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The Effect Of The Field Emission On The Breakdown Voltage Characteristics Of Air Microdischarges

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ABSTRACT : *This paper reports on theoretical studies of the field emission effects on the breakdown phenomena of air discharges for the gaps from 0.5 up to 100 microns. The Breakdown Voltage and Current Density in Microgaps Calculator have been used in order to evaluate the importance of various parameters on the breakdown voltage and current density in air microdischarges. Deviations from the standard scaling law observed in microgaps 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 small gaps 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. The negative slope of the Fowler-Nordheim plot also confirms the presence of the field emission effect. The obtained results clearly show that the gap size, the gas pressure, enhancement factor, the effective yield and work function strongly affect the breakdown characteristics of micodischarges.*

KEYWORDS: *field emission; enhancement factor; microdischarges; breakdown voltage*

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I. INTRODUCTION

Non-Equilibrium air plasmas at atmospheric pressure continue to attract considerable research interest due to their diverse applications, including high power lasers, opening switches, sputtering, remediation of gaseous pollutants, excimer lamps and other noncoherent light sources and biomedicine [1-5]. Atmospheric-pressure plasmas in air are of particular importance as they can be generated and maintained without vacuum enclosure and without any additional feed gases [6]. The air also represents the cheapest and inexhaustible insulation material widely employed in most high-voltage transmission lines and open air circuit-breakers. According to the practical applications in power system, air is often used to provide insulation protection for phase to phase as well as phase to ground. If a critical voltage is applied, the current in the air gap will suddenly surge, following by light and heat phenomenon at the same time. Then air will lose insulating properties and a conductive path will be formed. Thus, the understanding of the mechanism responsible for electrical breakdown in air at small interelectrode separations is of interest not only to the plasma community [7–10] but also to microelectronic industry. Although the mechanism responsible for electrical breakdown in air has been studied from the early days of gaseous electronics, many aspects are insufficiently explored, so this subject is still an active area of research. A number of groups performed experimental, modelling and theoretical studies of the breakdown mechanism in small air gaps [11–14]. Most of these studies have been focused on the limitation of the standard scaling law at micrometer gaps at atmospheric pressure. It was shown that the Paschen law is no longer satisfied in compressed gases when the electric field is very strong [15]. This deviation from the Paschen's law is associated with the onset of pre-breakdown current being attributed to the field emission of electrons from the cathode .

The breakdown voltage is usually represented by the so called Paschen law that describes the dependence of the breakdown voltage on the pd (the pressure times the gap spacing) products. The mathematical formulation of the Paschen's curve is derived from Townsend's description of the basic charge generation processes including electron impact ionization and secondary electron emission from the cathode due primarily to ion bombardment, though other bombardment processes may play a role [16]. The mechanism of breakdown is quite different in microgaps where a deviation from Paschen's law have been observed. The physical phenomena that occur in early phases of the electrical breakdown in air at the atmospheric pressure have a lot of similarities with the ignition phase of a low pressure gas discharge [17]. If the electric field at the surface is sufficiently strong, some of the conduction electrons in the metal lattice that stray too close to the surface are literally pulled out into the gap. This effect is called field emission. The electrons, now free, respond to the normal, applied field by accelerating rapidly toward the opposite, positive electrode. Even if the mean free path is now longer than the gap, so that the electrons can not gain sufficient kinetic energy to ionize atoms of the gas, other mechanisms such as localized heating can lead to a runaway process that results in a spark. At ambient pressure and normal temperature, in gaps less than a few microns, field emission coupled with other mechanisms is known to limit useable voltages to values well below those predicted by avalanche breakdown [18].

The motivation for our studies came from the fact that the 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. In order to investigate the effect of various parameters on the breakdown voltages and volt-ampere characteristcis we have performed calculations by using Breakdown Voltage and Current Density in Microgaps Calculator [19] for air microdsicharges 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 4.0 eV to 5.0 e V and the enhancement factor from 10 to 90.

II. THEORETICAL BACKGROUND

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 [17,18]. 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 tra nsmission coefficient D of the barrier [19]:

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

where is the fraction of the electron’s energy that is associated with the component of momentum no rmal to the surface 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 Fowler-Nordheim (F-N) equation provides connection between the current density of field emission electrons and the electric field at the surface of the emitter [20, 21]:

$$\boldsymbol{j_{FE}} = \frac{\boldsymbol{A}^2\beta^2\boldsymbol{E}^2}{\varphi \boldsymbol{t}(\boldsymbol{y})^2}\boldsymbol{e}^{\frac{B\varphi^{3/2}v(y)}{\beta E}}, \tag{2}$$

where j_{FE} is the current density and ϕ is the work function, A=6.2· 10^{-6} A/eV and B=6.85· 10^7 V/cm/eV$^{3/2}$ are constants. The impact due to changes of a tunneling barrier shape on the exponential term in the F-N equation are captured in the factors $v(y) \approx 0.95 - y^2$ and $t^2(y) \approx 1.1$ which represent corrections that were included later in the F-N theory, with $y \approx 3.79 \cdot 10^{-4}\sqrt{\beta}/\phi$ [21].

The field emission current for direct current (DC) fields is expressed by the Fowler-Nordheim (F-N) equation [**19**]:

$$I_{FE}^{DC} = \frac{1.54\times10^{-6}\exp(4.52\phi^{-0.5})(\beta E\,)^2 A_{\Xi}}{\phi}\exp\left(\frac{-6.53\text{x}10^9\phi^{1.5}}{\beta E}\right), \tag{3}$$

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]:

$$\frac{d\left(\log_{10} I_{FE}^{DC} / E^{2.5}\right)}{d\left(1/E\right)} = -\frac{2.84\text{x}10^9\varphi^{1.5}}{\beta}. \tag{4}$$

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 [22]. 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 $6x10^5$ Pa. Conditions also include: the enhancement factor from 10 to 40 and the effective yield between 0.01 and 1.

III. RESULTS

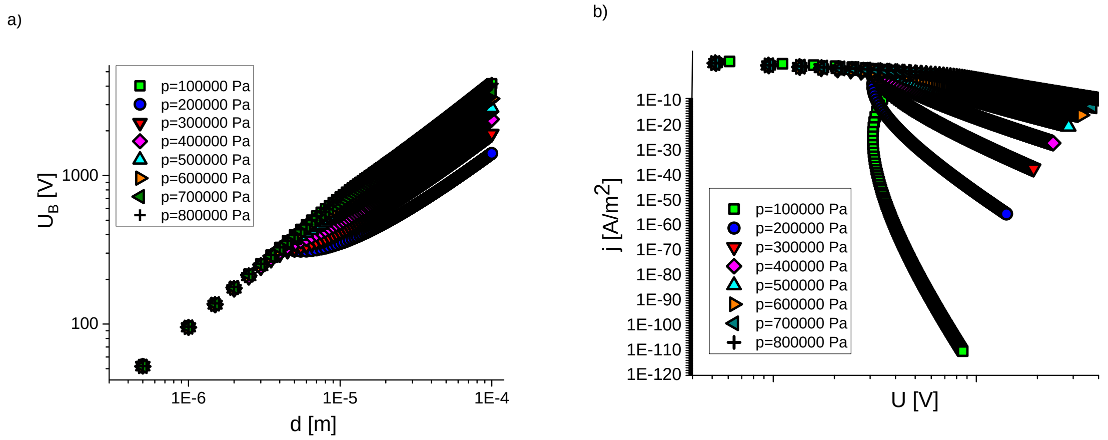

Fig. 1. The effect of the pressure on: a) the breakdown voltage curve and b) F-N current density.

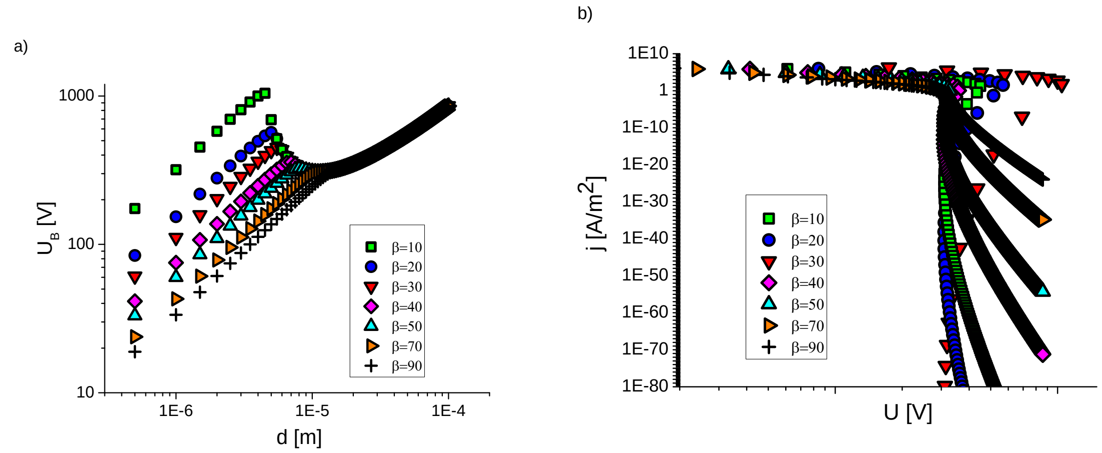

Fig. 2. The influence of the enhancement factor on the: a) breakdown voltage curve and b) F-N current density.

In Fig. 1 we plot: a) the breakdown voltage as a function of the gap size and b) the field emission current density versus the gap size for various gas pressures. For the gaps less than 5 microns, high electrcic field enhanced secondary electron emission leading to the lowering of the breakdown voltage and the departure from the standard scaling law. At larger gap sizes, however, field emission effect play no role so, the breakdown voltage follows the standard scaling law. Also, that the pressure strongly affects the right hand side of the breakdown voltage curves and the current density. With increasing the gas pressure, electrons may suffer a large number of collisions losing their energy and thus large electric field is needed to initiate the breakdown.
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 also to a gradual merging with the Paschen law as illustrated by Fig. 2a. In micro gaps, where field emission of electrons dominates, the breakdown voltage decreases with increasing the enhancement factor. On the other hand, the influence of □ □ parameter on the current density is described by Eq. (2) and displayed in Fig. 2b.

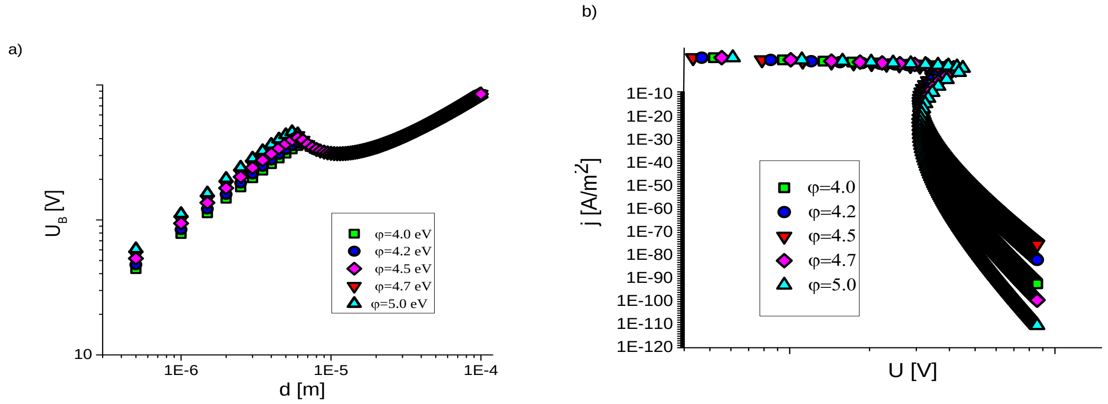

Fig. 3. The effect of the work function on the: a) breakdown voltage curve and b) F-N current density.

Fig. 3 contains results for: a) the breakdown voltage and b) current density for various work functions φ representing the effect of different electrode materials. The electrode materials strongly affect the slope of the curve on the left hand side as shown in Figure 3a. It is clear from Figure 3b that the F-N current density decreases at the same applied voltage with increasing work function.

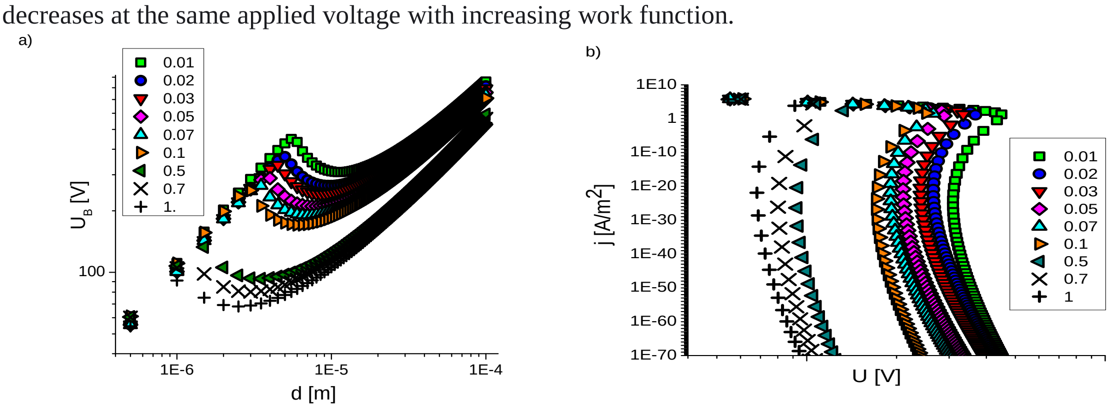

Fig. 4. a) The breakdown voltage curve and b) F-N current density for various values of the effective yield.

As can be seen from Fig. 4a, at larger gaps, when Paschen's curve holds true indicating that ion-enhanced field emission is negligible, while Townsend secondary emission cannot be ignored. However, for gaps below 5 μm, breakdown is no longer controlled by the processes within the gas. At small interelectrode spacings breakdown is initiated by the secondary emission processes instead of a gas avalanche process. The high electric reaches the threshold for field emission and allows for a rapid reduction of the breakdown voltage as gap size is reduced . This confirms that breakdown departures from Paschen's curve when emitted electrons are generated by ion-enhanced field emission rather than secondary emission.

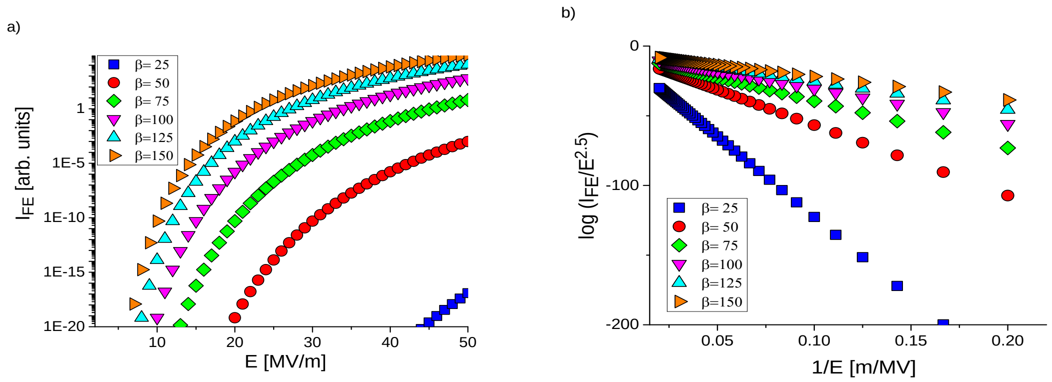

Fig. 5. a) F-N currents and b) F-N plots obtained by using expressions (3) and (4), respectively, for various enhancement factors for the cathode made of cooper (□ =4.7 eV) .

The F-N cuurent and and the corresponding F-N plot for various values of the engancement factor are shown in Fig. 5. In the scenario of electron field emission, the F-N plot should fit a straight line with the negative slope (see Fig. 5b).

IV. CONCLUSIONS

In this paper we have studied the influence of various parameters on the breakdown characteristics of discharges generated in microgaps. Breakdown Voltage and Current Density in Microgaps Calculator [16] based on theory developed in [22] have been used in order to study the discharge breakdown mechanism in air microdischargess. It was shown that the phenomenon of field emission plays a significant role in departure of the breakdown voltage from the standard scaling 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. Negative slope of the Fowler-Nordheim plot clearly demonstrate the effect of the field emission effect. Results, presented here, could be useful for determining minimum ignition voltages in microplasma sources as well as the maximum safe operating voltage and critical dimensions in microdevices.

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