The Effect of Electron Reflection from the Electrodes of an Obstructed Discharge

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Abstract: In this paper we report our investigations of an obstructed glow discharge in helium with a special attention to the effect of the reflection of electrons from the discharge electrodes. Our experimental investigations concerned the measurement of voltage - pressure characteristics of the discharge and spatially resolved electric field measurements using Stark spectroscopy. A model of the discharge was also developed and several discharge characteristics (electric field distribution, spatial dependence of ionization rate, electron energy distribution, etc.) have been calculated in a self-consistent way. The reflection of electrons from the anode was found to affect significantly the characteristics of the discharge. Besides the calculations we have also experimentally demonstrated the effect of electrode reflectance by using different anode materials.

1. Introduction

Obstructed discharges are characterized by increased voltage compared to "normal" operation mode glow discharges. The obstructed operation mode can be established by reducing the \( nL \) product \((n = \text{gas density}, L = \text{electrode separation})\) in a glow discharge. When the length of the cathode dark space \((D)\) becomes comparable to \( L \), the discharge voltage starts to rise considerably [1–4]. In the absence of negative glow the ionization necessary to maintain the discharge has to be created in the cathode dark space and this requires an enhanced voltage. Beside this effect with decreasing \( nL \) the number of high energy electrons absorbed by the anode increases and this also causes additional losses in ion production [5]. Because of this the rise of the voltage with further decreasing \( nL \) becomes quite steep as it can be seen in Fig. 1 displaying the measured voltage - pressure characteristics of a helium discharge at constant current.

The aim of this paper is to study the effect of electrode reflection on
- the spatial distribution of ion production (also combined with the energy distribution of ionizing electrons),
- energy distribution of electrons absorbed by the anode, and
- the electric field distribution.

In cold cathode glow discharges the processes responsible for the maintenance of the discharge (basically the ionization, excitation and secondary electron emission processes) take place in the cathode region. As the secondary electron emission coefficients depend sensitively on the properties (material and surface conditions) of the cathode, many discharge characteristics are determined by the cathode conditions. The properties of anode are usually less significant. However, in certain types of discharges, such as in obstructed discharges - as we will see later - the reflection of electrons from the anode, and thus the anode material
Fig. 1. The voltage-pressure characteristics of a helium discharge at \( I = 1 \) mA current and the change of the visual appearance of the discharge (CDS: cathode, NG: negative glow).

and its surface conditions, also play an important role. Another important example of the effect of electrode material on the characteristics of a (corona) discharge is given in [6].

We have studied an obstructed discharge in a discharge tube having two parallel plane graphite electrodes of 20 mm diameter separated by 4.6 mm. The discharge was confined into the volume defined by the electrodes. The experimental electric field measurements have been carried out on residuals of hydrogen in the discharge by recording the lineshape of the P polarized component of the \( \text{H}_\beta \) (\( \lambda = 410.2 \) nm) line. A Zeiss PGS-2 monochromator having a resolution better than 0.01 nm in the first order was used for lineshape recording. The data collection system was equipped by a HP54501A digitizing oscilloscope interfaced with an IBM-AT computer. The data acquisition was based on the decomposition of the measured lineshape into components arranged in corresponding P polarized \( \text{H}_\beta \) Stark pattern [7, 8]. All spectral components were assumed to have a gaussian lineshape influenced by the transfer function of the monochromator which was also experimentally determined. The details of the experimental setup and of the data acquisition procedure have been described in detail in [5].

2. The model of the discharge

In our model we assumed a radially uniform discharge between two plane electrodes. No edge effects were taken into account, the spatially resolved discharge characteristics were calculated as functions of the distance \( x \) measured from the cathode. However, the electrons were traced in the 3 dimensional space which provided a quite realistic description of their motion [9].

As both the high and rapidly changing values of \( E/n \) (electric field to gas density ratio) and the presence of boundaries induce non-equilibrium effects in the motion of electrons
(see e.g. [10]), Monte Carlo simulation was applied to follow the trajectories of electrons in the discharge gap. All the secondary electrons created in ionizing collisions were traced in the simulation. The elementary processes considered in the model were anisotropic elastic scattering of electrons from He atoms, electron impact excitation of He atoms and electron impact ionization of He atoms. The cross sections were taken from [11–13]. No ionization from the metastable and from other excited levels was considered. Volume recombination was also neglected. At low current densities and at high \( E/n \) these assumptions are realistic.

The input data of the model were the gas pressure and the experimentally determined voltage and current density of the discharge. Single electrons were released from the cathode of the discharge and their path was followed as they participated in the collision processes. The free path of each electron between successive collisions, as well as the type of the collisions that actually occurs after a free path, were assigned based on random numbers having appropriate distributions (for details see [9]). Finally the electrons were absorbed by the cathode or by the anode. All the secondary electrons created in ionizing collisions were traced in the simulation. The discharge gap was divided into a number of subintervals in which a linearly changing electric field distribution was assumed and the Monte Carlo procedure developed by Boeuf and Marode [9] was applied.

The \( E(x) \) electric field distribution was determined in a self-consistent way in an iterative manner. First, a linear decrease of the field from the cathode to the anode was assumed. Having traced a sufficient number of electrons the average velocity of electrons can be calculated from the electron energy distribution which is obtained during the simulation [9]. The calculation of the average velocity of the He\(^+\) ions is based on the hydrodynamic equilibrium assumption:

\[
<v^+(x)> = \left( \frac{2qE(x)}{Mn\sigma_s} \right)^{1/2},
\]

where \( q \) is the elementary charge, \( M \) the ion mass, \( n \) the gas density, and \( \sigma_s \) is the cross section of the symmetric charge exchange collision

\[
\text{He}^+ + \text{He} \rightarrow \text{He} + \text{He}^+.
\]

The \( \sigma_s \) cross section depends on the velocity of the ions:

\[
\sigma_s = k_1 - k_2 \ln<v^+(x)>,
\]

where \( k_1 \) and \( k_2 \) are constants within the ion velocity range of interest [14–16]. The average ion velocity \( <v^+(x)> \) was calculated by solving (1) and (2) simultaneously.

The fluxes of electrons \( (F^-(x)) \) and He\(^+\) ions \( (F^+(x)) \) per emitted electron can also be obtained from the simulation. Using the current density \( j \) determined in the experiment, we can calculate the current density taken by electrons \( (j^-(x)) \) and by He\(^+\) ions \( (j^+(x)) \):

\[
j^-(x) = j \frac{F^-(x)}{F^-(x) + F^+(x)}
\]
\[
 j^+(x) = j \frac{F^+(x)}{F^-(x) + F^+(x)} 
\]

(3b)

The electric field distribution can be calculated by using the Poisson equation (neglecting the negative space charge which is orders of magnitude less than the positive space charge):

\[
 \frac{dE(x)}{dx} = -\frac{1}{\varepsilon_0} \rho^+(x) = -\frac{1}{\varepsilon_0} \frac{j^+(x)}{\varepsilon_0 <v^+(x)>} 
\]

(4)

and

\[
 \int_{x=0}^{L} E(x) dx = V 
\]

(5)

where \( V \) is the discharge voltage and \( L \) is the electrode separation.

In each step of the iteration the modification of the original electric field due to the space charge was calculated and in the next step of the iteration this modified electric field distribution was applied. In our model the electron reflection coefficient \((R)\) was assumed to be independent of electron energy and the electron's angle of incidence. We have tested the range of reflectance \( R = 0-0.4 \). In the reflection process the velocity component normal to the surface was reversed.

3. Results

The results presented in Fig. 2–7 were obtained for the following (experimentally investigated) discharge conditions: electrode separation: \( L = 0.46 \text{ cm} \), helium pressure \( p = 5.7 \text{ mbar} \), discharge voltage \( V = 1020 \text{ V} \), current density \( j = 0.32 \text{ mA/cm}^2 \). The graphs representing spatial dependence of discharge parameters are shown as functions of normalized position \( x/L \), \( x/L = 0 \) corresponding to the position of the cathode.

The spatial distribution of ion production rate \( (dn^+/dt) \) is plotted in Fig. 2 for different values of the electrode reflection coefficient \((R)\). It can be seen that most of the ions are created near the anode especially at higher values of \( R \) Fig. 3 shows the dependence of \( dn^+/dt \) on \( R \) at the spatial positions \( x/L = 0.5 \) and \( x/L = 1 \). The electrode reflection has a very strong effect on ion production in the vicinity of the anode \((x/L = 1)\), the increase of \( R \) from 0 to 0.4 results in an about 9 times increase of \( dn^+/dt \).

The effect is less significant further from the anode (see \( x/L = 0.5 \) in Fig. 3). These data indicate that the electrode reflectance at the anode affects the discharge considerably. On the other hand the reflectance of the cathode (which was also taken into account in the simulation) seems to be negligible, compared to the effect of reflection of electrons from the anode.

The strong dependence of ion production rate explains the sensitivity of the obstructed discharge on minor changes of surface conditions (e.g. oxide layer, absorbed gas) which may influence the reflectance of electrodes \((R)\). In a glow discharge having fully developed cathode region (cathode dark space and negative glow) the electrons dissipate their energy
Fig. 2. The spatial distribution of ion production rate ($dn^+/dt$) for different values of the electrode reflection $R$ (at $p = 5.7$ mbar, $V = 1020$ V, $j = 0.32$ mA/cm$^2$).

Fig. 3. The dependence of the ionization rate on the reflection coefficient ($R$) at $x/L = 0.5$ and $x/L = 1$ (at $p = 5.7$ mbar, $V = 1020$ V, $j = 0.32$ mA/cm$^2$).
Fig. 4. The energy spectrum of electrons absorbed by the anode calculated at different electrode reflections: $R = 0$, $R = 0.2$ and $R = 0.4$. Discharge parameters: $p = 5.7$ mbar, $V = 1020$ V, $j = 0.32$ mA/cm$^2$.

Fig. 5a. The distribution of ionization events over normalized spatial position ($x/L$) and electron energy ($\varepsilon$) for electrode reflection of $R = 0.0$ ($p = 5.7$ mbar, $V = 1020$ V, $j = 0.32$ mA/cm$^2$).
Fig. 5b. The distribution of ionization events over normalized spatial position ($x/L$) and electron energy ($e$) for electrode reflection of $R = 0.3$ ($p = 5.7$ mbar, $V = 1020$ V, $j = 0.32$ mA/cm$^2$).

Fig. 6. The ionization rate corresponding to the three groups of electrons: primaries, secondaries and reflected electrons. ($p = 5.7$ mbar, $V = 1020$ V, $j = 0.32$ mA/cm$^2$).
mainly in the negative glow region. Therefore the electrons reaching the anode have much less energy than in the obstructed case. The reflection of these low energy electrons does not affect the ionization rate. These discharges - in contrast with the obstructed discharge - are less sensitive on the condition of the anode surface.

The energy spectrum of electrons absorbed by the anode (plotted in Fig. 4) also indicates that there is a considerable number of high energy electrons that are absorbed by the anode \((R = 0)\). If we take the anode reflectance \((R > 0)\) into account the distribution of absorbed electrons changes considerably. The number of low-energy electrons increases with increasing reflectance and the number of high-energy electrons significantly decreases. The absorbed electrons represent a loss for the maintenance of the discharge, since in a wider discharge gap (i.e. at higher \(nL\)) they could produce additional ionization.

Figs. 5a and 5b show distributions of ionization events on the \((x/L, \varepsilon)\) phase plane for \(R = 0\) and \(R = 0.3\) reflection coefficients, respectively. Both Figs. 5a and 5b contain information about 3500 ionizing events in form of dots corresponding to single ionization events. As the number of studied ionization events was the same in the case of \(R = 0\) and \(R = 0.3\), these plots show the importance of certain energy and spatial regions in ion production, but they are not comparable in terms of ionization rate (the latter was much higher in the case of \(R = 0.3\) (see Fig. 2)). Fig. 5a indicates that at low \(x/L\) (near the cathode) many ions are created by the electrons of highest available energy.

Above \(x/L = 0.5\) the electrons having \(\varepsilon = 200-300\) eV tend to be more important in ion production. At a higher value of \(R = 0.3\) - as it can be seen in Fig. 5b - most of the ionization occurs near the anode (mainly between \(x/L = 0.6\) and 1) by electrons having energies less than \(\varepsilon = 200\) eV.

The ionizing electrons can be divided into three groups:

- **primary** electrons (also called beam electrons, the electrons emitted from the cathode which have not lost energy in inelastic collisions)
- **secondary** electrons (the primaries after having lost energy in inelastic processes and the electrons created in ionizations)
- **reflected** electrons (electrons reflected by the anode electrode).

Fig. 6 shows the spatial distribution of the ionization rate due to the three different groups of electrons at an electrode reflectance of \(R = 0.3\). It can be seen in Fig. 6 that near the cathode (low \(x/L\) values) most He\(^+\) ions are created by primary electrons (beam ionization). In the region \(0.15 \leq x/L \leq 0.4\) the ionization is dominated by secondary electrons and above \(x/L = 0.4\) the reflected electrons play the most important role in the ion production.

The additional ionization due to the reflected electrons also changes the space charge density and the electric field distribution. Fig. 7 shows the results of the self-consistent electric field calculation for electrode reflection coefficients for \(R = 0, R = 0.2\) and \(R = 0.4\) (using the same, measured voltage and current as input parameters of the simulation). The measured electric field data are also plotted in Fig. 7 and a generally good agreement can be seen with the calculated field distributions. The data at the cathode side fit better for low values of \(R\) while the agreement at the anode side \((x/L \sim 1)\) is better for higher values of \(R\). Generally a reflection coefficient of about 0.3–0.4 gives the best agreement, whose range of values of \(R\) seems to be realistic.

To demonstrate the effect of electrode reflectance on the discharge characteristics another experiment was carried out. The discharge tube consisted of two discharge cells of identical geometry. The only difference between the cells was the anode material. One of
Fig. 7. Self-consistent electric field distribution calculated for different electrode reflections and the experimental results for $E(x)$. Discharge conditions: $p = 5.7$ mbar, $V = 1020$ V, $j = 0.32$ mA/cm$^2$.

Fig. 8. Voltage-pressure characteristics of helium discharges (at a constant current of $I = 1$ mA) with different anode materials. At higher pressures the voltages of the two discharges are close, with decreasing pressure the characteristics start to deviate indicating the differences in the electron reflectance of the anode.
the cells had a graphite anode and the other had a copper anode (copper is more reflective for electrons than graphite [17]). Both cells had graphite cathodes. We have measured voltage-pressure characteristics of the discharges at the same current. One pair of \( V(p) \) characteristics is plotted in Fig. 8. The voltages of the two discharges with different anode materials are close at higher pressures. It can be seen that with decreasing pressure the characteristics start to deviate. In the discharge with higher reflectance anode material (copper) the higher ionization rate results in a lower voltage compared to the discharge with a lower electrode reflectance material (graphite).

## 4. Conclusions

The effect of electron reflecting electrodes on the characteristics of an obstructed glow discharge has been investigated. The reflection coefficient \( R \) was assumed to be independent on electron energy and the angle of incidence of electrons on the electrodes. The spatial distribution of ion production and the energy spectrum of electrons absorbed by the anode were found to depend sensitively on the reflection coefficient \( R \). The sensitivity of the obstructed discharge on surface conditions of the electrodes was explained by the strong dependence of ionization rate on the reflection coefficient. The importance of spatial regions and electron energy ranges in the ion production was also studied. Taking the reflection of electrons into account a satisfactory agreement between the calculated (self-consistent) electric field distribution and the experimental data was found. The effect of electrode reflectance (anode material) on the voltage-pressure characteristics of the discharge was also demonstrated experimentally. It was found that this effect is important in the obstructed discharge regime.

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## References