Cathode sheath and hydrogen Balmer lines modelling in a micro-hollow gas discharge

Dj Spasojević
University of Belgrade Faculty of Physics, 11001 Belgrade, P.O.Box 368, Serbia
djordjes@ff.bg.ac.rs

Abstract. We present a model of the cathode sheath (CS) processes responsible for the broadening of the hydrogen Balmer beta line recorded from a micro-hollow gas discharge (MHGD) and used for simultaneous diagnostics of plasma and CS parameters. The MHGD was generated in a microhole (diameter 100 μm at narrow side and 130 μm at wider side) of a gold-alumina-gold sandwich in the pressure ranges: (100–900) mbar in argon with traces of hydrogen, and (100–400) mbar in pure hydrogen. The electron number density is determined from the plasma broadened line width of the central part of Balmer beta profile, while the average value of electric field strength in the CS and the CS thickness are determined from the extended line wings induced by the dc Stark effect.

1. Introduction
Microplasma is μm to mm size plasma operated in dc to GHz regime at higher (atmospheric) pressure. Due to small size and low power consumption, microplasma devices have various applications in material processing, biomedical treatment, and production of novel materials. Integrated into other technologies, microplasmas are also relevant for nanoparticle synthesis, thin film deposition, and production of printers, displays, semiconductor circuits, etc – see [1,2].

Micro-hollow gas discharges (MHGD) are miniaturized versions of classical hollow cathode gas discharges in noble gases or gas mixtures. They are realized in sandwich geometry (two metallic layers separated by insulator) with a central laser drilled hole (dia 100-300 μm) in which weakly ionized microplasma is ignited when a dc voltage is applied. Since its discovery (Schoenbach et al [3]), MHGD attracted a significant research interest and found many applications in industry and medicine. In this paper we report our results [4,5,6] of modelling of cathode sheath processes and of formation of profile of hydrogen Balmer beta line used for MHGD diagnostics.

2. Experimental
In figure 1 we show the schematic diagram of our experimental setup. The discharge source was a laboratory made MHGD device placed inside a vacuum tight chamber. The discharge was generated in a microhole (dia 100 μm at narrow and 130 μm at wider side) laser drilled in the center of a 250 μm thick alumina square piece (12 mm x 12 mm) with circular (dia 10 mm) gold electrodes.

The experiments were carried out with argon-hydrogen mixture (Ar+0.9% H2 by volume) in the pressure range (100-900) mbar, and with pure hydrogen (purity 99.999%) in the pressure range (100-400) mbar. The pressure and continuous gas flow of (0.1-1.0) L/min were regulated by two vacuum valves and one two-stage mechanical vacuum pump. The discharge was maintained by a current stabilized power supply (0-2 kV, 0-100 mA) current limited by a 50 kΩ series ballast resistor.
The light from the discharge was focused with unity magnification by an achromatic lens (focal length 75.8 mm) onto the entrance slit of a Czerny-Turner type spectrometer f/4.7 (0.67 m focal length with 1800 g/mm reflection grating; the reciprocal dispersion of 0.83 nm/mm in first diffraction order). The overall instrumental profile was very close to Gaussian with 0.029 nm FWHM. Signals from air-cooled-CCD detector (2048x512 square pixels, size 12 μm) were A/D converted and collected by PC.

Figure 1. Schematic diagram of the experimental setup: (1) Gas inlet, (2) gas outlet to vacuum pump, (3) gas inlet valve, (4) vacuum gauge and manometer, (5) vacuum valve, (6) vacuum chamber, (7) rear window, (8) front window, (9) achromatic lens, (10) to spectrometer, (11) Au electrodes, (12) alumina, (13) ballast resistor R=50 kΩ, (14) dc power supply (2kV, 100mA).

3. Experimental hydrogen Balmer beta line profiles from hydrogen seeded argon MHGD
In figure 2 we present the hydrogen Balmer beta (Hβ) line profiles recorded end-on from the cathode side of argon MHGD seeded by hydrogen for the optical emission spectroscopy diagnostics. Although all hydrogen Balmer lines are electric field sensitive (via linear Stark effect) and easily detectable, the Hβ line was selected due to proper intensity and well separation from other spectral lines – see [5].

Figure 2. The Hβ line profiles recorded end-on from the cathode side of hydrogen seeded argon MHGD, operated in the pressure range 100 – 900 mbar. Panel a) – schematic depiction of the observation side. Panel b) – profiles of the Hβ line recorded at four different values of discharge pressure. Panel c) – pedestals of the foregoing profiles, zoomed for better visibility of anomalously broadened wings.
The recorded Hβ line profiles have two components: 1) narrow central part, and 2) anomalously broadened wings. The appearance of the central part is well known – it is dominantly formed by the radiation of thermalized H atoms excited by electrons in negative glow (NG) and plasma producing a Voigt-type contribution $G_\text{V} (\lambda)$ of the overall line profile. On the other hand, the spread of wings suggest two things: i) the wings are comprised of radiation emitted by fast H atoms with kinetic energies $E_k \approx eU_D$, where $U_D$ is the discharge voltage and $e$ is the elementary charge, and ii) these atoms radiate in a strong electric field $E$ of the cathode sheath (CS) and the radiation profile is therefore broadened by the linear dc Stark effect. The aim of our theoretical model is to explain formation of fast H atoms, describe their distribution, and predict the shape of radiation wings.

4. Theoretical model

4.1. Formation of fast H atoms

We consider that the fast H atoms originate from positive H ions. These ions are mostly created in NG and thermalized in collisions with matrix gas. Those of them that diffuse into the tiny CS of discharge are subsequently accelerated towards the cathode by a strong cathode sheath electric field $E$ gaining kinetic energy $E_k$ that is comparable to the whole available energy $eU_D$.

For H+ ions, the mean free path $\lambda$ is greater than the CS thickness; for instance, at 500 mbar, the CS thickness is $\sim 25 \mu$m, and $\lambda$ (estimated at 1000 K with the aid of data from [7]) is $\sim 55 \mu$m. So, H+ ions move almost without collisions through the CS, forming a beam of ions directed normally towards the cathode; in the crudest approximation, the contribution of 2H+ and 3H+ ions can be neglected because their $\lambda$’s are 3 $\mu$m and 8 $\mu$m under the same discharge conditions.

The profile of the H+ ion beam at the cathode is taken in the form

$$B(v_z) = I_g \exp \left( -\frac{m_H}{2\Delta E_g} \left( v_z + \sqrt{2E_g/m_H} \right)^2 \right),$$

(1)

where $I_g$ and $E_g$ are the beam intensity and mean energy, respectively, $\Delta E_g \approx 0.1$ eV is the beam energy width inherited from the cold H atoms upon creation and thermalization of H+ ions in NG, while $m_H$ is the mass and $v_z$ is the $z$-component of velocity of H+ ion; note here that the $z$-axis is oriented away from the cathode, so $\langle v_z \rangle_g = -\sqrt{2E_g/m_H}$ is the mean $z$-component of velocity of H+ ions in the beam.

At the cathode H+ ions are neutralized. The majority of them are backscattered as fast H atoms, while the rest of them are captured and released later as cold atoms which don’t contribute to formation of radiation wings. Note also that other processes, like charge-exchange collisions, contribute negligibly to formation of fast H atoms because they take place in the CS which is very thin.

According to our simulations, performed with the aid of publicly available SRIM/TRIM program [8], the distributions of energies and directions of backscattered atoms are independent for normal incidence of (monoenergetic) H+ ions. We have found that the probability distribution of backscattering angle $\theta$ can be approximated by

$$dP^{(BS)}_{\text{ang}} (\theta) = \sin(2\theta) d\theta,$$

(2)

and the probability distribution of backscattering energy by

$$dP^{(BS)}_{\text{E}} (E) = A(e_s - E) e^{kE} dE,$$

(3)

for $E \leq e_s$ and 0 otherwise; here: $A$ is the normalization constant, $E = E_{BS}/E_i$ is the relative backscattering energy (i.e. quotient of backscattering energy $E_{BS}$ and incident energy $E_i$), while the threshold $e_s$ and exponent $k$ are the material constants for the cathode material in question. In the course of our simulations we have found that $e_s = 0.99$ and $k = 3.5$ for gold. We have also found that
our final results are rather insensitive to details of assumed energy distribution. Thus, the variation of $b_\varepsilon$ from 0.8 to 0.99 and $k$ from 2.5 and 6.5 change the values of the best fit parameters less than 1%. The same conclusion applies to the form of the beam profile, i.e. instead of (1) we could use any other sufficiently narrow beam profile of the same energy $E_B$, and the only real advantage of profile (1) is that it enables estimation of gas temperature $T_g \approx T_B$ via beam temperature $T_B = \Delta E_B/k_B$.

4.2. Radiation of the backscattered H atoms
On their subsequent motion through matrix gas, the backscattered H atoms occasionally radiate after being excited. The major part ($p_{iso}$) of them are excited in collisions with the most abundant heavy particles – Ar atoms in the case of MHGD in Ar, and H$_2$ molecules in the case of discharge in pure hydrogen. In the first approximation, these collisions can be treated as collision of rigid spheres because both colliding particles are neutral.

Collision of rigid spheres is isotropic in the centre of mass frame of reference. Due to mass ratio of 1/40, the collision of H atom and Ar atom is practically isotropic in the laboratory frame of reference too. The consequence is that the directional motion of H atom is on average wiped out after single collision, so the resulting end-on profile in Ar discharge is (almost) symmetric. On the other hand, the mass ratio for collision of H atom and H$_2$ molecule is $\frac{1}{2}$, so the colliding H atoms retain on average $\frac{1}{3}$ of their velocity. Nevertheless the radiation is again almost (but less) symmetric because H atoms experience on average more than one collision before excitation. Note also that a small $1 - p_{iso}$ part of the backscattered H atoms are excited by electrons and their radiation is blue-shifted.

4.3. The role of dc Stark broadening
The Doppler profile of radiation is broadened by the linear dc Stark effect in a strong CS electric field $E$. The broadened profile is the convolution $[S_\lambda * D](\lambda)$ of the radiation Doppler profile $D(\lambda)$ and the Stark shift operator

$$S_\lambda (\lambda) = \sum s_j \delta(\lambda - s_j E),$$

where $s_j$ and $c_j$ are the Stark manifold and intensity coefficients for the line in question.

The magnitude of Stark broadening is linearly dependent on the magnitude of electric field $E$ which vary throughout the CS. For the sake of simplicity, we have assumed that the effective distribution of electric field is

$$E(z) = E_0 \left(1 - z/z_g\right)$$

where $E_0$ is the electric field at the cathode surface, $z$ is the distance from the cathode, and $z_g$ is the CS thickness. Hence, the voltage in the CS is $U_{CS} = E_0 z_g / 2$, and the average electric field (a more robust quantity independent on details of electric field distribution in CS) is $E_a = U_{CS} / z_g = E_0 / 2$.

In end-on observations we record the emissions from all perceptible parts of discharge. Due to an approximate plan-parallel symmetry of the CS region, the Doppler profile varies only with distance $z$ from the cathode, $D(\vec{r},\lambda) = D_z(\lambda)$, so the end-on profile of wings is

$$G_w(\lambda) = \int dz \left[ S_{\lambda(z)} * D_z(\lambda) \right].$$

In this model we took that $D_z(\lambda)$ is

$$D_z(\lambda) = e^{-az} D_0(\lambda),$$

where
where $D_\lambda(\lambda)$ is the Doppler profile at the cathode, and $a$ is a coefficient of exponential attenuation of profile’s magnitude with distance $z$. Successive stages of wings formation according to our model are shown in figure 3.

**Figure 3.** Successive stages of wings formation for MHGD at $p = 500$ mbar. Experimental points are shown by empty circles connected by straight lines. The narrowest curve (line-connected solid squares) represents a beam of 140eV H$^+$ ions with normal incidence at the cathode. The backscattered beam is represented by the dashed curve prior to the angular scattering and by solid circles after the angular scattering. The effect of isotropic scattering is shown by triangles. Finally, the profile of wings is shown by the dotted curve.

4.4. The $H_\beta$ line model function

The final form of our model function for experimental line profiles is

$$G(\lambda) = \mathcal{I} \left[ G_w(\lambda) + G_l(\lambda) \right] + b$$

where $G_w(\lambda)$ is the model function for anomalously broadened wings, and $G_l(\lambda)$ is the Voigt profile pertaining to the central part of line profile. Here, the overall theoretical profile

$$G_{th}(\lambda) = G_w(\lambda) + G_l(\lambda),$$

i.e. the profile that would be recorded by perfect instruments, is convolved with the instrumental profile $\mathcal{I}$, taken in the form of a (zero-centred) Gaussian with 0.029 nm FWHM in accordance with calibration of our experimental system. Finally, the constant $b$ is introduced to take into account possible experimental offset of the data base line.

The model function $G_w(\lambda)$ for the shape of line wings has seven free parameters. The three parameters: intensity $I_w$, mean energy $E_w$, and energy-width $\Delta E_w$, describe the beam of H$^+$ ions at the cathode surface (1). The next two parameters, the voltage $U_{cs}$ and thickness $z_h$, are characteristics of cathode sheath. The last two parameters are the attenuation coefficient $a$ of the Doppler profile (7), and $p_{iso}$ - the part of the photons emitted by isotropically scattered H atoms. These two parameters describe fast H atoms, formed by the neutralization and backscattering of H$^+$ ions at the cathode. In addition, the Voigt profile $G_l(\lambda)$ is characterized by its intensity $I_l$, Lorentz width $w_L$, and Doppler width $w_D$.

5. Applications

5.1. Hydrogen seeded MHGD in argon

In four panels of figure 4 we present the experimental $H_\beta$ line profiles together with their best fit curves (8); implicitly involved Stark parameters $s_j$ and $c_j$ for the $H_\beta$ line are the same as in [9]. The experimental profiles are recorded in the pressure range 100-900 mbar. The discharge parameters and the values of the best fit parameters are given in table 1 together with calculated values for other relevant parameters. Parameter variation on discharge pressure is presented in figure 5.
Figure 4. Experimental Hβ profiles (symbols), their best fit curves (solid lines), and the base line level (dashed line). Zoomed wings are presented in insets, while the residuals are shown below each graph.

Figure 5. Best fit parameters versus discharge pressure.
Table 1. Best fit parameters and calculated parameters \((E_a, E_0, w_L, w_S, \text{and } N_e)\); percentage errors are given in parentheses.

| \(p\) (mbar) | \(p=100\) mbar | \(p=300\) mbar | \(p=500\) mbar | \(p=900\) mbar |
|---|---|---|---|---|
| \((U_{Di}=183 \text{ V}, I_{Di}=5.0 \text{ mA})\) | \((U_{Di}=190 \text{ V}, I_{Di}=5.5 \text{ mA})\) | \((U_{Di}=190 \text{ V}, I_{Di}=8.0 \text{ mA})\) | (UD\(I=183 \text{ V}, I=5.0 \text{ mA})\) | (UD\(I=190 \text{ V}, I=5.5 \text{ mA})\) |
| \(E_B\) (eV) | 95 (20%) | 120 (20%) | 140 (20%) | 170 (20%) |
| \(T_B\) (K) | 790 (30%) | 780 (30%) | 750 (30%) | 500 (30%) |
| \(U_{CS}\) (V) | 110 (15%) | 140 (15%) | 155 (15%) | 175 (15%) |
| \(z_g\) (\(\mu m\)) | 70 (15%) | 34 (15%) | 25 (15%) | 18 (15%) |
| \(a\) (1/m) | 1000 (30%) | 5700 (30%) | 10000 (30%) | 26000 (30%) |
| \(p_{ISO}\) | 0.73 (20%) | 0.80 (20%) | 0.75 (20%) | 0.90 (20%) |
| \(w_L\) (nm) | 0.027 (10%) | 0.067 (10%) | 0.10 (10%) | 0.15 (10%) |
| \(w_D\) (nm) | 0.0025 | 0.0018 | 0.0010 | 0.0012 |
| \(E_w\) (kV/cm) | 16 (30%) | 41 (30%) | 62 (30%) | 95 (30%) |
| \(E_0\) (kV/cm) | 32 (30%) | 82 (30%) | 125 (30%) | 190 (30%) |
| \(w_{VdW}\) (nm) | - | - | 0.017 | 0.028 |
| \(w_S\) (nm) | 0.22 | 0.053 | 0.087 | 0.119 |
| \(N_e\) (\(10^{20} \text{ m}^{-3}\)) | 0.4 (50%) | 1.4 (30%) | 2.9 (20%) | 4.5 (15%) |

The electron number density \(N_e\) is calculated from parameters of observed Voigt profile \(\mathcal{V} \ast G_r(\omega)\) pertaining to the central part of the H\(\beta\) line. This profile is convolution of instrumental profile \(\mathcal{V}\) and the true Voigt profile \(G_r(\omega)\), i.e. the Voigt profile which would be observed with an ideal spectrometer. The true Voigt profile is

\[
G_r(\omega) = G_L(\omega) \ast G_D(\omega),
\]

where \(G_L(\omega)\) is the resulting Lorentz profile with FWHM \(w_L\), and \(G_D(\omega)\) is the Doppler profile due to velocity distribution of H atoms that emit the H\(\beta\) radiation; the uncertainty of \(G_D(\omega)\)'s FWHM \(w_D\) is very large, so the values of \(w_D\) in table 1 are given only for illustration purposes.

The resulting Lorentzian is

\[
G_L(\omega) = G_s(\omega) \ast G_{vdw}(\omega),
\]

where \(G_s(\omega)\) is the Stark Lorentzian (induced by Stark broadening in microscopic electric field), and \(G_{vdw}(\omega)\) is Van der Waals (VdW) Lorentzian (induced by collisions of Ar atoms with H atoms). Therefore, \(w_L = w_s + w_{vdw}\), where \(w_s\) is FWHM of \(G_s(\omega)\) and \(w_{vdw}\) is FWHM of \(G_{vdw}(\omega)\).

The estimation of \(w_{vdw}\) is carried out as in [10] with remark that due to great uncertainty of \(w_D\) the beam temperature \(T_B\) was used instead of gas (Doppler) temperature \(T_g\), calculated from \(w_D\). Finally, \(N_e\) is evaluated from the Stark width \(w_s = w_L - w_{vdw}\) by empirical formula (2a) from reference [11].

5.2. MHGD in pure hydrogen

In figure 6 we show the H\(\beta\) experimental profiles with superimposed molecular H\(_2\) lines recorded in pure hydrogen MHGD at 100 mbar, 200 mbar, and 400 mbar. The experimental setup was the same as for the MHGD in argon. The profiles were fitted by the modified model function (8) which reads

\[
G(\lambda) = \mathcal{V} \left[G_{is}(\lambda) + G_{H_2}(\lambda)\right] + b .
\]
Here, $G_m(\lambda) = G_p(\lambda) + G_{t}(\lambda)$ is previously defined theoretical $H_\beta$ profile (9) and $G_{t}(\lambda)$ is a Voigt-type model function for the molecular hydrogen line 0.04 nm red-shifted relative to $H_\beta$ center. Being poorly resolved from the central Voigt, the molecular line obstructs fitting and greatly increases the uncertainty of the best fit parameters.

**Figure 6.** Hydrogen MHGD end-on spectra recorded around the $H_\beta$ line. Several molecular $H_2$ lines, superimposed on the $H_\beta$ profile, are visible. Inset: schematic depiction of MHGD and direction of observation.

In figure 7 we show the best fits of the foregoing experimental profiles, and in table 2 we give the corresponding values of the best fit parameters together with the values of calculated parameters.

**Figure 7.** a) ±2.5 nm excerpts from the central part of experimental $H_\beta$ profile recorded at $p = 100$ mbar and its best fit. b) and c) – the same as in a), but for $p = 200$ mbar and $p = 400$ mbar, respectively. Insets: a portion of the recorded $H_\beta$ spectrum with superimposed 483.1562 nm and 483.2330 nm $H_2$ lines; the best fit of 483.1562 nm $H_2$ line is used for determination of gas temperature $T_g$. 
Table 2. The most relevant best fit parameters and calculated values for $E_a$, $E_0$ and $T_g$, quoted with their percentage errors.

| Parameter | $p=100$ mbar $(U_D=300$ V, $I_D=4.5$ mA) | $p=200$ mbar $(U_D=250$ V, $I_D=7.0$ mA) | $p=100$ mbar $(U_D=400$ V, $I_D=12$ mA) |
|-----------|---------------------------------|---------------------------------|---------------------------------|
| $E_a$ (eV) | 300 (20%) | 240 (20%) | 300 (20%) |
| $w_a$ (pm) | 34 (30%) | 11 (30%) | 6.6 (30%) |
| $U_{CS}$ (V) | 300 (15%) | 250 (15%) | 300 (15%) |
| $z_g$ (μm) | 120 (15%) | 58 (15%) | 65 (15%) |
| $w_L$ (pm) | 99 (20%) | 144 (20%) | 195 (20%) |
| $w_G$ (pm) | 5.1 (60%) | 5.2 (60%) | 4.5 (60%) |
| $E_b$ (kV/cm) | 25 (30%) | 43 (30%) | 46 (30%) |
| $E_0$ (kV/cm) | 50 (30%) | 86 (30%) | 92 (30%) |
| $T_g$ (K) | 735 (0%) | 785 (0%) | 870 (0%) |

5.3. Comparison with Kushner’s simulation data

In figure 8, we compare our data with the Kushner’s simulation data [12] obtained in similar geometry and in the same pressure range, but with constant discharge current of 2 mA and variable discharge voltage. The discharge voltage and corresponding CS voltage vary with pressure roughly the same, whereas the data for electron number density $N_e$ almost agree within the experimental error bars.

![Figure 8](image)

**Figure 8.** Comparison of our data with Kushner’s simulation data [12].
(a) Discharge voltage (simulations) and the corresponding CS voltage (our MHGD).
(b) Electron number densities.

6. Discussion

In this work we have applied our model to the case of H$\beta$ line for two reasons: firstly, compared to other hydrogen Balmer lines, separation of H$\beta$ from neighbouring spectral lines is better, and secondly, the H$\beta$ line is neither too strong nor too weak; otherwise, the self-absorption has to be taken into account and/or the signal to noise ratio is poor. Nevertheless, the use of other lines is possible.

Next, although we didn’t test our model outside the current scope we expect that it should be valid for other MHGD’s provided that requisite changes in values of structural parameters (like Stark manifold and intensity coefficients, threshold $\varepsilon_0$ and exponent $k$ for different cathode material, etc)
are done. For this reason we expect that different MHGD’s manifest many similarities under like discharge conditions and MHGD design. On the other hand, some differences are to be expected as well. Thus, in the case of hydrogen seeded MHGD in argon and MHGD in pure hydrogen the following differences have to be noticed and discussed

- CS thickness in pure hydrogen is two times larger than in argon MHGD, most likely due to smaller momentum transfer cross-section of $H^+$ ions in $H_2$.
- In Ar MHGD the majority of $H^+$ ions are the ionized H atoms produced by destruction of $H_2$ molecules in collisions with Ar metastables; therefore, the beam temperature $T_B$ is approximately equal to the gas (i.e. argon) temperature $T_g$. In pure hydrogen, $H^+$ ions from dissociative ionization of $H_2$ molecules are only partially thermalized and a higher beam temperature $T_B$ is expected; for this reason, the gas temperature $T_g$ is estimated from the width of the $H_2$ 483.1562nm line.
- The $N_e$ calculations in pure $H_2$ are not reliable due to self-absorption, giving faulty larger $N_e$ values.

7. Conclusion
In conclusion, we have proposed a model of cathode sheath (CS) processes and formation of hydrogen Balmer lines’ profiles in micro-hollow gas discharges (MHGD). The model was applied to the hydrogen Balmer beta profiles (recorded in hydrogen seeded argon and in pure hydrogen MHGD), and used for simultaneous diagnostics of plasma and CS parameters. The average value of CS electric field and CS thickness are determined from the extended line wings, while the electron number density is found from the width of the central part of line profile. Our findings are in a good agreement with the results obtained by numerical simulations [12], whereas the agreement with the results of other similar experiments [13,14,15,16] is less satisfactory and requires explanation.

Acknowledgments
This work is supported by the Ministry of Science and Technological Development of the Republic of Serbia under Project No. 171027.

References
[1] Becker K H, Schoenbach K H and Eden J G 2006 J. Phys.D: Appl. Phys. 39 R55
[2] Tachibana K 2012 Microplasmas in The 2012 Plasma Roadmap, J. Phys.D: Appl. Phys. 45 253001
[3] Schoenbach K H, Verhappen R, Tessnow T, Peterkin F E and Bywszewski W W 1996 Appl. Phys. Lett. 68 13
[4] Spasojević D, Cvejić M, Šišović N M and Konjević N 2010 Appl. Phys. Lett. 96 241501
[5] Cvejić M, Spasojević D, Šišović N M and Konjević N 2011 J. Appl. Phys. 110 033305
[6] Spasojević D, Cvejić M, Šišović N M and Konjević N 2012 J. Appl. Phys. 111 096103
[7] Tabata T and Shirai T 2000 Atomic Data and Nuclear Tables 75 1; Phelps A V 1990 J. Phys. Chem. Ref. Data 19 653
[8] Ziegler J F, Ziegler M D, and Biersack “SRIM-2008” (www.SRIM.org)
[9] Videnović I R, Konjević N and Kuraica M M 1996 Spectrochim. Acta Part B 51 1707
[10] Djurović S and Konjević N 2009 Plasma Sources Sci. Technol. 18 035011
[11] Ivković M, Jovičević S and Konjević N 2004 Spectrochim. Acta Part B 59 591
[12] Kushner M J 2005 J. Phys. D: Appl. Phys 38 1633
[13] Penache C, Miclea M, Bräuning-Demian A, Hohn O, Schössler S, Jahnke T, Niemax K and Schmidt-Böcking H 2002 Plasma Sources Sci. Technol. 11 476
[14] Moselhy M, Petzenhauser I, Frank K and Schoenbach K H 2003 J. Phys. D: Appl. Phys 36 2922
[15] Lazzaroni C, Chabert P, Rousseau A and Sadeghi N 2010 Eur. Phys. J. D 60 555
[16] Sismanoglu B N, Grigorov K G, Caetano R, Rezende M V O and Hoyer Y D 2010 Eur. Phys. J. D 60 505