Stark broadening to determine the electron density in plasmas

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Abstract. In this paper, we present results of the spectroscopic measurements of the electron density in a microwave surface wave sustained discharges in Ar and Ne at atmospheric pressure. The discharge in the form of a plasma column was generated inside a quartz tube cooled with a dielectric liquid. The microwave power delivered to the discharge via rectangular waveguide was applied in the range of 200-1500 W. In all investigations presented in this paper, the gas flow rate was relatively low (0.5 l/min), so the plasma column was generated in the form of a single filament, and the lengths of the upstream and downstream plasma columns were almost the same. The electron density in the plasma columns was determined using the method based on the Stark broadening of H_β spectral line, including plasma region inside the waveguide which was not investigated earlier.

INTRODUCTION

Surface wave sustained plasmas (SWSP) find practical applications in elemental analysis, gas purification, diamond deposition, surface treatment, sterilization. All these applications require plasma sources able to work efficiently under various operating conditions. In the last decades, field applicators for such sources were developed, investigated and implemented in practice [1-3]. In the present investigations we used a surfaguide-type plasma source, based on WR 430 standard waveguide having a reduced-height section. The discharge was generated in Ar and Ne at atmospheric pressure inside a quartz tube cooled with a dielectric liquid. The discharge region consists of two plasma columns outside the waveguide and plasma region inside the waveguide. We present results of the spectroscopic measurements of the electron density in the entire discharge region. To our knowledge, no electron density measurements for the plasma region inside the waveguide (launching region) have been reported so far.

PRINCIPLES OF MEASUREMENT

In this measurement, a small amount (about 0.2 % vol.) of water vapour was added to the Ar and Ne flow to obtain a detectable intensity of H_β emission spectral line (486.13 nm) for the electron density measurement. The H_β spectral line of the hydrogen Balmer series was observed in the emission spectrum due to dissociation of the water vapour in the plasma columns. We checked that the 0.2 % water vapour additive did not change the colour and length of the plasma columns. The electron density in the plasma columns was determined using the method based on the Stark broadening of H_β spectral line spontaneously emitted by the plasma.

The profile of an emission line can be affected by different mechanisms of broadening [4]: natural, thermal Doppler, Stark (collisional) broadening, instrumental, etc. Generally, majority of the broadening mechanisms result in the emission lines with the Gaussian profile, except for the Stark broadening, which generates the Lorentzian profile of the emission lines [4]. The convolution of the Lorentzian (Stark) and Gaussian profiles results in the so-called Voigt profile.

In this investigations, the Voigt function was fitted to the measured H_β line profile in order to estimate the full width at half maximum (FWHM) of the Lorentzian (Stark) profile $\Delta\lambda^{Stark}(H_\beta)$.

The electron density in the plasmas was determined from FWHM using either GKS theory or Gig-Card theory.

In the GKS theory (disclosed in [5, 6]), the Stark broadening is estimated in a quasi-static approximation using the classic Holtsmark field, resulting in the relation [4]:

$$n_e = [10^9 \cdot \Delta\lambda^{Stark}(H_\beta)/(2.5 \cdot \alpha_{1/2})]^{1.5} \quad [cm^{-3}], \tag{1}$$

where $\Delta\lambda^{Stark}(H_\beta)$ is measured in nm, and the electron density n_e is expressed in cm^{-3}. The $\alpha_{1/2}$ parameter (fractional semi-half-width) is tabulated in [6]. The simple relation for n_e obtained by

Goktas et al [7], for the electron temperature in the range of 1-4 eV and electron density between 10^{14} and 10^{18} cm^{-3}, is

$$n_e = 1.09 \cdot 10^{16} \cdot [\Delta\lambda^{Stark}(H_\beta)]^{1.458} \ \ [cm^{-3}], \quad (2)$$

where $\Delta\lambda^{Stark}(H_\beta)$ is expressed in nm.

The more recent Gig-Card theory (disclosed in [8]) incorporates the ion dynamics to evaluate the Stark broadening of lines spontaneously emitted by the plasma [4]. It results in the relation between $\Delta\lambda^{Stark}(H_\beta)$, n_e and T_e as tabulated in [8]. We interpolated the values tabulated in [8], resulting in a simple relation between $\Delta\lambda^{Stark}(H_\beta)$ and n_e in the form of:

$$n_e = 10^{16} \cdot [\Delta\lambda^{Stark}(H_\beta)]^{1.55} \ \ [cm^{-3}], \quad (3)$$

where $\Delta\lambda^{Stark}(H_\beta)$ is in nm.

EXPERIMENTAL SETUP

The main parts of the experimental setup used in this investigation were a 2.45 GHz magnetron generator, surface wave launcher of surfaguide-type, microwave power supplying and measuring system, gas supplying and flow control system, spectrograph for emission line analysis equipped with a CCD camera, and a PC computer. As an SWSP source, the surfaguide [1] based on a standard WR 430 rectangular waveguide was used (Fig. 1). The plasma was generated in the form of a plasma column in a quartz tube placed vertically across the reduced-height section of the waveguide. The quartz tube was cooled with a dielectric liquid. The metal shield placed coaxially around the quartz tube protected the personnel and instrumentation from the electromagnetic radiation. The vertical slit in the metal shield made the observation of the plasma column and performing the spectroscopic measurements possible. The circular gap in the reduced-height section of the waveguide made the performing the spectroscopic measurements possible in the wave launching region. The inner and outer diameters of the quartz discharge tube were 1 mm and 5 mm, respectively. The microwave power, up to 1500 W, was fed directly via the waveguide from the magnetron generator at one end of the surfaguide structure while the opposite end was terminated with a movable plunger.

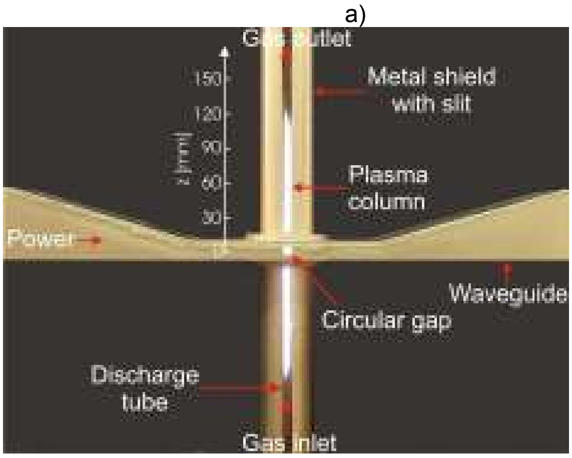
The operating gas (with a small amount of water vapour) flowed at a rate of 0.5 l/min in the quartz tube to be ionized and form the plasma column and finally to exit directly to the ambient atmosphere. The microwave power delivered to the discharge was calculated as P_I-P_R, where P_I and P_R are the incident and reflected powers, respectively.

To measure the H_β spectral line profile, the light emitted by the plasma column was focused onto the entrance slit of the spectrograph [DK-480 (CVI), (1200 grooves/mm)], where the emission lines were selected and then their intensities recorded with a CCD camera. The width of the entrance slit of the spectrograph was 100 μm. Two horizontal slits (that is, in a plane perpendicular to the plasma column) were placed between the plasma column and the optical lens to collimate the light from a selected section of the plasma column, about 5 mm in height and covering the whole plasma column width.

The instrumental line profile is assumed to be nearly Gaussian. The gas temperature in the plasma column was estimated to be in the range of 1000-2500 K [9], depending on the location within the plasma column. Within this temperature interval, the corresponding Doppler widths of H_β spectral line is approximately between 0.010 and 0.017 nm. Hence, we can assume that the Gaussian line profile width is about 0.14 nm.

In all investigations presented in this paper the gas flow rate was relatively low (0.5 l/min), so the plasma column was generated in the form of a single filament, and the length of the upstream and downstream plasma columns were almost the same.

a) b)



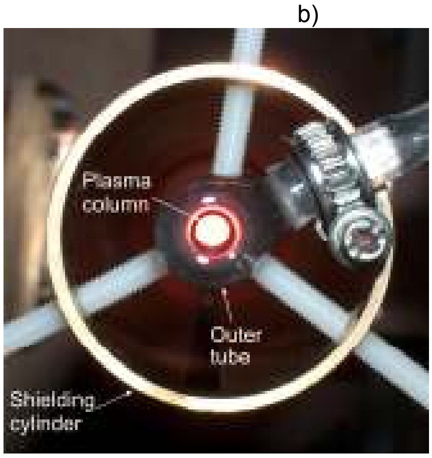


FIGURE 1. The photographs of the surfaguide shown front view (a) and top view (b).

RESULTS

The fitting to the line profile was made using the Voigt function with a Gaussian line width of 0.14 nm. The resulting value of the FWHM of the Lorentzian (Stark) profile $\Delta\lambda^{Stark}(H_\beta)$ enabled us to calculate the electron density using the formula (2) [GKS theory] or (3) [Gig-Card theory].

Generally, our results show that the electron density in Ar plasma column ranged from about 5×10^{14} cm^{-3} up to 4.5×10^{15} cm^{-3}, depending on absorbed microwave power (200-1500 W) and location along the plasma column. The electron density in Ne plasma column was about 2 times lower at the same conditions. The Gig-Card theory consistently gives lower (by about 20 %) values of the electron densities than the GKS theory. This behavior is in a good agreement with the observations described in [4].

Fig 2a shows electron density n_e (determined using Gig-Card theory) as a function of distance z (z – distance along the upstream Ar plasma column measured from the center of the reduced-height section of the waveguide, see the circular gap in Fig. 1) in the upstream Ar plasma column for two values of microwave power (500 W and 1000 W). As seen in Fig. 2a, the electron density decreased from about 1.5×10^{15} cm^{-3} to 5×10^{14} cm^{-3} at microwave power of 500 W and from about 2.8×10^{15} cm^{-3} to 5×10^{14} cm^{-3} at microwave power of 1500 W when increasing the distance z from 0 (center of the reduced-height section of the waveguide) to the end of the upper plasma column (z=130 mm and 225 mm). Except for a region inside the waveguide (wave launching region) and close to the waveguide, the electron density decreased approximately linearly.

Fig 2b shows electron density n_e (determined using Gig-Card theory) for microwave absorbed power of 500 and 1000 W as a function of the distance l-z, where l is the length of the upstream plasma column. The distance l-z means the distance measured from the end of the upper plasma columns, so the values of l-z = 0 correspond to the end of plasma columns. Values of l-z = 220 mm and l-z = 135 mm correspond to the region inside the waveguide for microwave powers of 1000 W and 500 W, respectively.

Fig. 2b shows, that at microwave powers of 500 W and 1000 W in the range of l-z from 0 to 110 mm, the distribution of the electron densities are the same. It can means that in this range of l-z, the plasmas are almost identical at different microwave powers delivered to the discharges. This behavior of the electron density along the plasma columns at different values of microwave power is in agreement with the theory of surface wave sustained discharges.

In the region, where l-z $\cong 0$ (close to the end of the plasma column), the electron densities ($\sim 5 \times 10^{14}$ cm^{-3}) are the same at different microwave powers. It can means that this value of the electron density ($\sim 5 \times 10^{14}$ cm^{-3}) is critical value for the sustaining the discharge.

The behavior of the electron density in the region inside the waveguide (launching region) and close to the waveguide is in a good agreement with calculated results described in [10].

CONCLUSIONS

In this paper we presented results of the spectroscopic measurements of the electron density in the surface wave sustained atmospheric-pressure Ar and Ne plasma generated by surfaguide

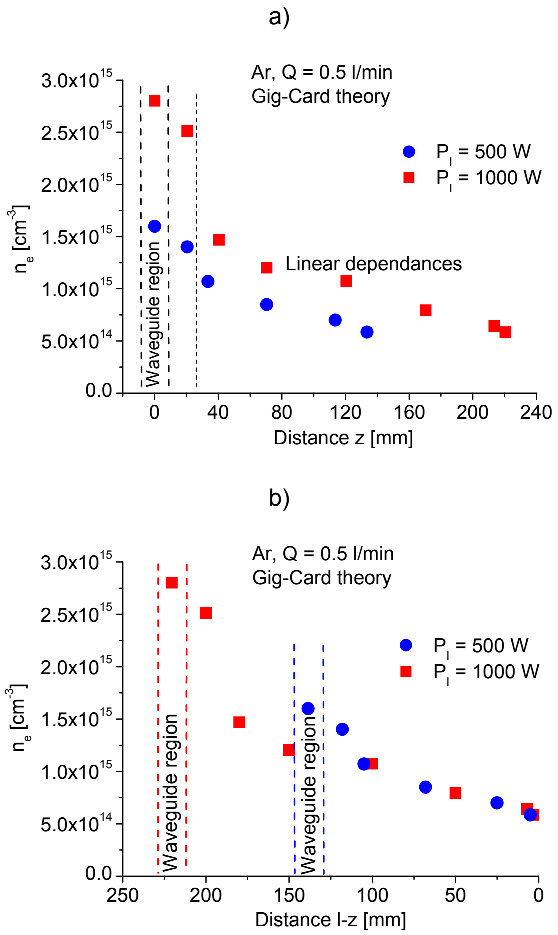


FIGURE 2. Electron density n_e in the Ar plasma columns as a function of the distance z (a) and distance l-z (b), where l is the length of the upstream plasma column and z is the distance along the upstream plasma column measured from the center of the reduced-height section of the waveguide.

cooled with dielectric liquid.

The electron densities in the surfaguide plasma was determined by the Stark broadening method, using both the GKS and Gig-Card theories. The measured electron densities ranged around 10^{15} cm^{-3}, depending on the discharge conditions and the location along the plasma column. Except for a region inside the waveguide (launching region) and close to the waveguide, behavior of the electron density along the plasma columns at different values of microwave power is in agreement with the theory of surface wave sustained discharges.

Our results include the electron density in plasma generated in the reduced-height section of the waveguide (launching region), which was not measured earlier.

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