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THEORETICAL STUDY OF THE THE BREAKDOWN MECHANISM IN BENZOL MICRODSICHARGES

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Abstract. In this paper, the role of the field emission in the deviation of the breakdown voltage from that predicted by Paschen's law has been studied. The expressions for the dependence of the breakdown voltage on the gap spacing and the pressure, separately, in DC microdsicharges in benzol have been derived. Semi-empirical expressions are based on the fitting of numerical solutions of the equation that describes the DC breakdown criteria in microgaps.

1. INTRODUCTION

Localized plasma processing may be required on integrated circuits for different purposes and therefore, studies of micro and nanoscale plasmas are of a great interest (Ito et al. 2001, Tachibana et al. 2005, Chen et al. 2006). Making the gap small is the easiest way to obtain a big force, which is restricted by the electric field of breakdown (Boyle and Kisliuk 1955, Torres and Dhariwal 1999, Radmilović-Radjenović et al. 2005). It is necessary to be aware of the breakdown voltage in microgaps. When changing the size of plasmas there are scaling laws that are helpful in determining the operating parameters of various sizes of plasmas.

In large scale systems, the experimentally observed Paschen law has been successfully explained by the Townsend theory (Paschen 1889).The Paschen's law is based on the observation that, over a large range of pressures and electrode separations, the probability of the ionization per collision in the gas and the probability of the production of electrons by ions by a secondary process are both dependent on the average kinetic energy of the electrons and ions and therefore on the reduced electric field E/N (Loeb 1939). The Townsend mechanism by which successive ionizations of gas molecules induce the gas breakdown describes the process satisfactorily at large separations (Meek and Craggs 1953). The significant parameter is *pd*, the product of the gap distance and the pressure. Typically, the Townsend's mechanism (and by extension Paschen's law) applies at *pd* products less than $1000\,\mathrm{Torr}\cdot\mathrm{cm}$, or gaps around a centimeter at one atmosphere (Radmilović-Radjenović and Radjenović 2006).

The mechanism of the electrical breakdown is, however, completely different in microgaps (Radmilović-Radjenović et al. 2005, Radmilović-Radjenović and Radjenović

2007). A rapid fall of the breakdown voltage with decreasing the gap size may be attributed to the onset of the ion-enhanced field emission in microgaps. Violations of the similarity law take place for the left hand branch, for such pd values where the electron mean free path is comparable with the gap. This regime can be determined from the condition:

$$d/\lambda_0 = \sigma n_0 pd \leq 1, \tag{1}$$

where λ_0 is the mean free path of the electron, σ is the effective cross section for the collisions of electrons with neutrals and n_0 is the gas density at a unit pressure (Radmilović-Radjenović and Radjenović 2008). When the electron mean free path is comparable with the electrode separation the electrical breakdown is based on the cathode-induced breakdown model.

In this paper, the expressions for the DC breakdown criteria including the ion-enhanced secondary emission coefficient (Radmilović-Radjenović and Radjenović 2008) has been applied to benzol in order to determine the breakdown voltage versus the gap spacing and the pressure, respectively.

2. SEMI-EMPIRICAL FORMULA

It was shown that the DC breakdown criteria:

$$\gamma\Big(\mathbf{e}^{\alpha d} - 1\Big) = 1, \tag{2}$$

combined with the expression for the yield:

$$\gamma = K\mathbf{e}^{-D/E}, \tag{3}$$

and for the ionization coefficient:

$$\frac{\alpha}{p} = A\mathbf{e}^{-Bpd/V}, \tag{4}$$

leads to the transcendental equation (Radmilović-Radjenović and Radjenović 2008):

$$K\mathbf{e}^{-Dd/V}\left(\mathbf{e}^{Apd\mathbf{e}^{-Bpd/V}} - 1\right) = 1, \tag{5}$$

which has to be solved numerically. In the equation (5), K and D are labels for the material and gas dependent constants, respectively, while A and B are numerical constants which values can be found elsewhere (Raizer 1991, Korolev and Mesyats 1998). Numerical solutions of the equation (5), result in expressions for the breakdown voltage as a function of the gap size d and the pressure p, separately.

3. RESULTS

For the gas pressure in the range from 1 atm to 5 atm, the obtained numerical solution of the equation (5) for the breakdown voltage are fitted by simple analytical expression:

$$V = a + b * d^c, \tag{6}$$

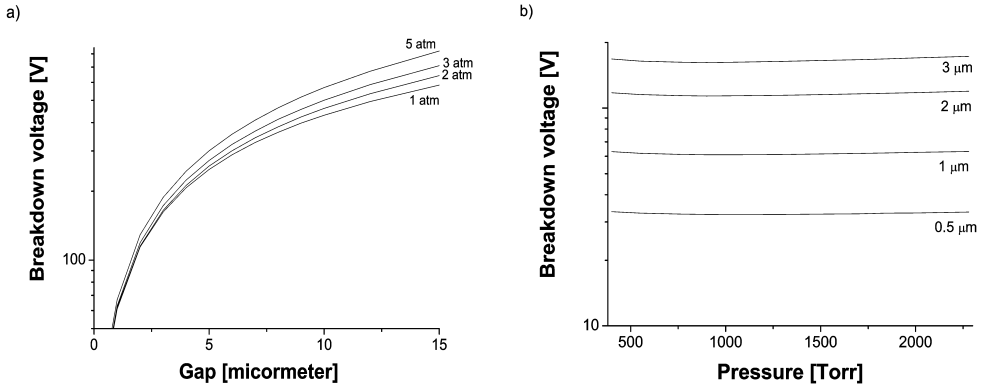

Figure 1: Breakdown voltage as a function of: a) gap spacing with varying pressure form 1 atm to 5 atm and b) pressure for gaps from 0.5 μm to 3 μm.

Table 1: Fitting coefficient for the expression (6).

Pressure [atm]	a	b	c
1	0.00	68.757	0.795
2	0.00	66.222	0.841
3	-6.578	70.134	0.859
5	0.00	68.63	0.918

where values of the fitting coefficients a, b and c, for various pressures are given in Table 1.

In similar way, for the gap spacing from 0.5 μm to 3 μm, the pressure dependence of the breakdown voltage has been fitted by using a simple functional form:

$$V = m * p^n, \tag{7}$$

with fitting coefficients m and n given in Table 2.

In Fig. 1 we have shown results obtained by using the semi-empirical expressions (6) and (7), for the breakdown voltage. The fall of the breakdown voltage for gaps less than 5 μm is observed in Fig. 1a. On the other hand, Fig. 1b demonstrate weak dependence of the breakdown voltage on the pressure.

Table 2: Fitting coefficient for the expression (7).

Gap [μm]	m	n
0.5	33.131	-0.00143
1	60.726	0.00278
2	107.125	0.01114
3	144.954	0.01917

4. CONCLUSIONS

This paper displays theoretical studies of the breakdown voltage in microgaps. Departures from the large scale similarity laws are expected with the onset of field emission on such small gaps. Failure of the Paschen law observed in microgaps indicates that Townsend mechanism is not sufficient to explain the breakdown at small gaps. The semi-empirical expressions based on the fit of the numerical solutions of the breakdown criteria including field emission effects in microgaps has been suggested. The results presented here should be useful for determining minimum ignition voltages in microplasma sources as well as the maximum safe operating voltage and critical dimensions in other microdevices.

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