Electric field distribution in the cathode sheath of an electron beam glow discharge

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We have measured the electric field distribution in the cathode sheath of an electron beam He glow discharge. Laser saturation spectroscopy was used to determine the quadratic Stark shift produced by the electric field. The experimental results are in good agreement with the calculations of a collisional model of the cathode sheath.

High-voltage cold-cathode glow discharges can be used to produce high-intensity electron beams.[1] These broad area beams have been recently applied to laser excitation and materials processing.[2–6] In low-pressure glow discharges a large voltage drop occurs in the cathode sheath. Ions from the negative glow region of the discharge are accelerated by the electric field in the cathode sheath and bombard the cathode, emitting electrons that are accelerated in the opposite direction to form the electron beam.

The energy distribution, current density, and efficiency of the electron beams generated in high-voltage glow discharges are closely dependent on the electric field distribution in the cathode sheath. Previously, the electric field distribution in the cathode region of glow discharges has been measured using electron beam probes[7–9] and Stark effect of Rydberg atoms[10,11] and molecules.[12] However, in the previous experiments with dc glow discharges, the electric fields were about an order of magnitude lower than in the electron beam glow discharge of the present investigation.

In this experiment, quadratic Stark shifts of the He I 2^1P_1–3^1D_2 transition produced by the electric field in the cathode fall region of a helium glow discharge are measured by laser saturation spectroscopy. The results are compared to calculations of a model of the cathode sheath. Although quadratic Stark shifts are less sensitive to small electric fields such as those in a positive column of a glow discharge,[13] it has some advantages in the type of discharges characterized by high electric field strengths and large current densities. The resolution obtained in this experiment is comparable to the linear Stark effect measured by optogalvanic spectroscopy in the cathode fall by Doughty and Lawler.[10] The most important advantage is that the conversion from measured frequency shift to electric field strength is straightforward. For the 2^1P and 3^1D levels, the quadratic Stark shift can be easily calculated from perturbation theory, using only the 2^1S and 3^1P levels as perturbers, respectively, and with the sum over the dipole matrix elements replaced by oscillator strengths.[14] In contrast, at the high electric field strengths encountered here (several kV/cm), the linear Stark pattern of high Rydberg transitions will be complicated. A second advantage is that a visible dye laser instead of a UV laser is used, which simplifies the experimental requirement.

The experimental arrangement is shown in Fig. 1. The discharge chamber is made from a 4-in.-diam five-way cross-stainless-steel vacuum chamber. The discharge is formed between a 3.2-cm-diam flat Mo cathode surrounded by an alumina tube and the walls of the vacuum chamber, about 15 cm away. High-purity He gas is continuously circulated to ensure a clean discharge. Measurements are made at various discharge pressures and currents. A single-mode cw dye laser operating with DCM dye is used to excite the He 2^1P–3^1D transition at 668 nm. The laser polarization is normal to the cathode so that only $\Delta m = 0$ transitions are induced. The laser beam travels parallel to the cathode surface and is focused to a diameter of 0.88 mm. The beam is mode matched and retroreflected so that the saturation signal can be obtained. The transition is monitored by the laser-induced resonance fluorescence from the 3^1D level. This fluorescence is collected with a lens, sent through a 1/4-m monochromator and detected with a photomultiplier. To discriminate against

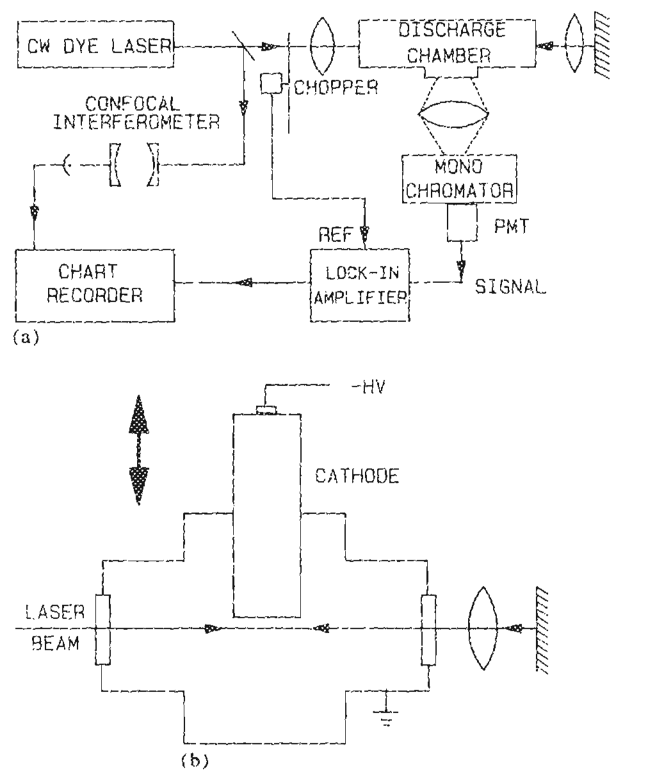

FIG. 1. (a) Schematic representation of the experimental setup. (b) Position of the laser beam relative to the cathode. The arrow indicates the direction in which the entire discharge chamber can be moved with respect to the fixed laser beam.

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the discharge background, the laser beam is chopped with a mechanical chopper and the signal is processed via a lock-in amplifier.

The saturation intensity of the 2^1P–3^1D transition is calculated to be 30 mW/mm^2. With an input intensity of $\simeq 100$ mW/mm^2, the saturation dip is about 5% of the Doppler fluorescence signal. The experimental width of 400 MHz is essentially limited by the short lifetime (0.6 ns) of the $2\,^1P$ level. Even so, a frequency shift of 30 MHz can be readily measured. To convert measured frequency shift to electric field, we note that the spectrum consists of two unresolved Stark components, namely the $m = 0 \rightarrow 0$ transition, and the degenerate $m = 1 \rightarrow 1$ and $m = -1 \rightarrow -1$ transitions. Thus the measured frequency shift corresponds to the shift of the centroid of these two components. We then calculate a quadratic Stark shift for the He 2^1P_1–3^1D_2 transition of $\Delta\nu = -1.28 \times 10^7 E^2$, where E is the electric field in kV/cm and $\Delta\nu$ is in Hz.

The spatial electric field profile is measured by translating the discharge chamber with a micrometer controlled stage. For each position the laser is scanned and a saturation spectrum is recorded. A part of the laser beam is sent into a confocal interferometer to provide frequency markers at 1.5 GHz intervals. The frequency shift of the saturation dip from the zero field (negative glow) Lamb dip is measured as a function of the distance of the laser beam from the cathode. The determined shift is then converted into electric field. The results are shown in Fig. 2 as open circles. Figure 2(a) is for a discharge pressure of 1.3 Torr, a discharge voltage of 5.11 kV, and a current of 35 mA. The experimental result shows the sharp downward bend of the electric field near the edge of the negative glow, but is relatively linear in the rest of the cathode sheath. This sharp bend was reported in the electron beam probing of discharges,[8] but, prior to this work, laser probing techniques were not able to confirm its existence. The electric field at the cathode is almost 8 kV/cm. The reduction of the width of the cathode fall region with the increase in pressure is clearly observed by comparing Figs. 2(a) and 2(b). The latter corresponds to a He pressure of 2.3 Torr, a discharge voltage of 4.97 kV, and a current of 70 mA. The error bars in the data correspond to how well the Lamb dip line center can be measured. However, possible laser frequency drifts are not included. The data points which fall below the horizontal axis do not represent negative electric fields. Rather, they have a measured blue shift relative to the zero field frequency. This indicates the large errors involved in using quadratic Stark shift to measure small electric fields.

The solid lines in Figs. 2(a) and 2(b) illustrate the electric field distribution calculated from our model developed for the cathode sheath of the high-voltage glow discharge. Details of this model will be presented in a separate report. Briefly, our calculations were made by solving Poisson's equation and the equations of continuity, in a self-consistent way, for the flux of energetic charged and neutral particles. The creation of charged particle pairs in the sheath due to collisions of beam electrons, fast ions, and fast neutrals with thermal atoms was also included in the equations. Fast neutral atoms created by charge transfer and momentum transfer of thermal atoms with energetic ions do not contribute to the space charge but are included because they can add to the emission of secondary electrons from the cathode.

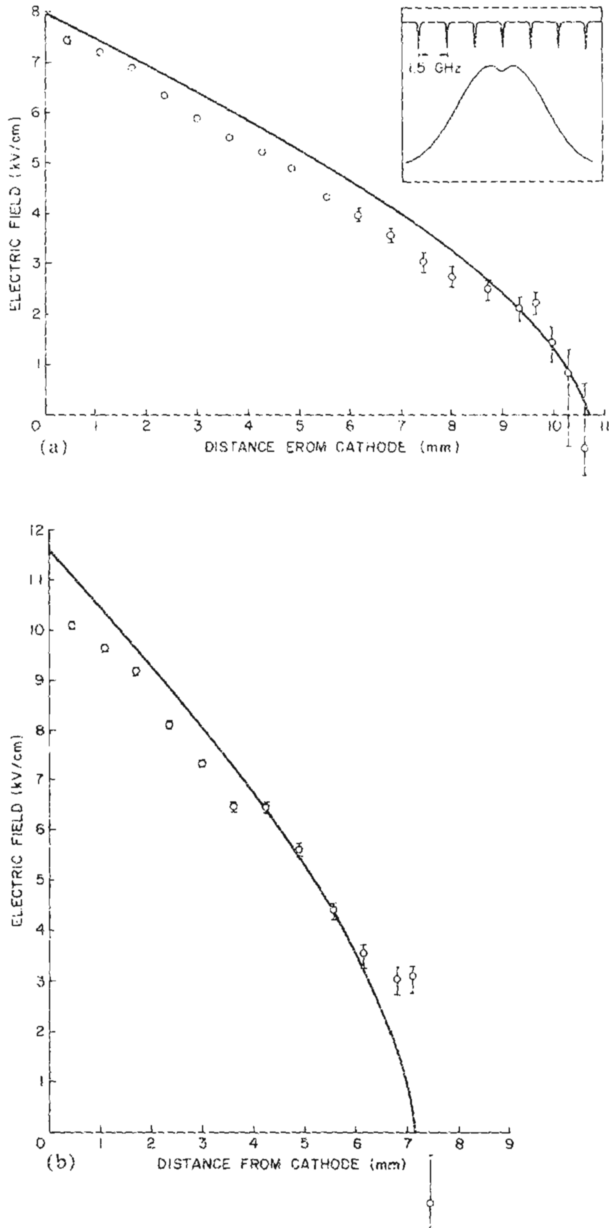

FIG. 2. Measured (open circles) and calculated (solid lines) electric field distribution in the cathode sheath. (a) He pressure 1.3 Torr, discharge voltage 5.11 kV, current 35 mA. The atomic temperature was measured to be 733 K. The inset shows a saturation spectrum with frequency markers. (b) He pressure 2.3 Torr, discharge voltage 4.97 kV, current 70 mA. Atomic temperature was measured to be 926 K.

The gas pressure in the discharge was measured with a Barratron gauge, and the atomic temperature was determined from the Doppler width of the 668 nm He I transition. The gas density obtained was used as an input to the model. The model calculates the energy spectrum of the energetic particles and the electric field as a function of the distance from the cathode for a given discharge condition. The electric field distribution calculated in this way agrees to within 10% with the majority of the measurements. This is a better agreement than models of simplified calculations based on free fall or diffusion approximations for the ion flux.[15]

In some applications of the electron beam glow dis-

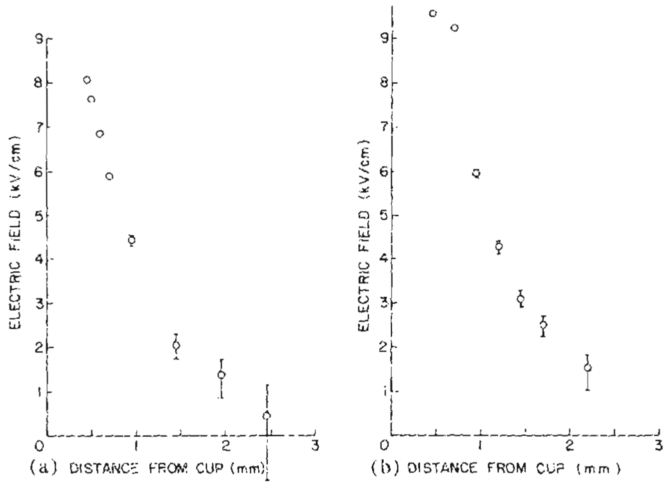

FIG. 3. Measured electric field distribution for the case in which a grounded metal cup with a slot is placed 1.5 mm from the cathode. This distance should be added to the value of the horizontal axis if the origin is to be placed at the cathode surface. (a) He pressure 2.25 Torr, discharge voltage 4.4 kV, current 12 mA. (b) He pressure 1 Torr, discharge voltage 6 kV, current 10 mA.

charge, the cathode emission is collimated to a rectangular region by means of a grounded metal cup placed close to the cathode.[5,6] We used a cup at approximately 1.5 mm from the cathode surface. The cup has a slot 3.2 cm long and 0.5 cm wide through which ions from the plasma reach the cathode and electrons are emitted. This geometry produces a sheath of beam electrons corresponding to the length of the slot and a thickness of a few mm. A second set of measurements, taken with the cup on, is shown in Figs. 3(a) and 3(b) for two different discharge conditions. In this case the laser beam was placed in the plane defined by the longest axis of the rectangular slot and the entire chamber was displaced with respect to the laser beam as before. It is interesting to note that the electric field distribution is significantly altered: The field is peaked near the cathode and steeply decays asymptotically to zero.

In summary, we have performed electric field measurements in the cathode fall region of a glow discharge by laser saturation spectroscopy. Most of the points of measured electric field distribution agree to better than 10% with the calculations of a model of the cathode sheath which includes ionization due to electrons, fast ions, and energetic neutral atoms.

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