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Determination Of The Temperature Distribution In The Cathode Sheath Region Of Hydrogen Glow Discharge Using R-Branches Of Fulcher-α Band

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Optical emission spectroscopy technique was used to measure rotational and gas temperature distribution in the cathode-sheath region of an abnormal glow discharge operated in hydrogen. The rotational temperature of excited electronic states of H_2 was determined from the relative line intensities of the R-branch of the Fulcher-α diagonal band $d^3\Pi^+_u$, v'=0 → $a^3\Sigma^+_g$, v''=0 and compared with published results for the Q-branch of the Fulcher-α diagonal band $d^3\Pi^-_u$, v'=0 → $a^3\Sigma^+_g$, v''=0. The population of excited energy levels, determined from the relative line intensities, was used to derive the rotational temperature of the ground state of hydrogen molecule. The boundary between the cathode sheath and negative glow region is determined using Stark polarization spectroscopy of the hydrogen Balmer alpha line.

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1. INTRODUCTION

Glow discharges (GD) have been extensively used in a wide variety of applications such as for the operation of an excitation source for analytical spectroscopy of metal and alloy samples [1, 2] or for depth profiling. Most glow discharge sources (GDS) are based on the original Grimm design [3] and are driven either by direct current or more recently by radio frequency (RF) excitation. As the most important part of abnormal GD, the cathode-sheath (CS) region has been subject of numerous experimental and theoretical studies [1-4]. The knowledge of discharge parameters (e.g., the electric field strength distribution, and excitation, rotational, vibrational, and gas temperature of molecules, etc.) in the CS region of hydrogen and hydrogen-containing low-temperature plasmas is of common interest in basic research and industrial applications, and for understanding the outer space phenomena, see Ref. [4]. In this study, the optical emission spectroscopy (OES) technique is used to determine electric field strength and rotational spectroscopic temperature in hydrogen at low-pressure Grimm-type GD. For this purpose, hydrogen H_α line is used for electric field strength mapping and boundary estimation between the CS and the negative glow (NG) region. For the temperature estimation, Fulcher-α, $d^3\Pi^+$, $\nu' \rightarrow a^3\Sigma^+$, ν'' ($\nu' = \nu''=0$) R-branch lines of diagonal band are recorded and analyzed in the CS region. The results are compared with previously published temperatures obtained from the Q-branch of Fulcher-α diagonal band.

2. EXPERIMENTAL

A detailed description of a modified Grimm GDS is given in Ref. [5] and thus only a few important details will be mentioned here. The experiment was realized in a hydrogen discharge and further details can be found in Ref. [6]. The axial intensity distribution of radiation has been observed side-on through the anode slot, see Figure 1. The discharge tube was translated in approximately 0.25 mm steps. The light from the discharge was focused with an achromatic lens (focal length 75.8 mm) with unity magnification onto the 20 μm entrance slit (height restriction 2 mm) of 2 m focal length Ebert type spectrometer with 651 g/mm reflection grating blazed at 1050 nm. For the line shape measurements, the reciprocal dispersion of 0.37 nm/mm is used throughout this experiment. All spectral measurements were performed with an instrumental profile very close to Gaussian form with measured full width at half maximum (FWHM) of 14 pm. Instrumental profile which is determined from a part of the negative plasma spectrum containing neutral copper lines. Thermoelectrically cooled Hamamatsu CCD (2048 × 506 pixels, pixel size 12 × 12 μm, -10 ºC) was used as a radiation detector, and the collected data were transferred to and processed by a PC.

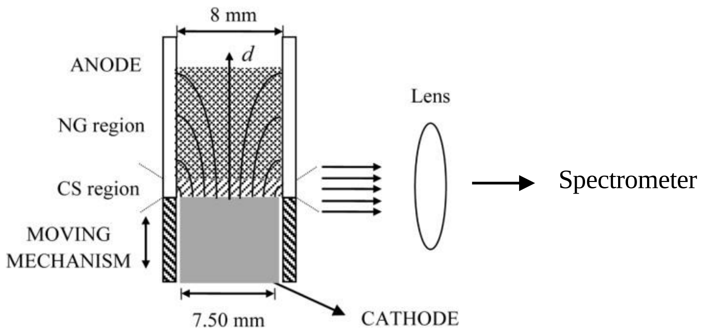

Figure 1: Schematic diagram of the central part of the Grimm GD for side-on observations. Symbols: CS – cathode sheath region, NG – negative glow region.

3. RESULTS AND DISCUSSION

The temperature obtained from Q branch of the Fulcher-α band may be considered as the most reliable for the temperature estimation, see details in Ref. [6]. Now, we investigate a possibility of using R branch of the $d^3\Pi^+, \nu'=0 \rightarrow a^3\Sigma^+, \nu''=0$ molecular system for temperature measurement in hydrogen Grimm GD. Apparently, R branch lines of the $d^3\Pi^+, \nu' \rightarrow a^3\Sigma^+, \nu''$ ($\nu'=\nu''=0$) electronic transition are well resolved in 590-610 nm wavelength region (wavelength data are taken from Ref. [7]), see Figure 2.

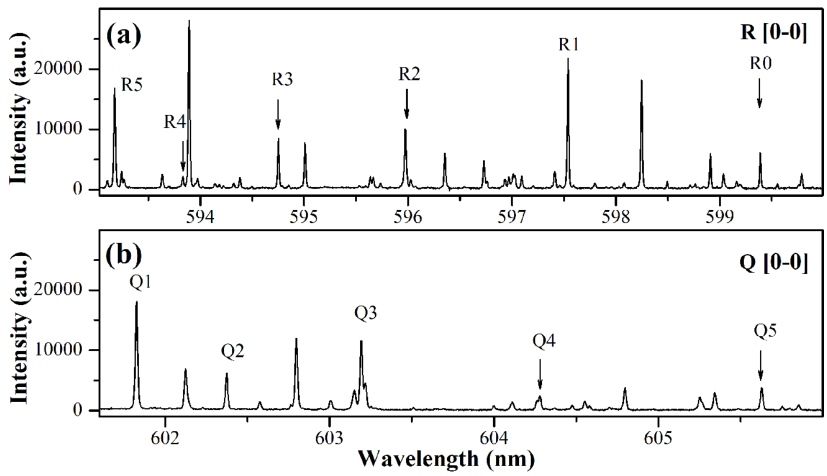

Figure 2: Emission spectra of rotational lines for $d^3\Pi^+ \rightarrow a^3\Sigma^+$ system; (a) R-branch with $\nu'=\nu''=0$ and (b) Q-branch with $\nu = \nu' = 0$ recorded in the second order of diffraction grating. Experimental conditions: cooper cathode Grim GD in H_2 at p = 4.5 mbar; I = 11 mA, and U = 889 V.

Also, the applicability of Hönl-London (HL) factors within $d\ ^3\Pi^+_u, 0 \rightarrow a\ ^3\Sigma^+_{g,0}$ transition [8] is investigated. Since the transition probabilities for the rotationally resolved rovibrational transitions are unknown, line strengths will be used as HL factors. In this case, the so-called rotational branching ratio must be determined experimentally from the line intensity ratios correlated with relative line strengths S_R/S_P. The example reported in [8] illustrates well the described procedure. The ratios of measured line intensities, obtained within one pair of lines (in R and P-branch) starting from the same rotational levels (see e.g., Grotrian diagram in Fig. 2(a) of [9] for Fulcher-α band transition $\nu' = \nu'' = 0$), have been used as good indicators for applicability of the HL factors for temperature measurements within the $d\ ^3\Pi^+_u$, $0 \rightarrow a\ ^3\Sigma^+_g$, 0 transition. The ratio values predicted by the HL formulae for Fulcher-α band ($\Delta\nu = 0$, $\nu' = 0$) are plotted in Fig. 3(a) as a function of the rotational quantum number. The comparison of data shows that the experimental ratio of line intensities for the R and P branch is close to the prediction of HL formulae.

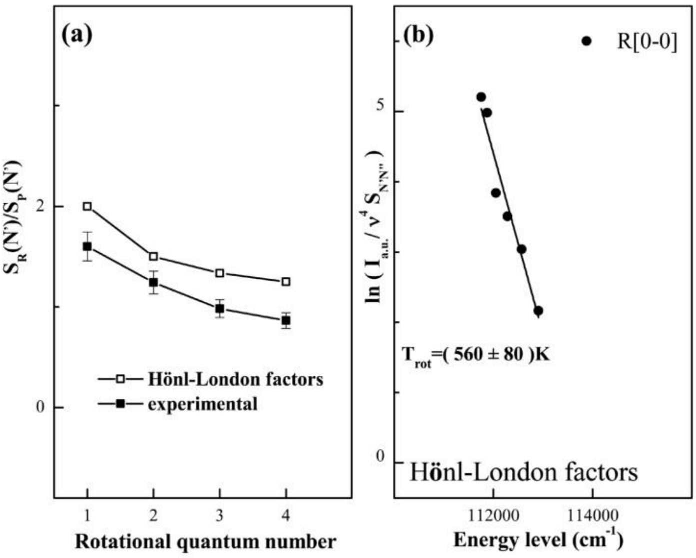

Figure 3: (a) The comparison of measured branching ratios with the ratios of Hönl-London (HL) factors for $d^3\Pi^+_u,0 \rightarrow a^3\Sigma^+_g,0$ and (b) Semi logarithmic plot of population densities for rovibronic levels of H_2 $d^3\Pi^+_u,0,N'$, calculated from the measured intensities using the HL factors of R branches.

The logarithm intensity of a spectral line of rovibronic transition (n', v', $N' \rightarrow n''$, v'', N'') is a linear function of the upper energy level. The values of $ln\ (I\ /\ \upsilon^4\ g_{a.s.}\ H_{N'\,N''})$, plotted against the term values for upper level in Fig. 3(b), lie on a straight line whose slope $hc/kT_{rot}(n',v')$ can be used for determination of the rotational temperature $T_{rot}(n',v')$ of the excited state; here, υ is the wave number, $g_{a.s.}$ is the statistical weight of the (n', v', N') rovibronic level caused by nuclear spin and the symmetry with respect to the permutation of the nuclei ('a' or 's'), while $H_{N'\,N''}$ are the HL factors see [4] and references therein. The rotational temperature $T_0\,(n',v')$ of the ground state, determined from the rotational population density distribution in an excited (n',v') state in the framework of the model discussed in [6], can be considered as a valid estimation of the ground state rovibronic temperatutre, i.e., H_2 gas temperature. The recalculated temperature T_0 is 2 times larger than the rotational temperature of excited state $d^3\Pi_u$, see in [6, 9]. For the estimation of the CS region thickness we employ the same technique previously described in [6]. The electric field strength distribution is determined by fitting the experimentally obtained profiles of the π-polarized hydrogen Balmer H_α line with a suitable model function, see Figure 4. This model function with all involved parameters, is explained in details in the reference [6]. Using the previously mentioned technique, we determined that the thickness of the CS region doesn't exceed 2.25 mm in pure hydrogen discharge, see Figure 5(a).

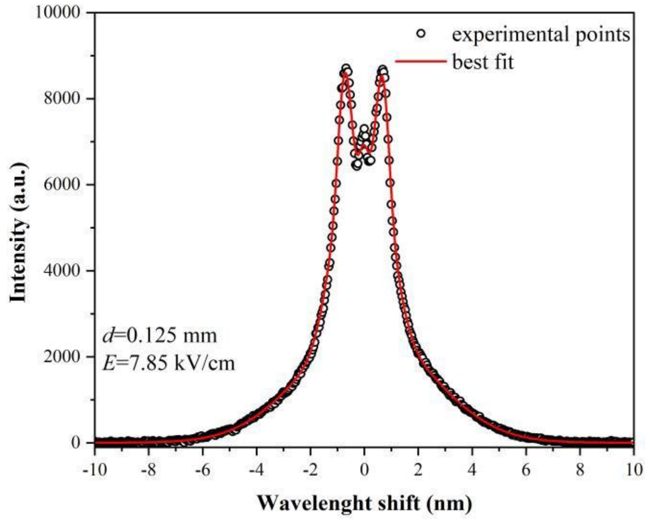

Figure 4. The π-polarized side-on experimental profiles (points) of the Hα line recorded in the CS region. The solid (red) line represents the best fit obtained by the model function (1) from [6]. The corresponding best fit values of electric field strength *E* and the distance *d* from the cathode are shown in the legend. Experimental conditions: cooper cathode, Grimm GD in H_2 at p = 4.5mbar; I = 11 mA; U = 889 V.

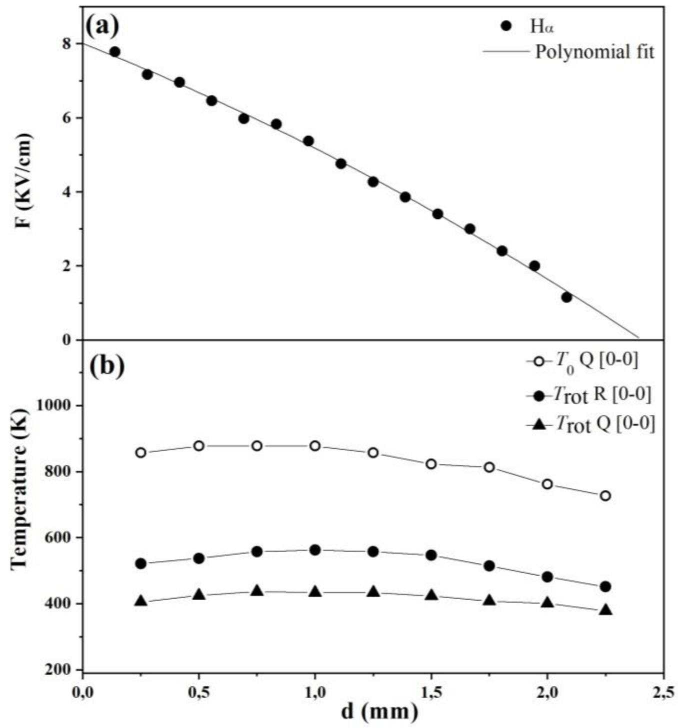

Figure 5: The dependence upon the distance from cathode *d* of: (a) Electric field strength *F* (b) Rotational (T_{rot}) temperature distribution of the excited state H_2 ($d^3\Pi_u$) and the rotational temperature T_0 recalculated from the population of Q-branch $\nu' = 0$ for the ground state $X^1\Sigma^+ (\nu = 0)$. Experimental conditions: cooper cathode Grim GD in H_2 at p = 4.5 mbar, I = 11 mA, and U = 889 V.

In Figure 5(b) we compare the results obtained from the R-branch with the results obtained from the Q-branch, previously reported in [6]. Our analyses give the results that deviate by no more than 30%, compared with those from Q-branch. This finding indicates that the R-branch can be used for determination of the rotational temperature with a reasonable accuracy as well as Q-branch of the Fulcher-α band considered as the most reliable for the temperature estimation, see [4].

Acknowledgments

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