

ON THE VALIDITY OF THE SURFACE LAW

V.LJ. MARKOVIĆ, S.R. GOCIĆ, S.N. STAMENKOVIĆ

Department of Physics, University of Niš, 18001 Niš, Yugoslavia

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Abstract.

In a recent paper [1] the pulse breakdown characteristics in nitrogen at low pressure was studied. The linearly rising (dynamical method) and step pulses (time delay method) were applied. The validity of the surface law was established, *i.e.* “voltage pulses applied on the gas diode erase constant surface in the voltage-time ($U - t$) plane until breakdown appears”. This and other results and conclusions of paper [1] are doubtful and here is the comment with the main corrections suggested.

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1 The Electrical Breakdown at Linearly Rising Pulses

The surface law can be expressed by the following relation:

$$S = t_d \times \Delta U / 2 = \text{const}, \quad (1)$$

where t_d is the breakdown time delay that elapsed from the static U_s to the dynamic breakdown voltage U_b [3], and $\Delta U = U_b - U_s$ is the overvoltage. Because $t_d = \Delta U / k$, where k [Vs^{-1}] is the voltage increase rate, it follows from (1) that

$$S = \frac{\Delta U^2}{2k} = \text{const}. \quad (2)$$

or, after averaging over all data in the series:

$$\bar{S}_k = \frac{\overline{\Delta U_1^2}}{2k_1} = \frac{\overline{\Delta U_2^2}}{2k_2} = \frac{\overline{\Delta U_3^2}}{2k_3} = \dots = \text{const}. \quad (3)$$

It is well known that the dynamic breakdown voltage U_b is a stochastic variable, whose distribution function can be expressed by [4]

$$F(U_b) = 1 - \exp \left[- \int_{U_{b,\min}}^{U_b} \frac{Y(U)P(U)}{k} dU \right], \quad (4)$$

where Y represents the number of electrons generated in the gap per second (electron yield), P is the probability that one electron may cause a breakdown, and $U_{b,\min}$ is the minimum breakdown voltage. The fraction of voltages exceeding U_b can be given by the relation:

$$\frac{n_i}{N} = \exp \left[- \int_{U_{b,\min}}^{U_b} \frac{Y(U)P(U)}{k} dU \right]. \quad (5)$$

It was applied to the experimental data from [2] in semi-log scale (Fig. 1).

In Townsend's model, which is applicable in this case [5], the breakdown probability is given by the relation:

$$P = \begin{cases} 0, & \text{for } q \leq 1 \\ 1 - 1/q, & \text{for } q > 1 \end{cases} \quad (6)$$

where $q = \gamma \exp(\alpha d)$, and γ is the effective secondary emission coefficient [3,5]. The secondary electron yield γ is determined from the breakdown criterion (Paschen law) [3]

$$\gamma_s = [\exp(\alpha d) - 1]^{-1} \quad (7)$$

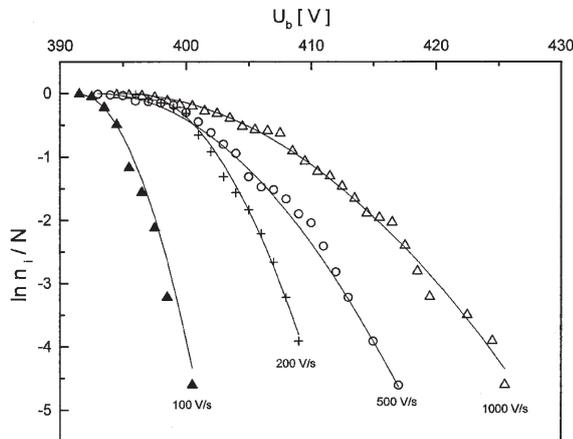


Fig. 1. The experimental distributions of breakdown voltages (symbols) fitted by theoretical distributions (solid lines).

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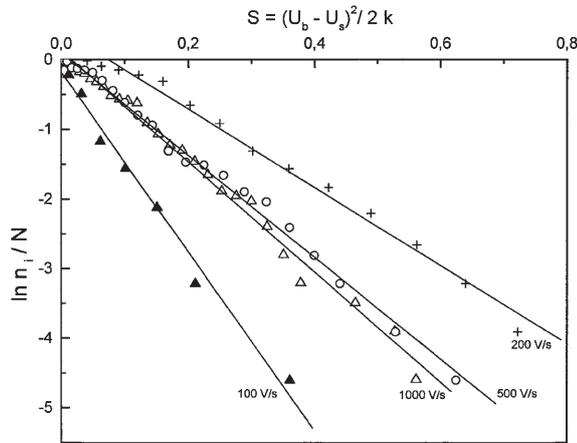


Fig. 2. The distributions of the surface values S at the different increase rates k (symbols) is nearly linear (solid lines).

for the static breakdown voltage $U_s = 390 \pm 1$ V, and for the minimum dynamic breakdown voltages $U_{b,\min}$, designated by $\gamma_{b,\min}$.

The fit of the experimental data for the dependence of electron ionization coefficient on the reduced electric field α/N (E/N) was used from [6], and it was based on the Townsend-type empirical formula:

$$\alpha/N = A \exp(-BN/E). \quad (8)$$

The following values for the parameters were obtained: $A = 310.8 \times 10^{18}$ cm², $B = 925.1$ Td for $E/N < 600$ Td, and $A = 408 \times 10^{18}$ cm², $B = 1082.3$ Td for $E/N > 600$ Td. E/N is the ratio of the electric field and the gas density, represented in units of Td (Townsend, 1 Td = 10^{-21} V m²), $E = U/d$ is the gap electric field, and $d = 1.2$ mm is the gap between the electrodes.

The γ was taken to be the linearly increasing function of the overvoltage $\gamma = \gamma_{b,\min}(1 + C_1 \Delta U)$, causing the electron yield to rise according to relation $Y = C_2 \gamma$, where C_1, C_2 are constants. The best fit of experimental data was obtained for the initial electron yield of $Y = 900$ s⁻¹ for all increase rates, $\gamma_{b,\min} = 0.00958, 0.00931, 0.00949, 0.00940$, and the relative γ and increase of 5%, 5%, 7%, and 13%, respectively (Fig. 1), according to increasing range of over volt ages and the slow increase of $\gamma(E/N)$ dependence [6].

The distribution functions of the surface values (2) were shown in the similar manner (Fig. 2). Because the diagram is linearized in the semilog scale, the distributions of the surface values within the same k is nearly exponential, and they are different for different k . Moreover, relation (3) was shown as $\overline{S}_k(k)$ dependence (Fig. 3). As can be concluded from Figs. 2 and 3, the surface values are not constant (*i.e.* the surface law is not valid), except possibly at larger increase rates (k) and smaller relaxation times (τ).

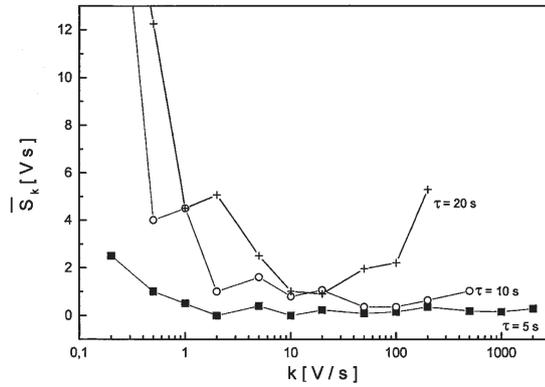


Fig. 3. The surface values \overline{S}_k as a function of the voltage increase rates k at different relaxation times τ .

2 The Electrical Breakdown at Step Pulses

In the case of step (rectangular) pulses, the surface law can be expressed by the relation:

$$\overline{S} = \overline{t_{d1}} \times \Delta U_1 = \overline{t_{d2}} \times \Delta U_2 = \overline{t_{d3}} \times \Delta U_3 = \dots = \text{const.} \quad (9)$$

where $\Delta U = U - U_s$, and U is the working voltage (more details about the application of the time delay method in the study of gas-phase and surface processes can

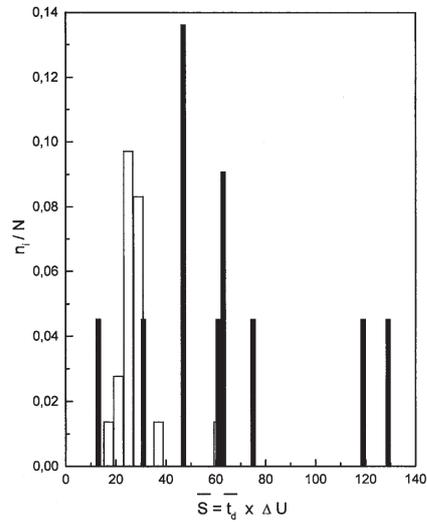


Fig. 4. The normalized histograms of the surface values \overline{S} at step pulses for measurements of [1] (white columns) and [6] (black columns).

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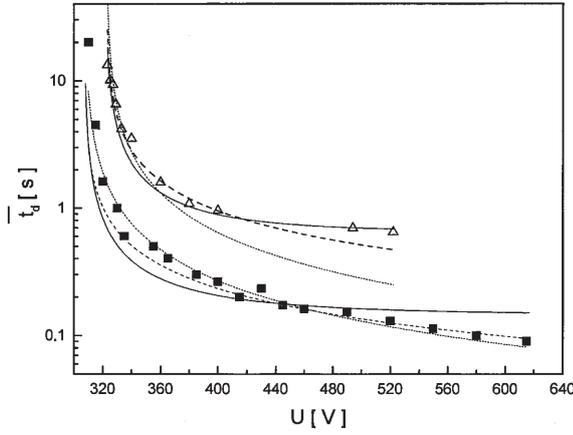


Fig. 5. The simple fits (solid lines) for the measurements of [1] (■) and [6] (△), accompanied by the power function fits (dashed $\propto \Delta U^{-0.75}$ and dotted lines $\propto \Delta U^{-1}$).

be found in [6–10]). The surface values $S = t_d \times \Delta U$ for the single measurements of breakdown delay times t_d at the same working voltage U follow the statistics of t_d [5,6]. The histograms for the $\bar{S} = \bar{t}_d \times \Delta U$ products of measurements from [1] and [6] (homogeneous electric field) are presented in Fig. 4, showing that this product is not constant, *i.e.* the surface law is not valid.

Moreover, the simple fitting procedure based on the Townsend's theory was carried out for $\bar{t}_d(U)$ dependences of [1] and [6] (Fig. 5). The time delay t_d of electrical breakdown is the sum of the statistical time delay t_s and the formative time delay t_f [3]. The formative time can often be neglected compared to the statistical time delay and therefore $t_d \approx t_s$ [5,6]. The mean value of the statistical time delay can be expressed by $\bar{t}_s = 1/(YP)$ [3], where the breakdown probability P is given by the relation (6), and the electron ionization coefficient α by the relation (8). The best fit of the measurements from [6] (△) for the homogeneous electric field is obtained for $Y = 1.5 \text{ s}^{-1}$ and $\gamma_s = 0.01446$ ($U = 321 \text{ V}$), and is shown in Fig. 5 (solid line). Thus, the formative time delay is negligible under these conditions and the breakdown mechanism is of the Townsend type. Formally, $\bar{t}_d(U)$ dependence for the homogeneous field can be fitted by the power function $\bar{t}_d = 25 \times \Delta U^{-0.75}$ (dashed line), much better than by $\bar{t}_d = 50 \times \Delta U^{-1}$ (dotted line), the latter stating the surface law (9).

As for the measurements from [1] (■), the best fit is obtained for $Y = 7 \text{ s}^{-1}$ and $\gamma_s = 0.01444$ ($U_0 = 307 \text{ V}$), and is shown in Fig. 5 (solid line). The probable cause for the disagreement between the experiment and theory is an inhomogeneous electric field or nonstabilized (“unconditioned”) copper cathode surface, electrolytically plated with Au. The $\bar{t}_d(U)$ curve does not reach the saturation value $\bar{t}_d^{SV} \approx \bar{t}_s^{SV} \approx 1/Y$, when $P \approx 1$ at high overvoltages [5–7]. Thus, an apparent agreement is obtained with the power function fits $\bar{t}_d = 7 \times \Delta U^{-0.75}$ (dashed

line), and $\bar{f}_d = 25 \times \Delta U^{-1}$ (dotted line).

In general, the surface law is not valid at low pressure and Townsend's breakdown mechanism by applying the linearly rising or step pulses, contrary to [1] where its validity is stated. Further comments are too numerous to be discussed, so only the most important ones were considered.

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