The breakdown voltage characteristics of direct current nitrogen microdischarges

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Abstract: *This paper reports on breakdown voltage characteristics of direct current nitrogen discharges from 0.5 microns up to 100 microns. 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 and current density 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. 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 and the effective yield strongly affect both the breakdown voltage and current density. 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.*

Key Words: *breakdown voltage, microdischarges, field emission*

1. 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 various enhancement factor, the effective yields and work functions in the range 4.1 eV to 5.0 eV.

2. FIELD EMISSION:

The field emission (FE) process is a unique type of electron emission as it is due exclusively to quantum-mechanical effects—tunneling of electrons into vacuum that in high electric fields. This phenomenon occurs in high electric fields. This 107− 108 V/cm [17,18]. In a metal, electrons are usually prevented from escaping by a potential barrier separating the Fermi level in the metal and the vacuum level. When the field strength is very high, electrons can tunnel through the potential hill. 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 conductorand is determined by the transmission coefficient D of the barrier [19]:

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

where □ is the fraction of the electron's energy that is associated with the component of momentum normal to the surf ace ofthe conductor, *E* is the electric field strength at the surface, and *e* is the electron charge. Tunneling that occurs when an electron passes through a potential barrier without having enough energy is a quantum mechanical phenomenon with no analog in classical physics. The field emission current for direct current (DC) fields is expressed by the Fowler-Nordheim (F-N) equation [19]:

$$I_{FE}^{DC} = \frac{1.54\times10^{-6}\exp(4.52\phi^{-0.5})\left(\beta E\right)^2 A_{\Xi}}{\phi}\exp\left(\frac{-6.53\mathrm{x}10^9\phi^{1.5}}{\beta E}\right), \qquad (2)$$

assuming that the emitter has an effective area A_{Ξ}, while □ represents the work function (expressed in eV) of the material of the cavity and □□is the enhancement factor defined as the ratio of the local emitter field over the applied field. Field emission results are more conventionally shown on the so called F-N plot [19]:

$$\frac{d\left(\log_{10} I_{FE}^{DC}/E^{2.5}\right)}{d\left(1/E\right)} = -\frac{2.84\mathrm{x}10^9\varphi^{1.5}}{\beta}. \qquad (3)$$

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 in [20]. We have studied the influence of the various parameters on the breakdown voltage characteristics of direct current nitrogen microdsicharges for the gap sizes from 0.5 up to 100 microns and the gas pressure between 10^5 and $6\mathrm{x}10^5$ Pa. Conditions also include: the enhancement factor from 10 to 40 and the effective yield between 0.01 and 1.

3. RESULTS:

In Figure 1 we plot: a) the breakdown voltage as a function of the gap size and b) the field emission current density versus the voltage for various gas pressures. Obviously, the pressure strongly affects both the breakdown voltage curves and the current density. For the gaps less than 5 microns, the breakdown voltage decreases with decreasing the gap size due to ion-enhanced field emission. At larger gap sizes, the breakdown voltage and the current density increase with increasing the gas pressure [20,21].

The dependence of: a) the breakdown voltage on the gap size and b) the field emission current density on the voltage for various enhancement factor is shown in Figure 2. 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. Larger □□will enhance field emission. Therefore, for the gaps less than 5 microns, field emission effects should be taken into account and the enhancement factor strongly affects the slope of the breakdown curve and the current density. Increasing the factor □ causes decreasing the breakdown voltage. For larger gaps, there are no large differences among the breakdown voltage curves calculated for different values of the parameter □□□ The influence of the enhancement factor on the current density is noticeable from Figure 3 showing: a) the Fowler-Nordheim current and b) corresponding the Fowler-Nordheim plot obtained for the cooper (□=4.7 eV) by using expressions (2) and (3), respectively. Increasing the enhancement factor leads to the enhanced field emission and thereby increasing the F-N currents. The negative slope of the F-N plots indicate the presence of the field emission effects.

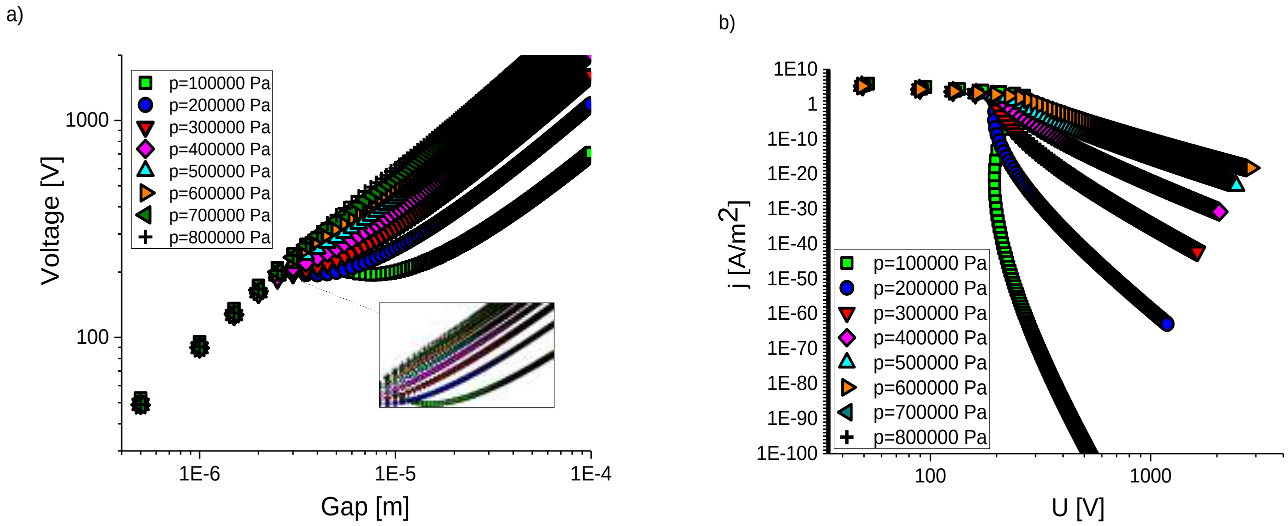

Figure 1. a) The breakdown voltage versus the gap spacing and b) the field emission current density, for various values of the gas pressure taken from 100000 Pa to 800000 Pa. Calculation conditions also include □□□□□□□ □=4.5 eV and the effective yield of 0.1.

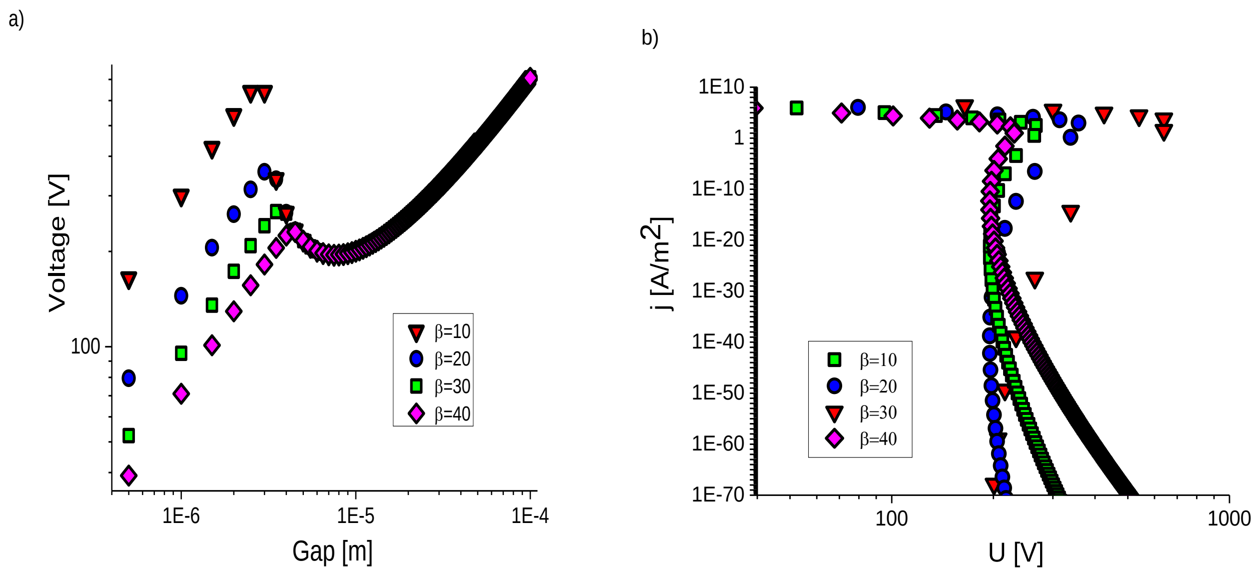

Figure 2. a) The breakdown voltage curves and b) the current density as a function of the voltage calculated for various enhancement factor b, f=4.5 eV, the effective yield of 0.1 and the pressure of 100000 Pa.

Work function of the cathode material also affects the breakdown voltage curves as can be seen from Figure 4. For the gaps of the order of a few microns when field emission effects can not be neglected, the larger work function leads to the larger breakdown voltage.

The strong influence of the effective yield on: a) the breakdown voltage and b) current density is depicted in Figure 5. As expected, the breakdown voltage decreases with increasing the effective yield and since enhanced field emission leads to the lowering of the breakdown voltage.

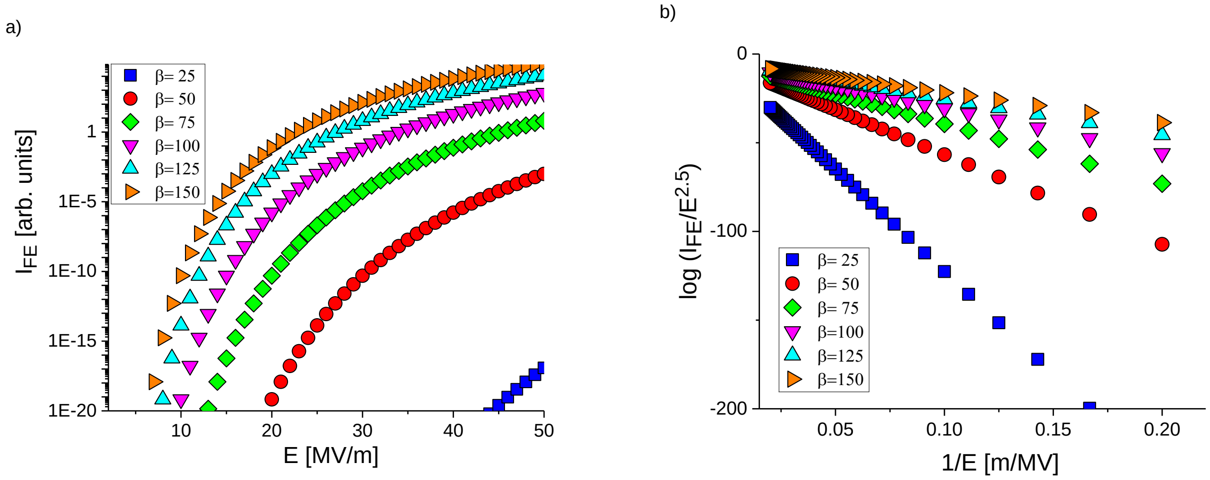

Figure 3. a) The Fowler-Nordheim currents and b) the Fowler-Nordheim plots obtained by using expressions (2) and (3), respectively, for various enhancement factors for the cathode made of cooper (□=4.7 eV) .

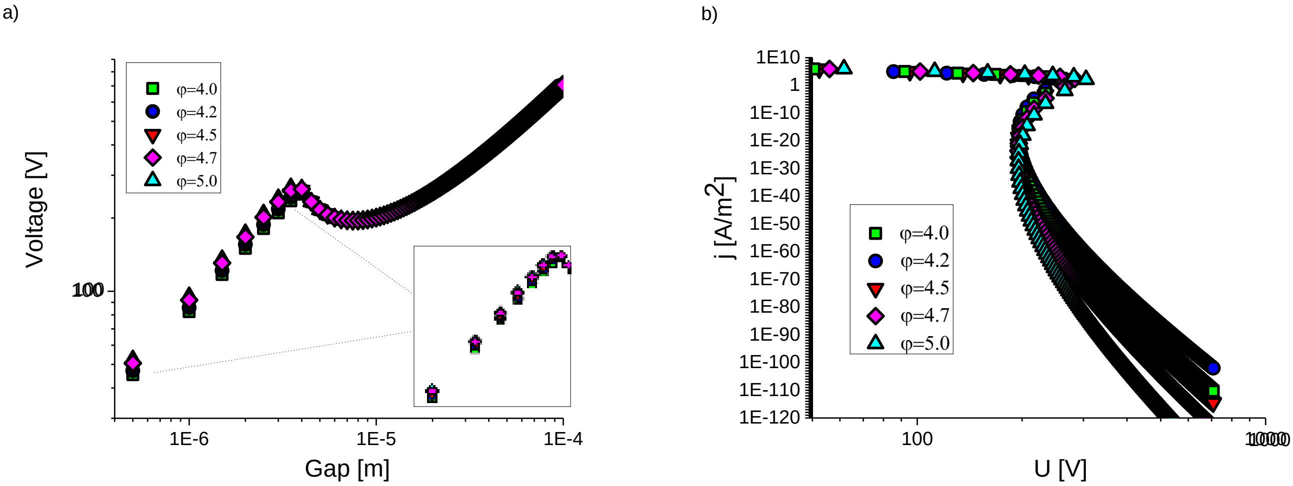

Figure 4. a) The breakdown voltage versus the interelectrode separation and b) the current density against the voltage for various values of the work function from 4.0 to 5 eV (□=30 and the effective yield of 0.1).

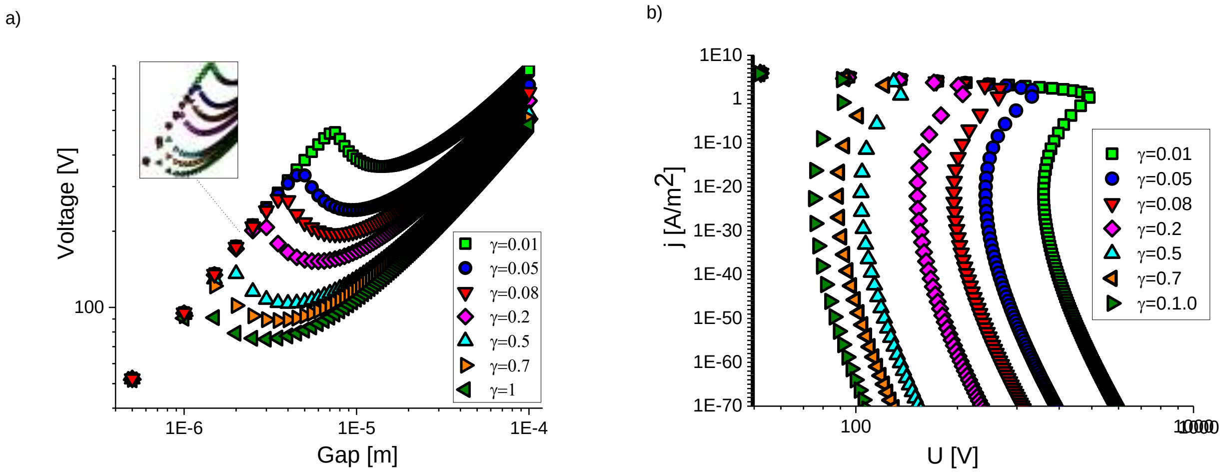

Figure 5. The breakdown voltage curves of nitrogen microdischarges calculated for various values of the effective yield, the work function □=4.5 eV, the pressure of 100000 Pa and the enhancement factor □=30.

4. CONCLUSION:

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 in [20] 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. 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 and changes in the current density. The effective yield and the work function also affect both the breakdown voltage curves and the current density.

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