Introduction

A systematic revision of Townsend’s theory of low pressure breakdown and low current dark discharges (Townsend discharges) has been recently started by Phelps and coworkers [1-3]. Standard Townsend theory could not explain some phenomena that were observed in experiments, such as negative differential resistance, oscillations and discharge constriction. Systematic, well defined measurements in the dark Townsend regime [1-3] led to reanalysis of the role of different elementary processes in electron/ion production in gas breakdown and in the maintenance of self-sustained discharges [3]. Extending these studies to higher current normal and abnormal glow discharges one may utilize the Volt-Ampere characteristics or the spatial profiles of emission to test the models of non-local electron transport and modelling of secondary electron yield that is to be applied for higher current discharges [4,5]. Finally, time resolved development of gas discharge structure can be related to kinetics of basic processes that participate to low-pressure breakdown and discharge maintenance. By tracking down time resolved structure of the discharge we were able to follow processes leading to the development of constriction, cathode fall and other features of glow discharges.

Studies similar to ours have been recently reported [6,7]. Those included spatiotemporal development of cathode-fall dominated DC discharges in argon [6] and of ignition of high current glow in complex geometry [7]. Our aim was to extend the studies to all typical modes of low-pressure discharges and to extend the knowledge of kinetics of formation and maintenance of these discharges in a simple geometry. Our work is based on temporally resolved imaging of light emission from discharge by fast ICCD camera, supported by voltage-current measurements. In particular, we followed the transition from steady-state Townsend regime to glow discharge and indications of the development of the space charge effects. The development of normal and abnormal glow discharges was recorded in side-on and end-on view, revealing axial development of the cathode fall and radial development of constrictions.

Experimental set-up

In our experiment, the discharge is established in a simple plane-parallel geometry. The cathode is made of copper, while the anode is made of quartz with transparent yet conductive thin film of platinum deposited on its surface. This way it is possible to record both radial and axial profiles of emission. The diameter of the electrodes is 5.4 cm while the electrode separation can be set at three different values – 1.1 cm, 2.1 cm and 3.1 cm.

We run a discharge at very low current (1-2 µA) by applying a DC voltage to resistors connected in series with electrodes. Triggering part of the circuit produces short voltage pulses superimposed on DC voltage. This technique enables us to reduce heating and conditioning of the cathode during the measurements. The delay generator built into the ICCD camera (Andor, iStar
DH720-18U-03) enables us to synchronize recording of the light emission with pulse development and voltage-current measurements. Details of experimental setup are presented in our previous papers (e.g. [4,5]).

**Results and discussion**

We performed measurements at \( pd = 250 \text{ P.acm} \), \( 150 \text{ P.acm} \) and \( 45 \text{ P.acm} \) (\( p \) – pressure, \( d \) – electrode gap) for three different electrode gaps, that covered formation and maintenance of different modes of discharge – low current diffuse (Townsend) discharge, constricted normal glow and abnormal glow discharge.

Paschen curve for argon in the range of conditions relevant for our study is shown in Fig. 1. The graph contains information on breakdown voltages and corresponding reduced electric fields in dependence on \( pd \). Operating conditions that we covered in our studies on time resolved development of discharge structure are indicated by open symbols.

Pressure times electrode gap values that are close to Paschen curve minimum (150 P.acm) were used as a test case. Higher \( pd \)-s were interesting to observe significantly constricted modes of a discharge, and lower \( pd \)-s to study contribution of heavy particles to discharge operation.

Fig. 2 shows steady state voltage-current characteristic in argon for selected conditions. VI characteristics exhibit behaviour typical for low-pressure nonequilibrium discharges [1-6].

We selected to present here temporal development of typical cathode fall dominated discharge and formation of constriction in normal glow at \( pd = 250 \text{ P.acm} \). Corresponding steady-state conditions are indicated by an arrow in Fig 2.
Fig. 3 shows current and voltage waveforms throughout the development of constricted regime of discharge. 2D images of the discharge are presented in Fig. 4. The discharge starts from Townsend’s regime, characterised by diffuse radial profile and exponential growth of intensity from the cathode towards the anode. Further on, the discharge gradually exhibits space charge effects. Peak of emission can be observed, which indicates formation of the cathode fall \[4.5\]. The peak of emission rapidly moves towards the cathode. At this point, the discharge gets somewhat curved towards the cathode (label 3 in Fig. 4). Detailed analysis of the discharge structure during rapid cathode fall development is presented in [8].

As the discharge current reaches maximum, the profile broadens radially and the peak intensity moves further towards the cathode (label 4). Following the decrease of the current, the intensity of emission decreases and the peak of emission moves away from the cathode (label 5), until Townsend-like profile develops (label 6). As the discharge approaches the steady state, formation of constriction can be observed. In this phase of discharge development, the peak of emission gradually moves axially towards the cathode and radially towards dielectric wall of the discharge chamber.

Our further analysis is based on the assumption that the discharge can be represented by parallel channels [8]. We have shown that during establishment of the stationary state, in the channel that corresponds to the highest emission intensity the discharge gradually develops from Townsend-like regime to normal glow regime of discharge operation. On the other hand, the remaining discharge channels retain Townsend-like behaviour with a gradual decrease of emission intensity. Axial emission profiles of the three selected channels in the stationary state are shown in Fig. 5. Under the given operating conditions, electric field is too low for the discharge to operate in Townsend regime. This mode of discharge clearly

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**Figure 3**

Current and voltage waveforms throughout the development of constricted regime of discharge.

**Figure 4**

2D scans of temporal development of discharge constriction. Labels 1-8 correspond to labels at Fig. 3. Dotted lines indicate position of the cathode (left) and the anode (right).

**Figure 5**

Axial emission profiles of three selected discharge channels in constricted regime.
operates in the non-self-sustained mode on the account of diffusion of charged particles from the constricted channel. Obviously, throughout formation of the constricted regime of the discharge, different discharge channels become dependent. The current growth in one of the channels leads to turning off of the remaining channels due to the decreased operating voltage.

Summary

Measurements of properties of low current discharges which include both Volt-Ampere characteristics and spatial profiles of emission proved to be a necessary basis for modelling. In our previous papers, measurements in different regimes of operation were analyzed by using a hybrid code and appropriate models of collisions, surface processes and in particular by using some aspects of secondary electron production as a fitting parameter [4,5]. Here we connect those studies with our recent measurements where space and time resolved recordings were made revealing some new phenomena such as curved front of emission and multi regime operation of the same discharge at the same time. Analysis of normal glow spatial structure development in time enabled us to follow kinetics of cathode fall formation. A constricted form of discharge is established, as the discharge approaches the steady state. In particular, it is important to note that coexistence of several modes of operation from Townsend to glow was observed in the same discharge at the same moment, depending on the local current density.

Our goal was partly to provide the experimental data that may be modelled by 2D models, which will provide further information on basic kinetic processes in the discharge. Nevertheless, based merely on inspection of the images one can reveal some new phenomena and settle some issues in the formation of gas discharges upon the breakdown of low pressure gases. Due to scaling laws, typical for space charge dominated discharges, these studies can also be very useful in investigations of micro discharges. They can also be extended to more complex systems used in specific applications and even to transients in cathode dominated high frequency discharges.

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References