DC BREAKDOWN IN AIR, OXYGEN AND NITROGEN AT MICROMETER SEPARATIONS

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The DC breakdown in Air, O_2 and N_2 has been studied in discharge system consisting of two parallel planar Cu electrodes at separations from 20 to 200 μm and in the pressure range between 6 mbar – 920 mbar. The results are presented in the form of breakdown voltage curves – Paschen curves. The analysis of the experimental data has been carried out in terms of semi empirical Paschen law. The effective secondary emission coefficient γ as a function of the reduced electric field has been estimated from the experimental data.

1. Introduction

In the last decade the microdischarges have attracted much attention as sources of stable and reliable non-equilibrium high pressure plasma [1-5]. One of the most common methods for generation of microdischarges represents the discharge tube with planar electrodes scaled down to the electrode gaps in the micrometer range [6]. Paschen law, which describes the dependence of the breakdown voltage as function of *p.d*, where *p* is the pressure and *d* is the electrode distance, represents an important scaling law. The validity of the Paschen Law was confirmed for variety of DC discharge conditions (pressures, distances, electrode materials) [7, 8]. However, already in fifties of the 20 century, the departures from the Paschen law have been observed at small electrode gaps [9, 10].

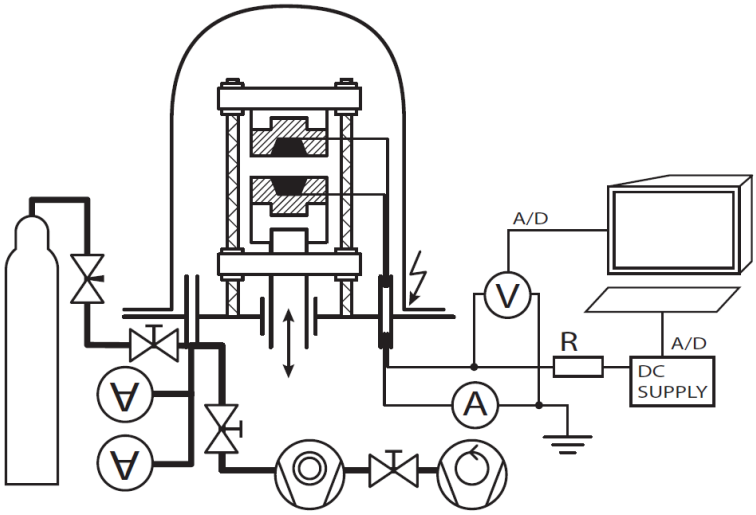

Fig. 1. Experimental setup.

2. Experiment

We have built a system to measure the DC breakdown at micrometer separations between planar metallic electrodes. The separation of the electrodes can be modified under vacuum conditions. The schematic view of the apparatus is shown in the Figure 1. The discharge system is located in the high vacuum chamber. The vacuum is generated by the turbo-molecular pump (Pfeiffer Vacuum TMU 071P) and the background pressure of $2x10^{-5}$ mbar has been achieved. The low pressures were measured by the ionisation gauge (Pfeiffer Vacuum, PKR 261) and the high pressures were measured by the capacitance gauge (Pfeiffer Vacuum, PCR 260 and MKS 626A 100Torr Barratron). The gases used in the experiment were O_2, N_2 (Linde, 5.0 purity) dry ambient air (X13 zeolites) and ambient air (50% humidity at 20°C).

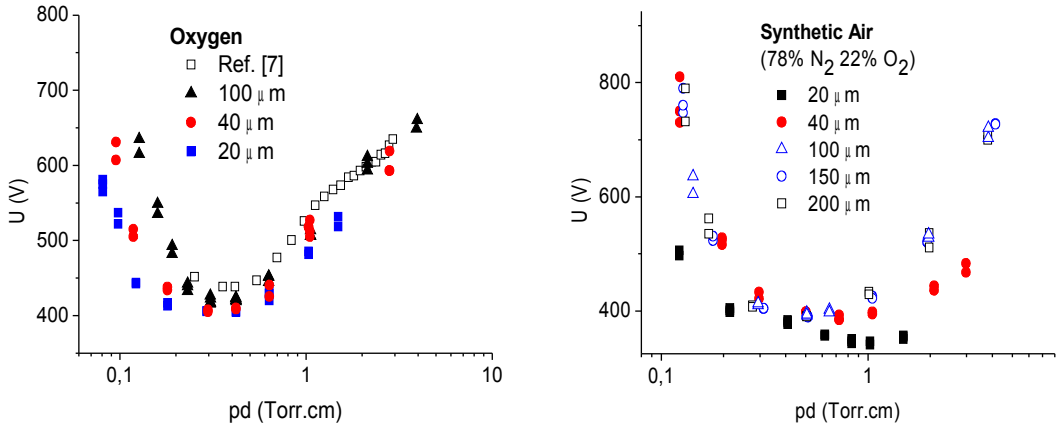

Figure 2 The experimental Paschen curve for DC breakdown for several electrode gasp a) in O_2, b) in synthetic air.

The discharge system for generation of the microdischarges consists of two planar copper electrodes with diameter of 5 mm. The electrodes were mechanically polished and chemically cleaned in ultrasonic bath. One of the electrodes was fixed and the other was movable continuously with micrometer scale linear feed-through. Both electrodes were equipped with dielectric cap (immune to vacuum, dielectric breakdown strength =13,8 kV/mm) to prevent the ignition of the discharge at longer path at low pressures. One of the electrodes was earthed; to the second electrode we have applied DC voltage (ISEG HPp 20 407). The 0 µm separation of the electrodes was established by checking the electrical contact between the electrodes and then the movable electrode was pulled away by the means of the micrometer screw. The gap between the electrodes was set to the required distance. Maximum current was set to 1,6 mA.
The DC breakdown voltage was determined from the time dependence of the potential difference across the discharge tube, which has been measured using a digital oscilloscope. We have applied very slowly increasing potential to one of the electrodes (ramp speed 0,05 V/s). The potential across the discharge tube was increasing until the point of breakdown was reached. Due to discharge breakdown the potential across the discharge tube decreased rapidly. The breakdown voltage was determined from the maximum potential achieved across the discharge gap. Using this method we were able to measure the breakdown voltage with high reproducibility.

3. Results and discussion

The DC breakdown voltage was measured for several discharge gaps from 20, to 200 µm as a function of *p.d* (Paschen curves). The pressure was varied in the range from 6 mbar up to 920 mbar. The Paschen curves have been measured for pure Oxygen (5.0) synthetic Air (78% N_2 and 22% O_2 both gases in 5.0 purity), dry ambient air, ambient air and N_2 (5.0).
In the Figure 2a we see the Paschen curves for pure oxygen measured at several discharge gaps. The left site of the Paschen curve is identical for all discharge gaps, however, the left site depends strongly on the electrode separation. For given value of *p.d* the DC breakdown voltage is decreasing with decreasing electrode separation. We attribute this behaviour to field emission and ion enhanced field emission of the electrons from the cathode and to the low pressure. Under these conditions the electrons from cathode are able efficiently ionise the gas and develop discharge. On the right site of the Paschen curve in O_2 is characteristic bump is present which was also observed earlier by Meek [7]. This structure in the Paschen curve could be associated with non-dissociative (three body) electron attachment to O_2 which is more efficient at high pressure and low reduced electric fields. With increasing reduced electric field the probability of the non-dissociative electron attachment is less efficient the mean free path of the electrons and the kinetic energy of the electrons is increasing which results in the decrease of the breakdown voltage.

The Paschen curves for synthetic air are presented in the Figure 2b. For large electrode gaps of 100, 150 and 200 µm the experimental Paschen curves are very similar in the shape and values. This indicates that at these electrode separations the Paschen law is valid and the breakdown voltage depends only on the *p.d*. The Paschen curves for electrode separations 20 and 40 µm show different behaviour.

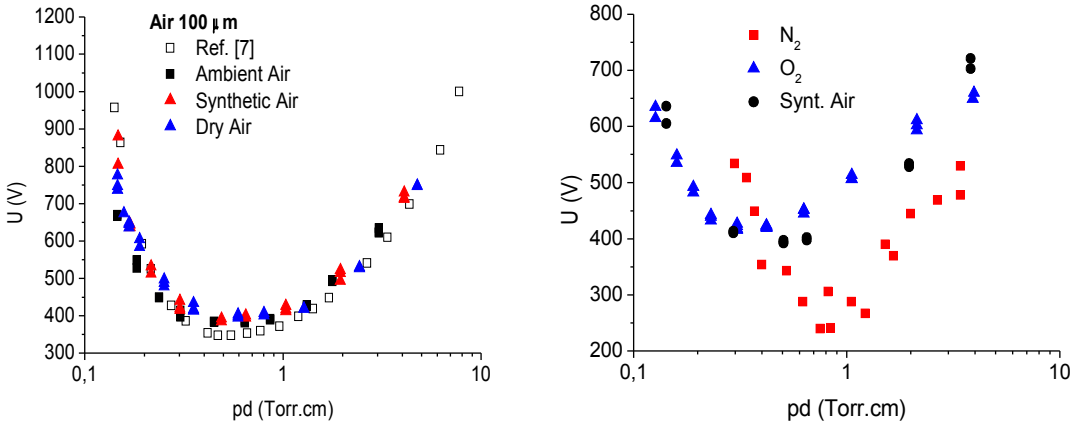

Figure 3 Comparison of the experimental Paschen curves for DC breakdown at one electrode separation a) in air, the data in [7] where measured at different electrode gap and different electrode material b) in N_2, O_2 and synthetic air

Usually the departures from Paschen law appear on the left site of the Paschen curve and are related to the field emission and to ion assisted field emission of the electrons from the cathode surface. However, in this case we observe deviation also on the right site. This effect could be explained by new surface processes appearing at the cathode in this case initiated by photons. In the Figure 4 a) we see that the effective secondary electron emission coefficient at low values of the reduced electric field shows higher values for short electrode gasps. This could support the hypothesis on the role of photons.

In the Figure 3 a) we see the comparison of the Paschen curves measured at electrode separation of 100 µm in ambient air, dry air and synthetic air. The Paschen curves for synthetic and dry air are practically identical in whole range of the *p.d* values. The Paschen curve for ambient air shows some difference to the previous two on the left site of the curve. This difference is resulting from the humidity of the ambient air (approximately 50% at 20° C).

We have tried to analyse the experimental data in the terms of the semiempirical Paschen law (1):

$$U(A,B,\gamma,pd) = \frac{B(pd)}{\ln\frac{A}{\ln(1/\gamma+1)} + \ln(pd)} \qquad (1)$$

where k represents the semi empirical factor equal to k = 1 for molecular gases and k =2 for rare gases [11, 12]. The A and B are the coefficients which are associated with ionization coefficient α, which has for the molecular ´gases form [8]:

$$\alpha = A.p_0\, exp\left(-\, B(p/E)\right) \qquad (2)$$

The Townsend's coefficients α and γ are related each to other via formula [13]:

$1+1/\gamma=\exp(\alpha d)$, (3a)

which can be rewritten in the form:

$\gamma=1/(\exp(\alpha d)-1)$ (3b)

We have used the experimental Paschen curves to obtain the effective secondary electron emission coefficient γ [13,14]. Using the formulae (2) and (3) we are able to derive the dependence of the coefficient γ on the breakdown voltage U and hence on reduced electric field E/p.

$$\gamma = \frac{1}{exp\left(A.pd.exp\left(-\,B\frac{pd}{U}\right)\right) - 1} \qquad (4)$$

For the calculations of γ we have applied the values of A and B coefficients given by Reiser [8]. From these calculations we were able to obtain the values of the γ as a function of the reduced electric field E/p. The results of the calculations for particular gas and electrode separations are displayed in the Figure 4.

The results show that the γ depends on the reduced electric field E/p and also depends on the electrode separation. For large electrode separations 100 and 500 μm the γ show similar dependence on E/p in whole range of the E/p (from 40 up to ~2000 $V.cm^{-1}.Torr^{-1}$). At narrow electrode gaps (20 and 40 μm) γ is in very good agreement with those obtained at large separation in the E/p range up to ~300$Vcm^{-1}Torr^{-1}$. For small electrode separations the γ increases strongly with E/p and the increase is

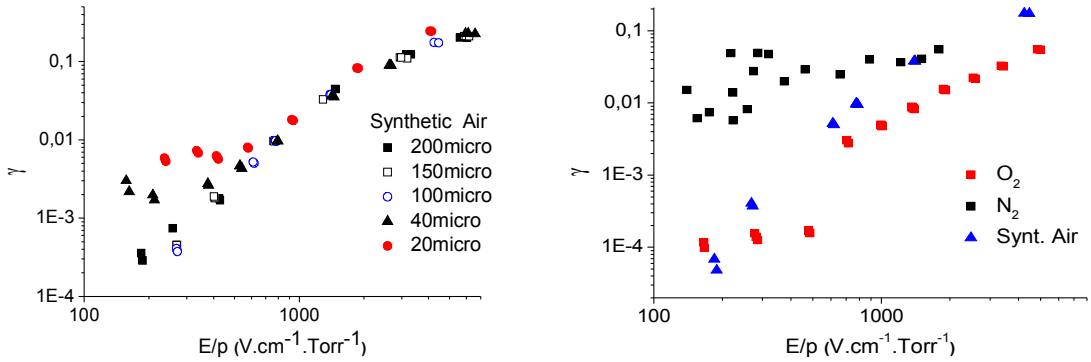

Figure 4. The second Townsend coefficient γ as determined from the experimental Paschen curves for a) synthetic air at different electrode separations b) in O_2, N_2 and synthetic air at electrode separation of 100μm.

more pronounce at 20μm than at 40 μm. We associate this behaviour with increasing role of the field emission, or ion enhanced field emission from the cathode under these conditions.

4. Conclusions

We have measured DC breakdown curves for ambient, dry and synthetic air, oxygen and nitrogen at micrometer separation of Cu electrodes. The experiment confirmed the validity of the Paschen law for electrode separation greater than 100 μm. For smaller electrode separation departure from Paschen law were observed in the left site of the Paschen curve mainly due to field emission and ion enhanced field emission from the cathode. In the case of air for electrode separations below 100 μm departure from the Paschen law occurs also on the right site of the Paschen curve.

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