NUKLEONIKA 2012;57(2):253–256

ORIGINAL PAPER

Diagnostics of non-equilibrium plasma generated in dielectric barrier discharges

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Abstract. Results of electrical and spectroscopic diagnostics of dielectric barrier discharges by applying ceramic plates made of high permittivity material are presented. The spectroscopic diagnostic is based on analysis of spectral and spatial distribution of the hydrogen H_α emission in the gas gap. From these measurements, e.g. the distributions of electric field strength and kinetic energy of excited hydrogen atoms in the discharge volume have been determined.

Key words: dielectric barrier discharges • hydrogen spectrum • line broadening • plasma diagnostics • Stark effect

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Received: 21 September 2011
Accepted: 21 November 2011

Introduction

Diagnostics of non-equilibrium plasmas, generated in small volumes by various sources are reported in numerous recent papers, see e.g. [11–13]. Main reasons for the growing interest in such studies are possible applications of the emitted radiation (visible, UV, VUV) as well as the emission of electrons, excited atoms, ions and molecules from these plasma sources. Miniature devices have been designed, constructed and developed, e.g., for modification of surfaces, sterilization of medical materials and physicochemical analysis. Among this kind of devices also plasma sources based on dielectric barrier discharges (DBD) have been applied [1, 4, 8, 12, 15]. In particular, small size light sources based on DBD discharges, emitting UV and VUV radiation have been intensively studied since the eighties of the 20-century [2, 3]. Applying high permittivity $BaTiO_3$ ceramic plates as barrier material, such investigations were also performed by the authors of this paper [6].

Among plasma parameters characterizing DBD discharges, the local electric field strength E in the discharge volume and the spatial distributions of kinetic energies (temperatures T_e, T_i, T_a) of the individual plasma components (electrons, ions, atoms) are very crucial for possible technical and commercial applications [7, 9]. Therefore, spectroscopic studies of such small size DBD plasma sources require the use of sensitive detection systems with high spatial and spectral resolution. An important question in such studies is also the determination and control of electrical parameters crucial for generation of stable plasma.

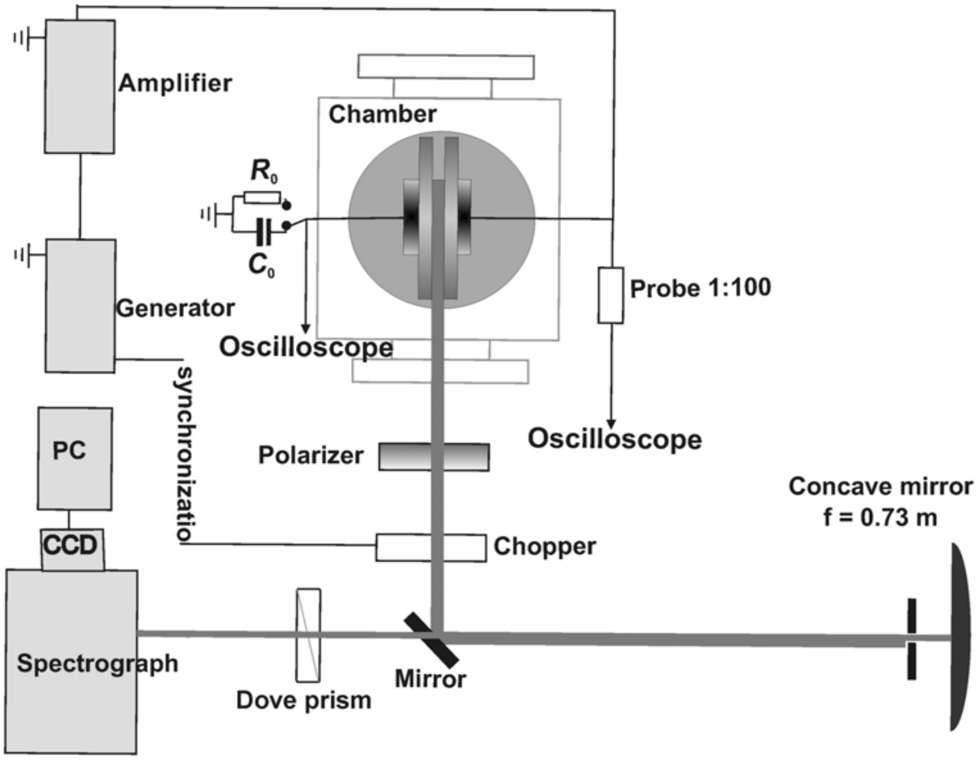

Fig. 1. The scheme of the experimental setup is shown.

Experimental setup

Studies of DBD plasma properties have been performed for various gas mixtures at pressures corresponding to the minima of the breakdown voltages (for the given gas mixture). The electrodes made of $BaTiO_3$ ceramics, spaced by 0.5 mm, were supplied with AC (alternating current) voltage of frequency $f = 1$ kHz and amplitude U_{max} between 250 and 1100 V. The scheme of the experimental setup is shown in Fig. 1.

The optical detection system allows performing measurements with a spectral resolution of 0.015 nm and a spatial resolution (in direction perpendicular to electrodes) of 0.057 mm. The chopper, synchronized with the voltage generator, allows detecting light pulses corresponding to a given half-cycle of the alternating voltage, i.e., light emitted during a fixed polarity of the electrodes. The polarizer placed in the optical path allows measuring separately the radiation from the plasma: polarized in direction perpendicular (σ) and parallel (π) to the applied external voltage.

Results and discussion

The "electrical" parameters of the DBD discharge have been determined from measured current- and voltage--oscillograms (by applying respectively the voltage probe and the "measuring" resistance R_0) as well as from measured charge loop $Q = f(U)$ (by using the voltage probe and the "measuring" capacitor C_0) – see Fig. 1. Typical results are shown in Figs. 2a and 2b.

In Fig. 2c, the parameters of the charge loop (Lissajous figures), characterizing quantitatively the repolarizing conditions are presented: U_{max} – the amplitude of the voltage, ΔQ – the charge transferred between the electrodes, and U_b – the breakdown voltage.

By applying the "peak detect" mode being implemented in the oscilloscope, current pulses with widths

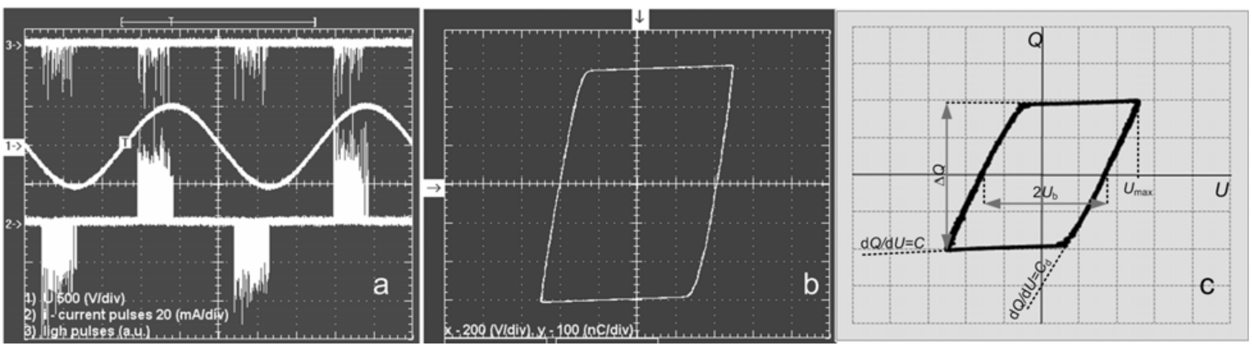

Fig. 2. Shown are: (a) typical waveforms of the applied voltage, discharge current and light pulses (upper trace) excited by $U_{max} = 0.5$ kV, $f = 1$ kHz alternating voltage, registered in the "peak detect" mode; (b) Lissajous figure (Q–U loop) corresponding to discharge conditions shown in part (a), obtained applying the "average" mode; (c) the characteristic parameters of the Lissajous Q–U loop presented in part (b).

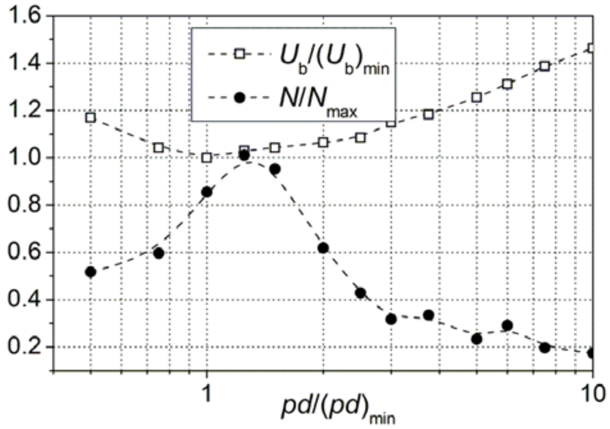

Fig. 3. The normalized number of current pulses N/N_{max}, generated during a half cycle of the repolarizing voltage and the normalized breakdown voltage $U_b/(U_b)_{min}$ are shown vs. the normalized product $p{\cdot}d/(p{\cdot}d)_{min}$.

of the order of 10^{-9} s could be registered, allowing to perform statistical analysis of the pulses. On the other hand, the "average" mode permits suppressing the noise and increase the determination accuracy of the charge loop parameters $Q = f(U)$. As an example of such analysis, results obtained in case of DBD discharges in the $N_2 + H_2$ gas mixture are shown in Fig. 3.

The normalized number of current pulses N/N_{max} generated during a half cycle of the repolarizing voltage and the normalized breakdown voltage $U_b/(U_b)_{min}$ are shown vs. the product $p{\cdot}d$ (where p is the gas pressure, and d is the gas gap, as is typical of Paschen curves). As expected, the efficiency of DBD discharges is around the minimum of the Paschen curve. This result is important for possible applications – the larger number of micro-discharges at smaller amplitudes provides better stability of the discharge.

The Balmer alpha (H_α) radiation, originating from different plasma layers in the slit between ceramic electrodes was measured in conditions close to the minimum value of the breakdown voltage. In Fig. 4, the results of H_α line profile studies from DBD discharge in $N_2 + H_2$ gas mixture are presented as an example. For details see the caption of Fig. 4.

In Fig. 5, the results for the same selected plasma layer are shown, but applying additionally the polarizer in the light path (see Fig. 1): in Fig. 5a the contribution arising from the π, and in Fig. 5b from the σ components of the H_α line profile has been measured. Each profile was fitted (solid line) applying the procedure described in detail by Janus [5]. The fit consists of contributions arising from the strongest Stark components and from an additional component representing the non-

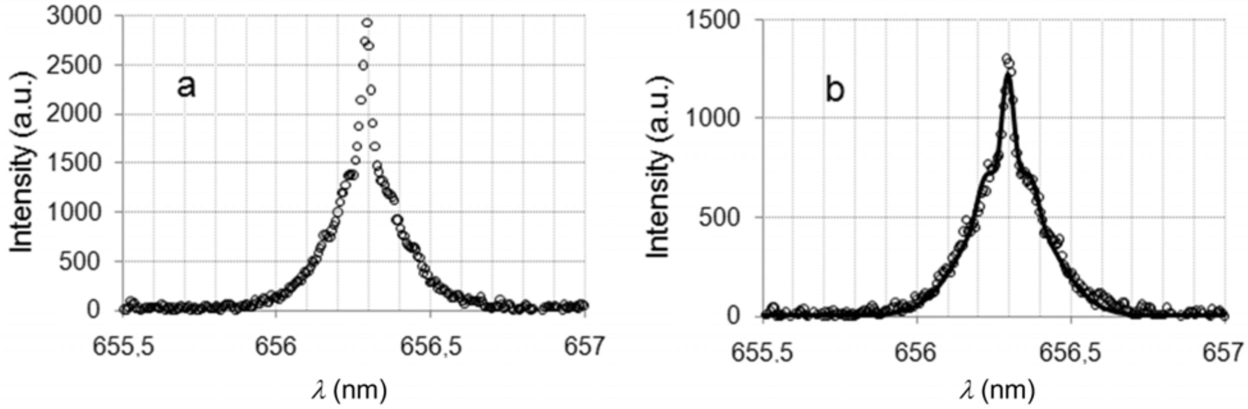

Fig. 4. Two H_α profiles taken from a selected plasma layer are shown: in part (a) the light was averaged over numerous full cycles of the discharge; while in part (b) the chopper (Fig. 1) transmitted only the radiation emitted during numerous (but defined) half cycles. The solid line in part (b) is the sum of all fitted profiles to the data presented in Figs. 5a and 5b.

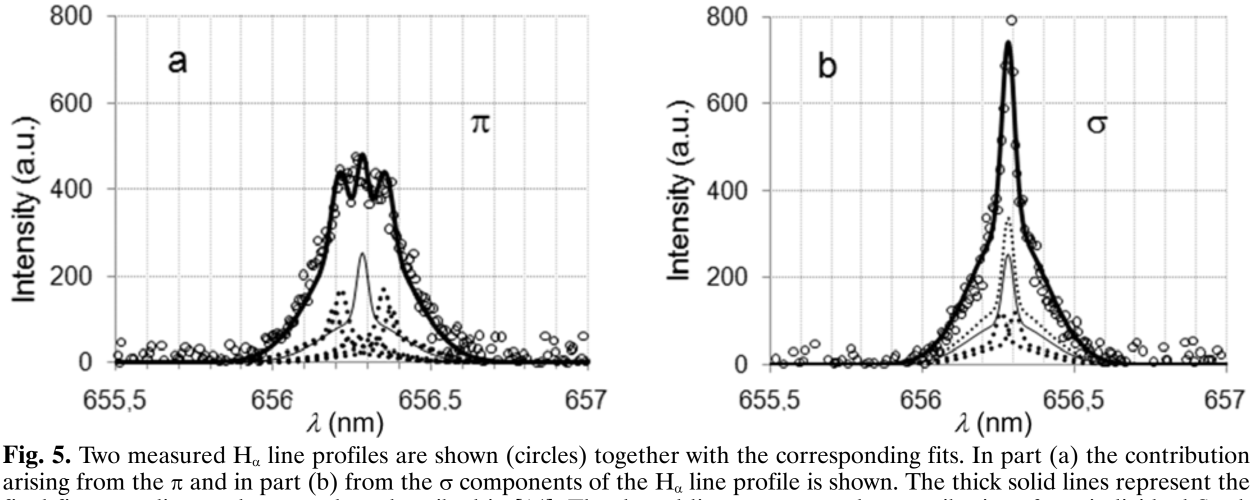

Fig. 5. Two measured H_α line profiles are shown (circles) together with the corresponding fits. In part (a) the contribution arising from the π and in part (b) from the σ components of the H_α line profile is shown. The thick solid lines represent the final fits according to the procedure described in [14]. The dotted lines represent the contributions from individual Stark components situated at wavelength positions corresponding to a given value of electric field E; the solid lines in the lower part of each figure represent the contribution from non-polarized light.

-polarized light, i.e., the light emitted without acting electric field on the hydrogen atoms. These individual contributions are shown on the basis of each figure: the dotted lines represent the contribution from individual Stark components situated at wavelength positions corresponding to a given value of electric field E; the solid line at the line center represents the contribution from non-polarized light.

Each Stark component consists of a sum of two Doppler (Gauss) profiles, the first one (narrow profile), representing the contribution from atoms with thermal energy (near ambient temperature) and the second (broader), representing the contribution from excited H-atoms with significantly larger kinetic energy, originating from the dissociation process of the excited H_2 molecule [16]. Within the fitting procedure, for each Stark component, we assumed (somewhat arbitrarily) the same ratio between "amplitudes" of these two Doppler profiles. With this assumption, in the case of this particular plasma layer (0.1 mm from the ceramic plate), the determined density of "fast" excited H atoms is about 4.5 times larger than the density of "slow"(thermal) atoms. This value varies in the gas gap from 3.5 to 5.5.

From the fitted positions of individual Stark components the electric field strength E could be easily deduced. The local electric fields determined in this way are nearly constant in the major part of the gas gap – the E values are between 8.2 and 7.8 kV/cm. The determined parameters of the non-polarized component, allows to conclude that the H_α photons, emitted from the plasma in the time interval being free from external electric field, varies in the gas gap from 25 to 30%. Our analysis allows also obtaining the fraction of "fast" and "slow" excited hydrogen atoms, and thus contributes to the discussion (see e.g. [10]) concerning the interpretation of hydrogen line profiles observed from low pressure discharges. The results may be useful for modeling of low-pressure discharges and technical applications of small size plasma sources.

References

1. Babaeva NY, Kushner MJ (2010) Intracellular electric fields produced by dielectric barrier discharge treatment of skin. J Phys D: Appl Phys 43:185206–185218
2. Boeuf JP (2003) Plasma display panels: physics, recent developments and key issues. J Phys D: Appl Phys 36;6:R53–R79
3. Eliasson B, Kogelschatz U (1991) Nonequilibrium volume plasma chemical processing. IEEE Trans Plasma Sci 19:309–323
4. Iza F, Kim GJ, Lee SM *et al.* (2008) Microplasmas: sources, particle kinetics, and biomedical applications. Plasma Process Polym 5:322–344
5. Janus HW (2007) Contribution of Stark broadening to the Balmer H_α line profile observed from barrier discharges in Ar/H_2 gas mixtures. J Phys D: Appl Phys 40:3608–3615
6. Janus HW, Jeleński W, Musielok J, Kusz J (1991) Study of VUV radiation of an argon-plasma generated near ceramic surfaces at pressures below 0.1 MPa. Appl Phys B 52:376–379
7. Kogelschatz U (2007) Applications of microplasmas and microreactor technology. Contrib Plasma Phys 47:80–88
8. Kozlov KV, Wagner HE (2007) Progress in spectroscopic diagnostics of barrier discharge. Contrib Plasma Phys 47;1/2:26–33
9. Kuchenbecker M, Bibinov N, Kaemlimg A, Wandke D, Awakowicz P, Viol W (2009) Characterization of DBD plasma source for biomedical applications. J Phys D: Appl Phys 42:045212–045222
10. Loureiro J, Amorim J (2011) Anomalous Doppler broadening caused by exothermic reactions: application to hydrogen Balmer lines. Eur Phys J D 63:421–429
11. Mariotti D (2008) Nonequilibrium and effect of gas mixtures in an atmospheric microplasma. Appl Phys Lett 92:151505–151508
12. Neidholdt EL, Beauchamp JL (2011) Switched ferroelectric plasma ionizer (SwiFerr) for ambient mass spectrometry. Anal Chem 83:35–43
13. Sismanoglu N, Grigorov KG, Santos RA *et al.* (2010) Spectroscopic diagnostics and electric field measurements in the near-cathode region of an atmospheric pressure microplasma jet. Eur Phys J D 60:479–487
14. Spasojević D, Cvejić M, Šišović NM, Konjević N (2010) Simultaneous plasma and electric field diagnostics of microdischarge from hydrogen Balmer line shape. Appl Phys Lett 96:241501–241504
15. Tachibana CK (2006) Current status of microplasma research. IEEJ Trans 1:145–155
16. Wujec T, Janus H, Jeleński W (2003) Spectroscopic measurements of electric field distributions in dielectric barrier discharges in hydrogen. J Phys D: Appl Phys 36:868–877