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Influence of combined gas and vacuum breakdown mechanisms on memory effect in nitrogen

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ABSTRACT

The phenomenon of memory effect in nitrogen and air has been investigated in presence of combined vacuum and gas breakdown mechanisms. The experiment sample allowed the gas pressure at constant value, while the inter-electrode distance were changed from 0.01 cm to 0.18 cm. Shown dependence of static breakdown voltage vs. the product of gas pressure and inter-electrode distance confirmed the constant voltage value in region of vacuum breakdown mechanism, as well as the existence of Paschen's minimum for $pd \approx 0.8$ mbar cm. The processes responsible for discharge sustaining in nitrogen were discussed using the memory curves for two different values of product of gas pressure and inter-electrode distance *pd*. In addition, the comparative analysis of the difference in electrical time delay values in nitrogen and air has been also performed.

1. Introduction

Recent years a large number of experimental and theoretical investigations [1–7] devoted to study of electrical discharges in nitrogen and air at low pressures in the presence of vacuum and gas electrical breakdown. A boundary of low-pressure gas breakdown for the electrodes system depends on several parameters, such as the type of gas, the intensity of electric field, the material and shape of electrodes. However, below this boundary in gas-filled tube, electrical discharge being observed is unusual because the ionization process is basic mechanism of each discharge. The breakdown appearance under these conditions in so-called technical vacuum, in which the free electron mean length is larger than the inter-electrode distance, is caused by the existence of an avalanche mechanism which creates free electrons and ions. The avalanche process starts when a free electron is positioned in such a way that in its path it could take over enough energy to ionize neutral gas atom. Then, that free electron becomes an initial. However, formation of the avalanche does not necessary lead to gas breakdown. Breakdown only results when one avalanche form and condition for initiating of the next one are made. In this case, it is possible to explain by bringing one of the electrodes in a state of thermal instability. That is reflected in the electrode material evaporation and the formation of metal vapors in the inter-electrode gap within it is possible to cause a breakdown by the gas breakdown mechanism.

Thermal instability of electrodes could be caused by emission mechanism, by micro-particles accelerated in electrode material or through the avalanche effect in the adsorbed residual gas layer on the electrodes [8]. Depending on the way in which it is possible to do, four initiation breakdown mechanisms exist, such as cathode vacuum breakdown, anode vacuum breakdown, micro-particle breakdown and avalanche breakdown. During cathode vacuum breakdown, thermal instability of the cathode happens when the emission current from cathode micro-spices exceeds a certain critical value at which the micro-spices are melting and evaporate. On the other hand, thermal instability of anode is caused by the energy submitted to it by the electron beam emitted from the cathode, which leads to local heating causing the breakdown. Then, the anode material melts and evaporates, while the emitters, cathode micro-spices, are thermal stable. The micro-particles which present on the cathode are responsible for the micro-particle breakdown mechanism. Namely, they are weakly related to cathode surface or free and electrify by electric force when voltage is applied to the electrodes. After multiple collisions, they attain sufficient energy and evaporate. Finally, the avalanche breakdown is based on the formation of multiple charged particles in collisions with molecules from adsorbed gas layers on the electrodes or with molecules of impurities. These particles move through the inter-electrode gap in different direction, ionizing new particles on their way, which finally develops into gas breakdown.

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These two mechanisms (vacuum and gas) have also been the subject of research in paper [6] for nitrogen- and air-filled tubes for two different values of product of gas pressure and inter-electrode distance *pd*, which amounted to 0.28 mbar cm and 2.64 mbar cm. The differences between memory effect in nitrogen and air had been discussed.

In paper [9] results of investigation of breakdown voltage and electrical time delay in air-filled tube for $pd = 0.1$ mbar cm, when the both of mechanism present, had been presented.

The results of this paper will refer to the area of low pressure and small inter-electrode distance in nitrogen-filled tube, i.e. the area when the breakdown is initiated by combination of Townsend's gas and vacuum breakdown mechanisms. It should be noted the dependence of the static breakdown voltage of the product of inter-electrode distance and gas pressure with an emphasis on its values on the left side of Paschen's minimum, which has enabled a more detailed analysis of the impact vacuum breakdown mechanism on the nitrogen memory effect. Based on the research consists of memory curves (the dependence of the electrical time delay vs. afterglow period) recorded for two different values of *pd* as well as comparison of previously recorded curves for air and nitrogen at different values of *pd*. Besides, the comparative analysis of electrical time delay were performed for nitrogen and air for different values of product *pd*.

2. Experiment

The cylindrical borosilicate glass (8245 Schott technical glass) tube used in these experiments has a shape shown in Fig. 1. The tube volume was about 1 l. It was connected in circuit with one fixed and one movable iron electrode, so that the inter-electrode distance could be vary by a permanent magnet from outside. Electrodes' diameter was 1 cm. The tube had be baked out and evacuated before the nitrogen was admitted in a process similar to that for the production of X-ray and the other electron tubes. After that, the tube was filled with Matheson research grade nitrogen at pressure of 6.6 mbar with the claimed abundance of impurities such as $CO < 0.5$ ppm, $CO_2 < 0.5$ ppm, $O_2 < 1$ ppm, THC < 0.2 ppm and $H_2O < 1$ ppm.

Before taking the dependence of the electrical time delay $\bar{t}_d$ vs. the afterglow period τ, so called the memory curve, the cathode surface had been prepared by performing several thousand breakdowns. After that the static breakdown voltage was estimated for every value of the inter-electrode distance using the discretized dynamic method which is described in detail in Ref. [10]. The estimated values of U_s for nitrogen-filled tube at 6.6 mbar pressures for two values of inter-electrode distance of 0.015 cm and 0.1 cm were 418 V and 386 V, respectively. The electrical breakdown time delay measurements were performed for overvoltage 50% higher than static breakdown voltage. During the measurements, after breakdown the current of 0.5 mA has flowed through the gas for time period of 1 s. This time is sufficient to attain the steady-state discharge conditions. The experimental setup for measurement and data acquisition of breakdown voltage and electrical time delay are given in detail in paper [11].

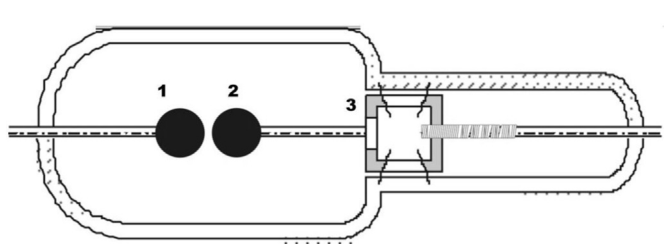

Fig. 1. Nitrogen-filled tube with one fixed and the other movable electrode: 1 – fixed electrode, 2 – movable electrode and 3 – rotation shaft from iron.

3. Theory

When the electric field in the inter-electrode distance is sufficiently high to create the multiplication of electrons and ions, the avalanche appears. If this multiplication creates a sufficient concentration of electrons and ions, it will lead to the electrical breakdown. The breakdown criterion in Townsend's theory is [12]

$$\gamma\left[\exp\left(\int_0^d \alpha \mathrm{d}x\right)\right] = 1, \tag{1}$$

where α is the primary ionization coefficient, and γ is the effective secondary ionization coefficient which includes secondary processes induced by positive ions γ_i, metastable atoms (molecules) γ_m, and photons γ_{ph}, i.e., $\gamma = \gamma_i + \gamma_m + \gamma_{ph}$. Coefficient γ depends on cathode material and gas type, as well as on E/p ratio [13]. Using the empirical formula for the primary ionization coefficient [14]

$$\alpha = Ap\exp[-B/(E/p)] \tag{2}$$

and breakdown condition in the case of parallel-plate electrodes

$$\gamma[\exp(\alpha \mathrm{d}x) - 1] = 1, \tag{3}$$

it leads to the following equation for the static breakdown voltage U_s:

$$U_s = \frac{Bpd}{\ln(Apd) - \ln[\ln(1 + 1/\gamma)]}, \tag{4}$$

where A and B depend on gas type [13].

If the electrical breakdown time delay t_d is measured at the static breakdown voltage U_s, where U_s is the largest voltage for which the breakdown probability is zero [15]. Because of that, t_d is measured at applied voltage U_w larger than the static breakdown voltage U_s. In this paper t_d represents the time interval between the moment of U_w application on the tube and the moment when the tube current exhibits a detectable.

4. Experimental results and discussion

The dependence of static breakdown voltage vs. the product of gas pressure and inter-electrode distance, $U_s = f(pd)$ for the nitrogen-filled tube at 6.6 mbar pressure is shown in Fig. 2. The represented curve was obtained changing the inter-electrode distance from 0.01 cm to 0.18 cm at fixed value of pressure. The symbols in the figure represent the static breakdown voltage value at certain value of inter-electrode gap. The insignificant change of U_s value for $pd \leq 0.5$ mbar cm is probably consequence of vacuum breakdown mechanism existence. It can be emphasis that the insignificant changes in U_s are also observed for small *pd* values for N_2 [16,17], SF_6 [18], Ar [19,20] and air [9]. For $pd > 0.8$ mbar cm value U_s, *pd* value increases which is in agreement with our earlier obtained Paschen's curve for above mentioned gases where Townsend's breakdown mechanism is dominant. To verify the anomalies Paschen's law it is taken more points to the left of Paschen's minimum where it occurs combined gas and vacuum mechanisms of breakdown initiation.

From Fig. 2 it can be seen that the Paschen's minimum of shown dependence appears about $pd \approx 0.8$ mbar cm corresponding to