2\Pi$; $v = v' = 0$) spectra at 306 nm with some identified lines.

non-contact mode. The AFM tips, having a radius of curvature less than 35 nm, were silicon nitride (Park Scientific instruments) cantilevers. No filters were used for image processing except line-to-line levelling. The force constant of each cantilever was measured by calibrated cantilevers and found to be 0.1 and 0.16 N/m for cantilevers of two different dimensions.

In the previous work it was shown that HF discharge makes changes to the glass surface. We compare the changes of the inner surface of dumbbell-form lamps

filled with Ar + H₂ mixture with and without the additional training at 2.4 GHz frequency applied.

3. Results and Discussion

3.1 Plasma Temperature

Determined plasma temperature as a function of excitation generator current is shown in Fig. 3. It can be seen that the plasma temperature in capillary part of the lamp is the lowest (from 630 K to 750 K) compared to the plasma temperature in other parts of the lamp and it

Fig. 3 Measured plasma temperature at different parts of the dumbbell-form lamp as a function of excitation generator current

does not change significantly by varying the excitation generator current, while the changes of the temperature in spherical part are more pronounced; in this part of the lamp plasma temperature varies in the range from 1,120 K up to 1,730 K.

The difference between plasma temperatures in all three parts of the lamp can be explained by the effectiveness of energy coupling into the discharge volume, as well as by the configuration specifics of each part. Temperature in capillary part is lower because the volume of the discharge is very small and energy of the electromagnetic field cannot be efficiently transferred to the plasma here (the diameter of the induction coil is much larger than the diameter of

the capillary). In addition, the discharge vessel here is like a tube with open both ends, which leads to the dissipation of the temperature to other parts of the lamp. On the contrary, the spherical part represents an optimal configuration for energy input into plasma under the current experimental conditions.

As it can be seen from the results (Fig. 3), there is no significant difference between plasma temperatures before and after the training at 2.4 GHz frequency.

3.2 Lamp Inner Surface Studies

The results of lamp inner surface topography measurements are shown in Figs. 4 and 5, and the surface parameters are given in Tables 2 and 3.

Fig. 4 Image of inner surface of (Ar + H₂) dumbbell-form HFEL trained at 100 MHz frequency: (a) spherical part, (b) capillary part and (c) cylindrical part.

Fig. 5 Image of inner surface of (Ar + H₂) dumbbell-form HFEL trained at 2.4 GHz frequency: (a) spherical part, (b) capillary part and (c) cylindrical part.

Table 2 Surface parameters for different parts of dumbbell-form lamp, trained at 100 MHz.

Parameter	Spherical part	Capillary part	Cylindrical part
Standard deviation	13.615 nm	21.810 nm	10.114 nm
Max	289.102 nm	142.243 nm	103.755 nm
Min	-39.260 nm	-63.376 nm	-22.387 nm
Average deviation	4.068 nm	13.515 nm	4.007 nm

Table 3 Surface parameters for different parts of dumbbell-form lamp, trained at 2.4 GHz.

Parameter	Spherical part	Capillary part	Cylindrical part
Standard deviation	2.014 nm	7.688 nm	5.319 nm
Max	28.031 nm	62.024 nm	66.734 nm
Min	-10.282 nm	-54.602nm	-8.822 nm
Average deviation	1.262 nm	7.688 nm	2.671 nm

Analyzing the surface parameters for the lamp trained at 100 MHz frequency (Table 2 and Fig. 4), it can be concluded, that the roughest surface is in the capillary part of the lamp, however in the spherical part we can see some very high grains (reaching height of about 290 nm).

After the training at 2.4 GHz frequency all parts of the lamp are much smoother (Fig. 5 and Table 3), the peaks on the surface of spherical part are much lower (reaching only 28 nm), but the surface in capillary part is still the roughest.

The surface changes are unlike at different parts of the lamp (spherical, capillary, and cylindrical parts of the dumbbell lamp). This difference might be determined by different plasma conditions (e.g., temperature) and OH group density in different parts of the lamp. From comparison of the results of temperature measurements and surface topography it can be seen that the surface in capillary part is the roughest and plasma temperature is the lowest. At the same time the temperature in other two parts of the lamp is much higher and the surface is smoother. It shows that the plasma temperature affects surface topography as well.

4. Conclusions

The SiO₂ glass surface topography measurements with AFM showed significant differences in the surface parameters when operating lamp at different frequencies (megahertz of gigahertz). From the results it could be concluded that training at higher frequency

(2.4 GHz in the current study) affects the modifications on inner surface of the lamp by making the surface smoother, however it does not influence the plasma temperature after the training. The comparison of the plasma temperature and surface topography measurements showed that the plasma temperature affects surface topography as well, namely at higher temperature the surface becomes smoother.

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