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Electric Field Enhancement Factor defined by nanoprotrusions on the electrode surface in microgaps in needle-plate configuration

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***Abstract*—Proper description of the electrical behavior of miniaturized devices requires better understanding of the breakdown phenomena in microgaps (< 10µm) at atmospheric pressures. In microgaps the breakdown characteristics deviate from those defined by the Paschen's law. It is now well accepted that the departure from Paschen's law is due to the contribution of field electron emission. Apart from the small distance, the presence of protrusions on the cathode surface can largely intensify this phenomenon. In this work, the electric field distribution is simulated in needle-plate configuration in presence of various nanoprotrusions on the cathode surface. The purpose is to find conditions when the nanoprotrusions can initiate field electron emission due to a local enhancement of the electric field. The maximum electric field is determined by the location and the geometry of the nanoprotrusions. Surprisingly, for a semi-circle shape of nanoprotrusions, the maximum electric field does not depend on the size of nanoprotrusions.**

Keywords— microgaps, nanoprotrusions, FEMM, Electric Field Enhancement Factor (EFEF), breakdown

I. Introduction

In many electrical applications (microelectronics, micro-switches, etc.) the aim to reduce the device size often leads to a reduction of the distance between two parts at different electrical potentials. Frequently, the gas remains the only insulator between these two parts and breakdown phenomena are observed. Decreasing the device dimensions with the same operating voltage undoubtedly results in an increase of the electric field. For example, the exploration of gas breakdown phenomena at micro-scale gaps has been a great challenge in microelectromechanical switches (MEMS). The breakdown in gases is generally due to the contribution of two ionization processes: (*i*) ionization of gas molecules by electron collision in the volume and (*ii*) release of electrons from the cathode surface after ion impact (secondary electron emission). The Paschen's curve considers both mechanisms and uniquely relates the breakdown voltage and the pressure times distance (p × d) product. According to the Paschen's law, at atmospheric pressure and for microscale distances, the breakdown voltage should be very high [1]. However experimentally observed breakdown voltages are much lower than the ones expected from the Paschen's law for microgaps (< 10 µm). The idea of modifying the Paschen curve appeared in a series of papers from BELL laboratories through Germer's study [2], and Boyle and Kisliuk [3] who were the first researchers to explore the field electron emission as an additional mechanism. They conclude that this process has a key role in discharge ignition in micro- and submicron electrode separations. In 1999 Torres *et al.* [4] showed experimental evidences of departure from Paschen's law on the left branch of the curve. The same was confirmed by other researchers [5],[6],[7]. It is now generally accepted that the field electron emission is at the origin of the departure from Paschen's law for atmospheric pressure and small inter-electrode spacing. Recently Fu *et al.* have theoretically studied the effect of microprotrusions (100 – 200 µm) in 100µm inter-electrode distances [8], [9]. They demonstrate that at atmospheric pressure the discharge ignition is mainly determined by the shortest inter-electrode distance with a contribution of the electric field enhancement due to the protrusions.

When the gap between the electrodes is of only a few µm, the electrode roughness can also be seen as a kind of protrusion. Then it could change the electric field distribution and, in turn, the breakdown characteristics. In this work, we study a needle–plate geometry where the plan electrode is the cathode and the needle is the anode. We show that a nanoprotrusion located on the plate electrode change drastically the electric field distribution and thus the breakdown conditions. We limit the presentation here to a single semi-circle protrusion. The effect of many nanoprotrusions acting together is also studied.

II. Simulation geometry and method

All simulations are performed with FEMM software (ver 4.2). It is suited to solve electrostatic problems using finite element method. FEMM solves the nonlinear differential equation, for the potential V, over the user-defined domain with user-defined sources and boundary conditions. It discretizes the problem's domain using triangular elements, which form a mesh consisting of a large number of nodes. The solution over each element is approximated by linear interpolation of the values of potential at the three vertices of the triangle. Figure 1 presents the geometry of the simulated device in this work. The anode is a needle and the cathode is a plate electrode. The anode curvature radius is kept r=5 µm

and the gap is fixed to 5 µm. A semi-circle protrusion is located on the cathode. The two-dimensional planar electrostatic problem has been defined, with a solver precision value of 10^{-8}. In order to fix the voltage, Dirichlet conditions have explicitly been defined in the problem's domain. The applied voltage is on the anode $V_{anode} = 300$ V, while the cathode is grounded ($V_{cathode} = 0$V).

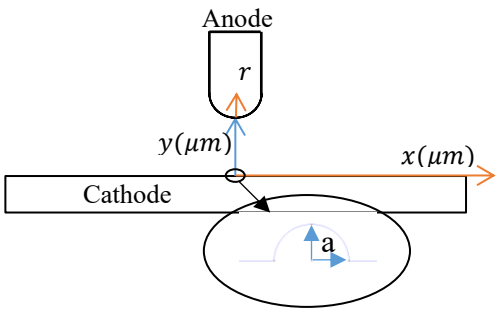

Fig. 1: Sketch of the simulated configuration.

III. Result and Discussion

For a semi-circle protrusion, we change the size (a) and the position of the protrusion (x_p). The zero position is when the protrusion faces the anode. Figure 2 presents the maximum electric field for three protrusion sizes at different protrusion locations. The maximum electric field is always found to be located on the top of the protrusion.

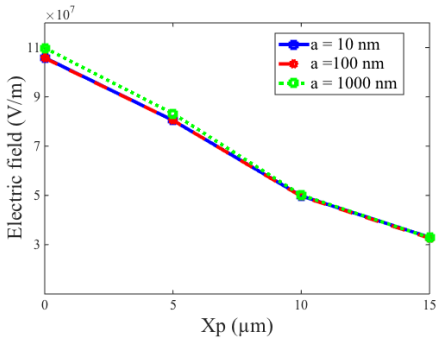

Fig. 2: Electric field versus position of the protrusion for different size of protrusion (10, 100 and 1000 nm).

Firstly the electric field decreases with the position of the protrusion. As expected, the far away the protrusion from the anode, the lowest the maximum electric field is. Secondly, the electric field is hardly modified by the size of the protrusion, in the range 10-1000 nm. This result is particularly surprising but can be explained as follow. On one hand, an increase of the size of the protrusion changes the distance between the electrodes. For a constant applied voltage, it tends toward an increase of the electric field. On the other hand, an increase of the protrusion size diminishes the curvature of the protrusion. Then, the electric field lines are less contracted close to the protrusion. Both phenomena counterbalance themselves. However it would be hasty to conclude that the protrusions have no effect on the electric field.

We have defined the Electric Field Enhancement Factor (EFEF) as the ratio of the maximum electric field on the surface with protrusion to the electric field without protrusion:

$$\beta' = \frac{E_p}{E_0}. \qquad (1)$$

To keep the difference clear with the field enhancement factor usually extracted from an experimental Fowler–Nordheim plot (the β factor, voltage-to-barrier field conversion factor or geometric factor, used to account for the existence of local emitting spots with field enhancement) the EFEF in our case is called β'.

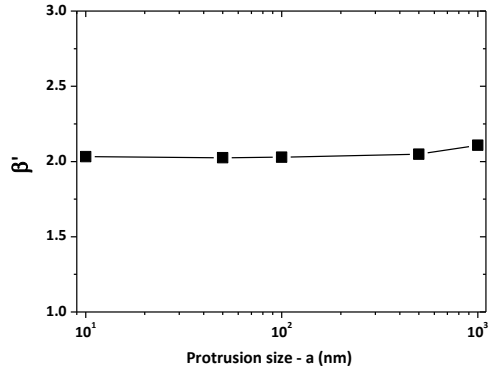

Fig. 3: *Electric Field Enhancement Factor for semi-circle protrusions with different size. The protrusion is located at x_p=10 nm.*

As observed in Fig. 3 the electric field enhancement is not modified by the size of the protrusion. However, the simple presence of one protrusion in the plate electrode doubles the electric field at that point (β' = 2). It can be enough to drastically increase the field electron emission at the protrusion location and to provoke unexpected breakdown.

IV. Conclussion

The effect of nanoprotrusions on the cathode surface in a needle-plate configuration is simulated in microgaps (< 10µm). For a semi-circle protrusion, the presence of a protrusion doubles the electric field but the size of the protrusion does not affect the electric field. To get closer to the reality and takes into account the roughness of a surface, the effect of many protrusions acting together will be presented in a full version of the paper.

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