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The Effect of the Field Emission on the Breakdown Voltage Characteristics of Nitrogen Microdischarges

Marija Radmilovic-Radjenovic* and Branislav Radjenovic
Institute of Physics, University of Belgrade, Pregrevica 118, Belgrade, Serbia.
*Corresponding author email id: marija@ipb.ac.rs

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***Abstract* – This paper contains results of theoretical studies of the breakdown voltage mechanism in direct current nitrogen discharges from 0.5 micrometers up to 100 micrometers. The aim of this paper is to contribute to a better understanding of the electrical breakdown in microgaps and to determine modified Paschen curves. For that purpose, the breakdown voltage curves in nitrogen microdischarges have been calculated by using a Breakdown Voltage and Current Density in Microgaps Calculator including ion-enhanced field emission. The obtained results clearly show that electrical breakdown across micron-size gaps may occur at voltages far below the minimum predicted by the standard scaling law that could be explained by the enhance of the secondary electron emission yield due to the quantum tunnelling of electrons from the metal electrodes to the gas phase. The high electric fields generated in microgaps combined with the lowering of the potential barrier seen by the electrons in the cathode as an ion approaches lead to the onset of ion-enhanced field emissions and the lowering of the breakdown voltage. Based on the analysis of the obtained results we may conclude that the gap size, the gas pressure, enhancement factor, the effective yield and work function strongly affect the breakdown voltage characteristics. Presented results could be useful for determining minimum ignition voltages in microplasma sources as well as the maximum safe operating voltage and critical dimensions in microdevices.**

***Keywords* – Field Emission, Microdischarges, Breakdown Voltage, Yield, Enhancement Factor.**

I. INTRODUCTION

In the past few decades, the field of microdischarges has evolved into the most interesting field of the physics of collisional nonequilibrium plasmas [1-5]. Although, the initial motivation for studies of microdischarges came from the need to optimize plasma screens [6], new applications developed very rapidly requiring an understanding of the physics governing the new small-scale discharges.

Microdischarges are non-equilibrium discharges, spatially confined to submillimeter dimensions. One of the advantages of using discharges in microgaps is the low voltage and power that is necessary to drive a discharge [7-9]. The generation of microplasmas usually involves breakdown of the gas, where electrons when accelerated in a high enough electric field cause avalanche ionization. Electrical breakdown in microgaps occurs at voltages far below the pure Paschen curve minimum and that the modified Paschen curve should be used instead for micrometer and sub-micrometer gaps [10-12]. Electrons from the field emission are one of the possible reasons why the breakdown and sparks occur in a vacuum, which of course is not possible if one only considers the Townsend avalanche mechanisms for the gas phase and the surface ionization that are normally used to generate the Paschen curve. The standard Fowler-Nordheim theory has been widely used and achieved great success in description of deviation of the standard scaling law in microgaps [13-15]

In this paper we have studied the influence of various parameters on the breakdown voltage curves and volt-ampere characteristics. Calculations were performed by using Breakdown Voltage and Current Density in Microgaps Calculator [16] for nitrogen microdischarges generated between 0.5 up to 100 microns. The gas pressure was varied between 10^5 and $6x10^5$ Pa. Conditions also include work functions in the range 4.1 eV to 5.0 e V and the temperature interval from 100 K to 500 K.

II. METHOD

Field emission also known as Fowler-Nordheim tunneling represents the emission of electrons by a solid or liquid conductor under the action of an external electric field of high strength [17-20]. In a metal, electrons are usually prevented from escaping by a potential barrier separating the Fermi level in the metal and the vacuum level. The width of the barrier decreases with increasing field. When it becomes thin enough, the probability for electrons to tunnel through the barrier becomes non negligible, and a field emission current arises.

The field emission current density j is part of the flux density n of electrons incident on the barrier from inside the conductor and is determined by the transmission coefficient D of the barrier [21]:

$$j = e\int_0^\infty n(\delta)D(\delta,\mathrm{E})\,\mathrm{d}\,\delta, \qquad (1)$$

where □ is the fraction of the electron's energy that is associated with the component of momentum normal to the surface of the conductor, E is the electric field strength at the surface and e is the electron charge.

Field emission has a major role in reduction of the electrical breakdown voltage across micron and sub-micron size gaps. The high fields generated in microgaps may enhance the secondary electron emission and such enhancement would lead to a lowering of the breakdown voltage and a departure from the standard scaling law [22, 23]. When the electric field near the cathode is sufficiently large, electrons tunnel from the metal to the gas phase. As an ion approaches the cathode, it lowers the potential barrier seen by the electrons in the metal resulting in an ion-enhanced electron field emission. Kisluik and Boyle have

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suggested an analytical expression for the electron yield that encompasses an ion-enhanced field emission [24]:

$$\gamma_{eff} = Ke^{-B/E}, \qquad (2)$$

where *K* and *B* are material and gas dependent constants and E is the electric field near the cathode. According expression (2) when the electric field in the cathode region becomes larger than the threshold value given by B, the electron yield per ion increases rapidly. In Figure 1 we have shown the effective yield obtained from the breakdown voltage curves recorded for nitrogen microdischarges and published in [23]. Since field emission is mainly governed by the electric field *E* rather than the reduced electric field *E/N* (electric field to the gas number ratio), deviations from the Paschen curve are expected when the secondary emission process is governed by ion-enhanced field emissions rather than ion impact.

In this paper we present results obtained by using Breakdown Voltage and Current Density in Microgaps Calculator [16]. This interface calculates breakdown voltage and Fowler Nordheim emission driven discharges using the formulation developed by Venkattraman and Alexeenko [22]. We have studied the influence of the various parameters on the breakdown volatge characteristics of direct current nitrogen microdsicharges for the gap sizes from 0.5 up to 100 micrometers and the gas pressure between 10^5 and $6x10^5$ Pa. Conditions also include: work functions in the range 4.1 eV to 5.0 e V, the enhancement factor from 10 to 40, the effective yield between 0.01 and 1, and the temperature interval from 100 K to 500 K.

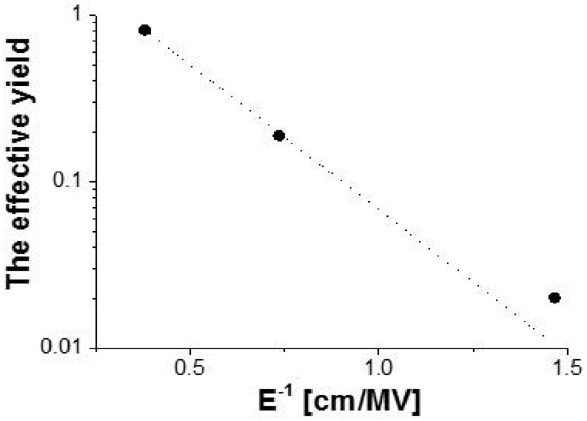

Fig. 1. The effective yield versus the inverted electric field for nitrogen [23].

III. RESULTS

The breakdown voltage as a function of the gap size for various gas pressure is plotted in Figure 2. For the gaps less than 5 microns, the breakdown voltage decreases with decreasing the gap size due to ion-enhanced field emission. For such gap sizes, the breakdown voltage does not strongly depend on the pressure. At larger gaps, the breakdown voltage increasing with increasing the pressure and follows the standard scaling law [22, 23].

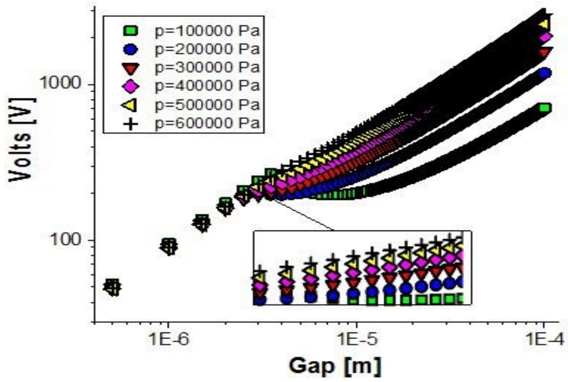

Fig. 2. The breakdown voltage versus the gap spacing for the gas pressure.

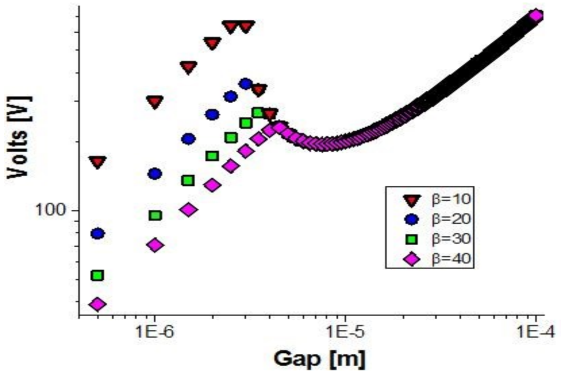

Fig. 3. The breakdown voltage curves calculated for various enhancement factor.

The dependence of the breakdown voltage on the gap size for various enhancement parameter is illustrated in Figure 3. The enhancement factor □ is defined as the ratio of the local emitter field over the applied field representing geometrical effects at the surface of the cathode. For the gaps less than 5 microns, the enhancement factor strongly affects the slope of the breakdown curve and increasing the factor □ causes decreasing of the breakdown voltage. For larger gaps, there are no large differences among the breakdown voltage curves calculated for different values of the parameter □□□

As can be seen from Figure 4, the work function of material affects the breakdown voltage curves only for the gaps of the order of a few microns. The larger work function leads to the larger breakdown voltage.

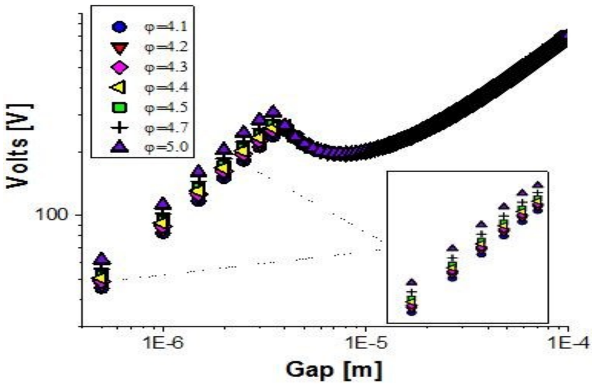

Fig. 4. The breakdown voltage as a function of the gap size for work function from 4.1 to 5 eV.

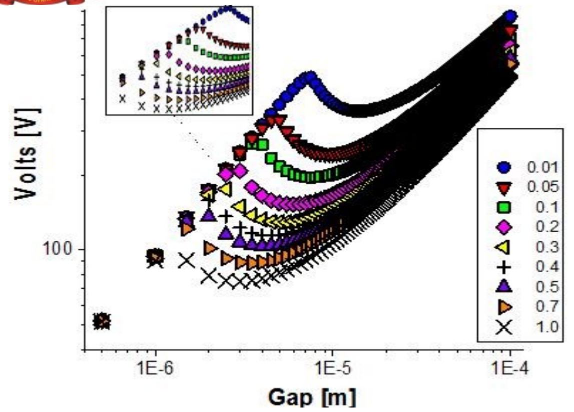

Fig. 5. The breakdown voltage curves of nitrogen microdischarges calculated for various values of the effective yield.

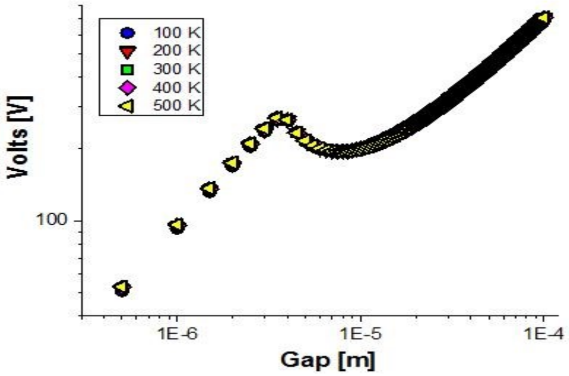

Fig. 6. The breakdown voltage curves in nitrogen microdischarges for various temperature.

The strong influence of the effective yield on the breakdown voltage is shown in Figure 5. As expected, the breakdown voltage decreases with increasing the effective yield. On the other hand, the temperature does not cause differences in the breakdown voltage curves as captured in Figure 6.

IV. CONCLUSIONS

This paper contains some theoretical aspects of the breakdown voltage curves in microgaps. Breakdown Voltage and Current Density in Microgaps Calculator [16] based on theory developed by Venkattraman and Alexeenko [22] have been used in order to study the discharge breakdown mechanism in nitrogen for microgaps. It was shown that the phenomenon of field emission plays a significant role in the deviation of the breakdown voltage from that predicted by Paschen’s law within the range of high electric fields. As gap size is reduced, the exponential dependence of the field emission on the electric field strength pins the electric field during breakdown to the threshold for field emission and allows for a rapid reduction of the breakdown voltage [24]. Electrons from the field emission are one of the possible reasons why the breakdown occurs in vacuum, which is not possible if one only considers the Townsend avalanche mechanisms for the gas phase and the surface ionization that are normally used to generate the Paschen curve. The obtained results reveal that the breakdown voltage characteristics strongly depend on the gap size rather than pressure. The field-enhancement factor is shown to be the most sensitive parameter with its increase leading to a significant drop in the threshold breakdown electric field. The effective yield and the work function also affect the breakdown voltage curves strongly, while the temperature seems to have almost negligible effect on the breakdown voltage.

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AUTHORS’ PROFILES

Prof. Dr. Marija Radmilovic-Radjenovic is research professor at the Institute of Physics Belgrade. She was a visiting professor at POSTECH, University of Science and Technology, Ruhr University and Comenius University. She was a secretary of the scientific committee of 5th EU-Japan Workshop on Plasma Processing. Dr Radmilovic-Radjenovic is a member of the scientific committees of the ICPIG and Symposium on applications of Plasma Processes. She published more than 100 articles in international scientific journals and 7 chapters in the books. Her papers have been cited more than 1400 times according Google Scholar.

Prof. Dr. Branislav Radjenovic is research professor at the Institute of Physics. He was a visitng professor at POSTECH, University of Science and Technology, Pohang, S. Korea and Comenius University, Bratislava, Republic of Slovakia. He is a leader of bilateral project Serbia-Slovakia, a member of Optic Society of Serbia and editor of the Open Physics. Dr Radjenović has published more than 80 articles in the international scientific journals and 7 chapters in the books. He was also author/co-author of 20 invited lectures presented at the international conferences. His papers has been cited more than 800 times according Google Scholar.

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