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A contribution to breakdown voltage characteristics in air for inter-electrode distances 1 - 10 μm at various pressures

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Abstract—Knowledge on the breakdown voltage behavior in microgap distances at different pressures, from few tens of Pa up to atmospheric pressure, is extremely useful for designing electric power subsystem components in aircraft applications operating at as low as 10% of atmospheric pressure. In this work we report on breakdown voltage measurements performed in air for inter-electrode distances of 1-10 μm at different pressures. The obtained results show departure from the Paschen's law with different contributions of the field electron emission to the discharge mechanisms.

I. INTRODUCTION

The actual trend of compact design of low/medium voltage equipment implies lower distances between active parts, which may be as low as a few microns. In such circumstances, knowledge about breakdown voltage characteristics of many insulating materials is needed in order to reduce losses and to prevent operational failure caused by either partial discharges or dielectric breakdown [1, 2].

The gaseous insulation breakdown mechanisms in uniform field at relatively small gaps between electrodes are generally explained by Townsend's process. The relation between breakdown voltage and pressure times distance ($p \times d$) in gas insulation obeys Paschen's law [3]. It describes an electron avalanche phenomenon driven by the first Townsend's coefficient (ionization coefficient) and the secondary electron emission from the cathode, leading to the electrical breakdown of the insulating gas. Nevertheless, there are significant amount of work that shows some departure from Paschen's law when the gap is reduced to below 10 micrometers at atmospheric pressure. Breakdown voltage decreases when $p \times d$ is reduced until it reaches the left branch of the Paschen's law below its minimum (Stoletov point). It is interesting to notice that electrical breakdown mechanism occurs on the microscale gap not only at atmospheric pressure but also at lower pressures: either the gas fails as an insulator, or the gas still acts as an insulator but there are any other electrical breakdown mechanisms which come at play. Knowledge about breakdown voltage behavior in the microgap distance at low pressure will also be very useful for designing electric power subsystem components in aircraft applications operating at 10% of atmospheric pressure.

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II. RESULTS AND DISCUSSION

A. Experimental set-up

The principle of the discharge detection circuit is depicted in Figure 1. The electrodes consist of a controlled radius needle (10 microns) facing an Al metallized wafer, thus forming a point-to-plane geometry. The needle is connected to a sourcemeter, consisting in a DC power supply ($V_{\text{max}} = 1100 \text{ V}$) and an ammeter, in series with a 10 M Ω resistor in order to limit the breakdown current. The positive voltage is applied to the tip electrode and the plate electrode acts as ground reference. The current is measured by the ammeter and the background noise was estimated to about 60pA. For distances above few micrometers, one might consider that this electrode system provides a quasi-uniform distribution of the electric field around the tip. To limit the degradation of the electrodes, the voltage is stopped as soon as the breakdown is detected.

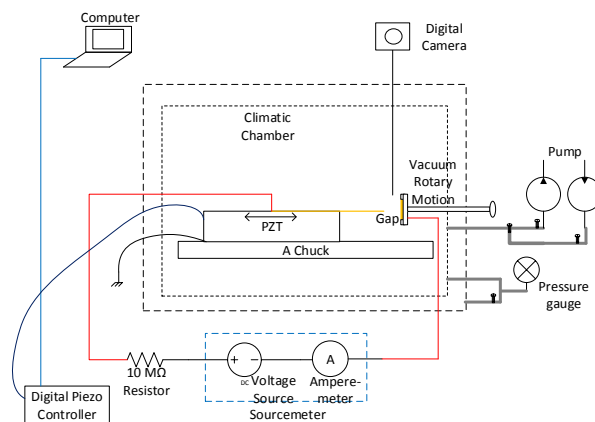


Fig. 1. Schematic Design of BDV Measurement System

A high precision PZT linear stage actuator (PI Hera 621.1UD) is used to control the gap between electrodes (varying from 500 nm to 10 μm). The actuator has 100 μm travel range, 0.2 nm resolution, and 10^{-5} hPa vacuum compatibility, when driven by a digital piezo controller E.709-CRG equipped with capacitive sensors. The baseplate of the actuator is mounted on a chuck and is installed together with the electrode system inside a vacuum chamber. The pressure inside the chamber is obtained by a combination of scroll dry pump/turbo-molecular pump and is monitored by a digital pressure gauge.

The needle electrode is made of tungsten and presents a curvature radius of 10 μm . Its position relative to the plate electrode is controlled by the PZT actuator along a single axis (x-axis), while the electrode plate is kept in a fixed position.

The fixed electrode consists of a thin layer (250 nm) of aluminum (Al) deposited on a 5 mm x 5 mm glass substrate. Several such assemblies are positioned on a rotating stainless steel base and they are electrically connected to ground by using epoxy silver glue with a volume resistivity of 0.00004 Ωcm at room temperature. The stainless steel base can be rotated from outside the chamber through a vacuum rotary motion system, able to perform 5° increments once the breakdown occurs at one position, thus shifting the testing area laterally for a new test. The contact point between electrodes ($x=0$) was determined prior to the breakdown voltage measurement. The tip electrode is fed by a 1.5V DC voltage, and then gradually approached toward the plane electrode at a speed 100 nm/s until a current I_b higher than 0.0015 μA is detected by the sourcemeter. This value is a compliance current programmed in the sourcemeter, and it was chosen one hundred times smaller than short circuit current and about 25 times higher than background noise. When the movement of the tip is stopped, then its position defines the contacting position of the two electrodes.

The procedure of breakdown voltage measurements consists of several steps. Firstly, the desired pressure inside the chamber is set by the pumping system and the tip's position is set to the desired distance d from the plate by digital piezo controller. The actual tip's position can be monitored visually by a digital camera and by *PI NanoCapture*, a monitoring and control software provided by PI on the personal computer. The next step is applying the DC voltage of 15 V on the tip electrode. Then, the applied voltage is increased incrementally by 1 V/s until a current I_b higher than 0.015 μA , is detected. Note that the compliance current programmed to the sourcemeter is 10% of the short circuit current value and about 250 times higher than the background noise. The voltage measured by sourcemeter, which corresponds to I_b , is defined as the breakdown voltage. Three up to eight points of measurements were performed for each distance. The distance is increased by 1 μm steps, from 1 μm to 10 μm . Finally, a 20 μm inter-electrode distance is measured for completing the procedure.

B. Impact of the gap distance in point-to-plane configuration on the breakdown voltage

Fig. 2 shows the obtained results for the breakdown voltage as a function of the distance in air for distances between 1 – 10 μm at various pressures, including the atmospheric pressure. Results obtained by Torres and Dhariwal [4], as well as the theoretical Paschen's law plot are also plotted. At larger distances between electrodes, i.e. for 5 $\mu\text{m} < d < 10 \mu\text{m}$, the gas discharge mechanism obeys the Paschen's law (the mechanisms in charge for the discharge breakdown are ionization in the volume of the gas and secondary electron emission from the electrode) which is the only one responsible of the electrical breakdown [5]. The breakdown voltage remains slightly constant, presenting a plateau with different levels according to the gas pressure. If the applied pressure is decreased, less neutral particles will be present in the air so that a higher voltage is needed to reach breakdown, to ensure that enough electrons are created when there are fewer collisions.

At smaller distances, $d < 5 \mu\text{m}$, a departure from Paschen's law is observed. Then the question is on the

additional mechanism that would lead to the electrical breakdown [1, 2, 5]. Field induced electron emission will be the trigger of electrical breakdown when the electric field is extremely high. Curvature radius of the tip and gap distances, as used in this experiment, yield very high electric field near the end of the tip. Consequently the recorded breakdown voltage decreases at atmospheric pressure (Fig. 2). If pressure decreases, then the atom number density decreases as described by the ideal gas law and the collision frequency for ionization decreases. The current discharge flows in minimum of $(p \times d)_{min}$ which might differ from the designed inter-electrode distance d [2]. In these conditions, the resulting breakdown voltage remains in a plateau; the corresponding voltage only depends on the pressure, and increases as the pressure decreases.

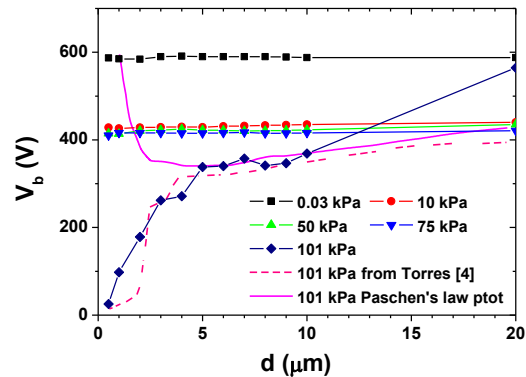


Fig. 2. Results for breakdown voltage in air as a function of the distance for distances 1 – 10 μm at various pressures; Data from Torres et al., [4] and theoretical Paschen's law plot are given for comparison.

III. CONCLUSION

In this work, a point-to-plane geometry is used, where the distance separation between electrodes is controlled by a high precision linear piezoelectric stage actuator. Breakdown voltage measurements are performed for gap distances varying from 1 μm to 10 μm in air, for pressure variations between 30 Pa and 10^5 Pa at room temperature. The obtained results show that two different electrical breakdown mechanisms, depending on the distance and the imposed pressure separately, can occur on the left branch of the Paschen's law leading to its departure.

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