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A mechanism of pulse breakdown evolution in polymeric films

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Received April 12, 2022

Revised April 12, 2022

Accepted April 19, 2022

We present the results of an experimental study of the pulse electrical strength of polyethylene terephthalate and polypropylene films when they are subjected to a single electric pulse. It has been found that the breakdown of these films is possible both at the front and at the plateau of the pulse, and the probability of breakdown at the front increases with pulse amplitude. We recorded a jump in the durability of the films at the transition from breakdown at the front to breakdown at the pulse plateau. It is shown that the processes that prepare the film electrical breakdown develop faster at the pulsefront than at the plateau. We discuss a possible physical mechanism to explain this effect.

Keywords: polymers, polypropylene, polyethylene terephthalate, pulsed electrical breakdown, electroluminescence.

DOI: 10.21883/PSS.2022.08.54610.346

1. Introduction

For several decades, much attention is paid to the study of pulse electrical strength of polymer dielectrics. It is due to both the practical and scientific significance of the phenomenon. On the one hand, polymeric materials are widely used in different electronic devices as dielectric and insulating layers and can be affected by strong electric fields, and on the other hand, despite the problem topicality, a physical theory, adequately explaining all the known regularities of pulse breakdown of polymers, has still not been elaborated.

The current existing viewpoints on the physical mechanism of pulse electrical breakdown of polymers differ greatly. The collision ionization hypothesis is the most widespread one. It is believed that such ionization occurs in polymer dielectrics when exposed to a strong electric field causing the formation of electron avalanches. Despite the wide and long discussion of this mechanism of electron avalanche formation [1–4], its implementability in polymers raises doubts.

The authors of [5–8] believe that the formation of electron avalanches in polymers is hindered in the conditions of carrier hopping transport, which is typical for organic materials. Indeed, electron free path length in such materials does not exceed 1 nm, which corresponds to the intermolecular distance, therefore, the energy gained by an electron on the free path length even in a field of 10^7 V/cm will not exceed 1 eV. This value is significantly smaller than the ionization energy of polymer dielectric macromolecules equal to 5–7 eV [8–10]. Such argumentation to explain the impossibility of collision ionization development, at least at the initial stage of polymer electrical ageing when they are

still free from pores and disordered regions, where electrons on the free path length can gain the required energy, seems to be convincing.

The authors of [8] explained the regularities of electrical ageing and breakdown of polymer dielectrics in a constant electric field by a physical model of polymer breakdown not related to collision ionization. It is based on the idea of field-induced ionization of macromolecules which results in the formation of positively charged molecular ions (holes) and electrons. According to this model, a burst-line increase of charge carrier concentration is caused by Debye shielding of charges, which leads to a decrease of macromolecule ionization energy, and, as a result, to self-acceleration of their field-induced ionization. The papers [9,11] have shown the usability of this model not only for explaining the regularities of polymer breakdown in a constant electric field, but also when considering reasons for pulse electrical breakdown of polymer films.

Importantly, pulse electrical breakdown of polymers occurs not instantaneously after the voltage application, but after a certain period called the delay time. Regardless of the actual physical mechanism of breakdown (collision or field-induced ionization of macromolecules), delay time is necessary to attain a charge carrier concentration which allows for the flow of high-density current through the polymer and, due to the electrocaloric effect, heating of a local region of the polymer, which will result in the formation of a breakdown path in it. Thereat, the substance being at a low temperature will turn into conductive plasma at a high temperature. A breakdown path in polymer films in the conditions of quasi-homogeneous electrical field forms the fastest — within one step. Breakdown development time in this case does not exceed several

nanoseconds, while current density in the breakdown path exceeds 10^7 A/cm^2 [12,13]. This time in bulk polymer samples increases considerably, which is, apparently, related to the multistep penetration of the dendrite in the dielectric bulk [1]. The paper [14] has theoretically demonstrated that a single-step pulse breakdown of a polymer dielectric, resulting in the formation of a conductive through breakdown path in it, can occur in the film if its thickness does not exceed $10 \mu\text{m}$.

Thus, the aforesaid makes it possible to conclude that polymer film less than $10 \mu\text{m}$ thick are the most suitable objects for studying the electron form of pulse electrical breakdown occurring in the condition of a homogeneous electrical field. The aim of the present paper was to reveal the regularities of pulse electrical breakdown in thin polymer films and to discuss the possible reasons and peculiarities of its development. High-speed methods for breakdown recording with a high time resolution were used to reveal the conditions of breakdown occurrence on the pulse front and plateau.

2. Procedure

The objects of study were biaxially oriented films of industrially manufactured polyethylene terephthalate (PET) and polypropylene (PP), 2.5 and $2.0 \mu\text{m}$ thick respectively. PET is a weakly polar polymer, permittivity ϵ of which is equal to 3.0 – 3.1 , while PP is a nonpolar polymer with $\epsilon \approx 2$. Films made of these polymers are widely used to manufacture pulse high-voltage capacitors. Their properties have been studied well. Attention should be paid to the fact that breakdown intensity F_{br} for these films in a quasi-constant electric field under suppression of partial discharges differently depends on rate of sample voltage increase dU/dt [15]. While F_{br} of the PET film increases with increase of dU/dt , no dependence of F_{br} on dU/dt is observed for the PP film. The authors of [15] made an assumption that this peculiarity in polymer films is due to different values of coefficients of overvoltages arising in polymers upon volume charge accumulation. It should be also noted that in case of pulse breakdown of the PET film there is a dependence of F_{br} on pulse rise rate [9], while PP films do not feature this dependence [11].

Thus, the present paper aims at studying the pulse electrical strength of polymer films having significantly different electric properties, which, in our opinion, will allow for clarifying the peculiarities of volume charge influence on polymers' pulse electrical strength when comparing electric test results for such films.

Electrical breakdown tests of these films were performed at the temperature of 295 and 343 K and included their single exposure to a negative polarity high-voltage pulse. Pulse amplitude varied from 1000 to 2500 V . Pulse rise rate depended on pulse amplitude and increased linearly from 7.5 to 12.5 V/ns when the amplitude increased in the specified limits. Pulse plateau length was fixed and equal to $\sim 100 \mu\text{s}$.

The film under study was fastened in a special ring mandrel installed between two steel polished electrodes. One of the electrodes (the flat one) was under the ground potential, while a negative polarity high-voltage pulse was supplied to the second one (spherical electrode 6 mm in diameter). The interelectrode space was filled with capacitor oil to eliminate marginal and surface discharges. In such an electrode system field distribution in the region of the minimum electrode spacing is close to homogeneous, that's why electric field intensity F can be calculated using the ratio

$$F = \frac{U}{d}, \quad (1)$$

where U is sample voltage, d is film thickness.

It should be noted here that the use of electrodes which provide a small area of electrode contact with the film makes it possible to determine the electric strength of the polymer material, but not the electric strength which depends on presence of various defects in a polymer film. Indeed, the spherical electrode area, within which the high electric field intensity is maintained, is small. Accordingly, the polymer volume where breakdown is possible is small, therefore, it is unlikely that a large film pore or defect will form within the said „hazardous“ volume.

The measurement setup allowed for recording of film breakdown (with a high time and amplitude resolution) both on the pulse front and plateau, if the sample lifetime, i.e. time till its breakdown (t_{br}) at a given amplitude of the high-voltage pulse did not exceed $100 \mu\text{s}$. Fig. 1 shows typical oscillograms of signals recorded at a breakdown on the high-voltage pulse front (*a*) and plateau (*b*). If breakdown of a film sample did not occur within the recording time, i.e. when $t_{br} > 100 \mu\text{s}$ the test result was considered as absence of breakdown.

Minimum 50 tests were carried out at each pulse amplitude value. Given the stochastic nature of electric breakdown, the values of breakdown voltage U_{br} , determined on the pulse front, as well as values of t_{br} were characterized by a considerable spread. Therefore, average values and variation coefficients U_{br} and t_{br} were calculated for each test series.

3. Experimental results and discussion

The data obtained during the electric tests of PET and PP films were used to calculate the relative percentages of the broken down samples of these films on the pulse front and plateau, as well as percentages of non-broken down samples at different pulse amplitudes at 293 and 343 K . The calculation results are given in Fig. 2. It should be noted that the percentages of broken down or non-broken down samples determine the breakdown probabilities on the pulse front p_{fr} and plateau p_{pl} , while the percentage of non-broken down samples determines the probability of absence of breakdown p_{no} . Evidently, $p_{fr} + p_{pl} + p_{no} = 1$.

Let us first consider the obtained results for the PET film. It is seen that breakdown of this film (Fig. 2, *a*) at 295 K and

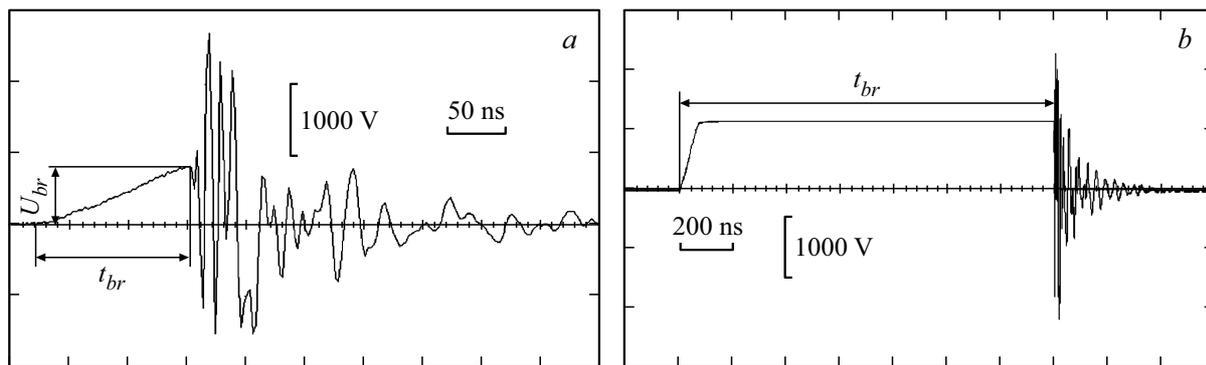


Figure 1. Oscillograms of signals recorded at a breakdown on the high-voltage pulse front (a) and plateau (b).

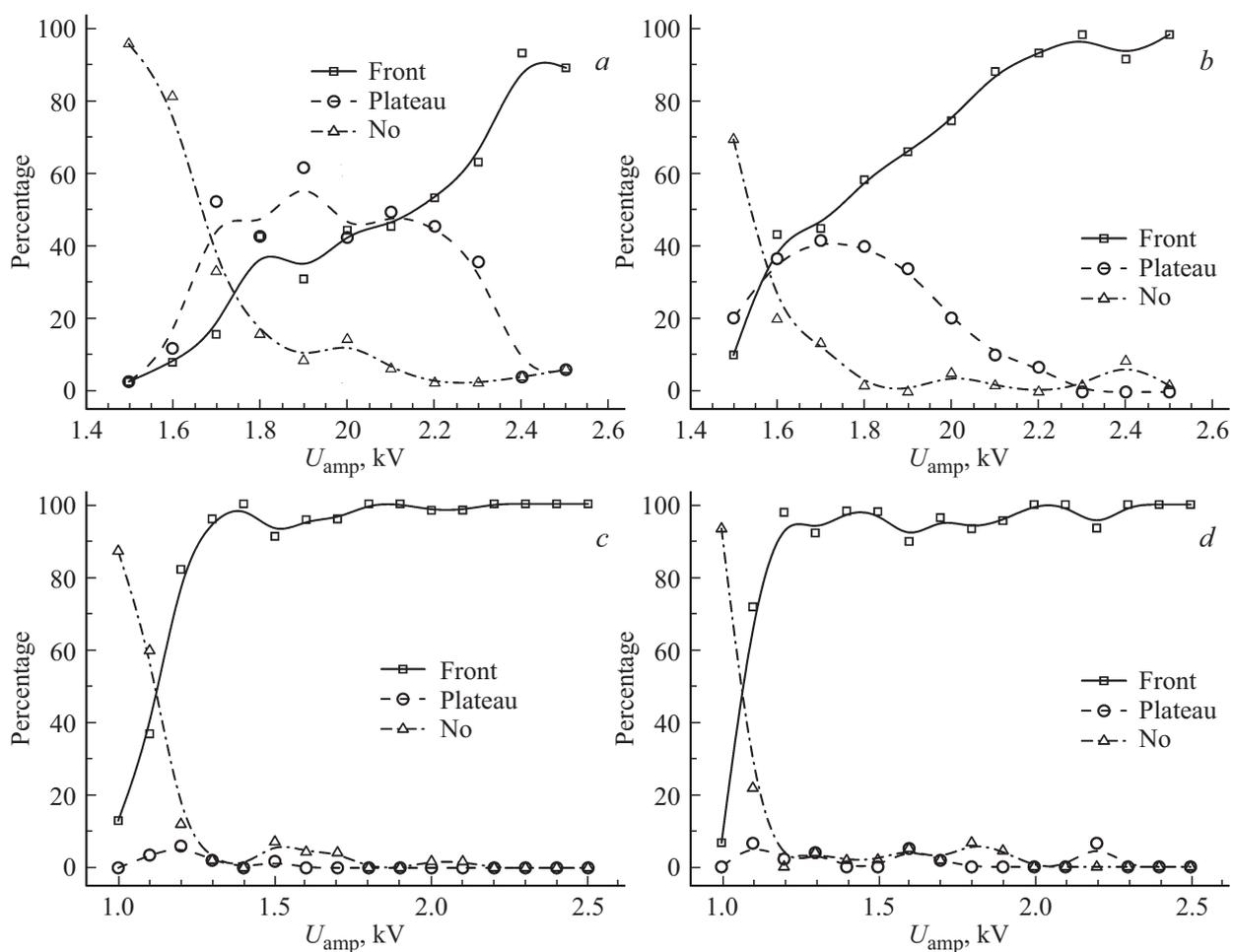


Figure 2. Percentages of samples in relation to the total number of samples in a series, corresponding to absence of sample breakdown, breakdown on the pulse front and breakdown on the plateau at different values of pulse amplitude (electric field intensity attained in a pulse) for PET at the temperature of 295 K (a) and 343 K (b); for PP at the temperature of 295 K (c) and 343 K (d).

$U_{amp} \approx 1500$ V is almost absent. At this pulse amplitude, field intensity in the PET film is $F_{amp} \approx 600$ MV/m according to correlation (1). As pulse amplitude increases, quantities p_{fr} and p_{pl} smoothly increase, while p_{no} decreases. The maximum value of p_{pl} is attained at $U_{amp} \approx 1900$ V ($F_{amp} \approx 760$ MV/m), and breakdown on the plateau in

the considered region of change of U_{amp} turns out to be more probable than on the front. With further increase of pulse amplitude, p_{pl} decreases, but p_{fr} continues increasing. At $U_{amp} > 2300$ V ($F_{amp} > 920$ MV/m), breakdown of almost all samples occurs, usually on the pulse front, i.e. $p_{fr} \approx 1$.

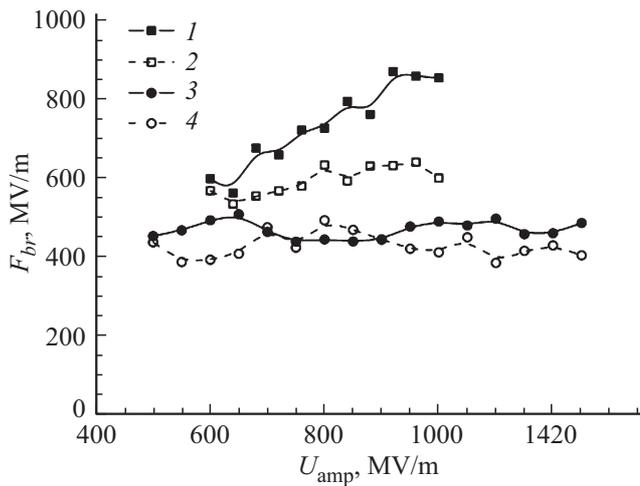


Figure 3. Dependences of $F_{br}(F_{amp})$ for films: PET at 295 K (1) and 343 K (2); PP at 295 K (3) and 343 K (4).

Temperature increase to 343 K (Fig. 2, b) does not cause a considerable change in the pattern of dependence of p_{fr} , p_{pl} and p_{no} on pulse amplitude. We should only note the fact that the maximum of dependence $p_{pl}(U_{amp})$ in this case shifts to the region of lower amplitude and is observed at $U_{amp} \approx 1700$ V ($F_{amp} \approx 680$ MV/m).

In case of PP film pulse breakdown, the pattern of change in probabilities p_{fr} , p_{pl} and p_{no} at pulse amplitude increase differs considerably from the similar dependences found for the PET film. Transition from breakdown absence to breakdown is more abrupt. There is almost no film breakdown at $U_{amp} < 1000$ V ($F_{amp} < 500$ MV/m) at 295 K (Fig. 2, c). However, due to pulse amplitude increase to $U_{amp} \approx 1300$ V ($F_{amp} \approx 650$ MV/m) breakdown of most samples occurs on the pulse front, while breakdown of PP films on the plateau or absence of breakdown are virtually absent. Heating of PP films to the temperature of 343 K (Fig. 2, d) does not significantly affect the pattern of change of probabilities p_{fr} , p_{pl} and p_{no} when pulse amplitude increases.

Taking into account the rather complex interrelation between a breakdown on the front or plateau and absence of film breakdown at different electric pulse amplitudes, which manifests itself differently in different polymers, it is necessary to determine a method for estimating their pulse electric strength and the possibility of comparison of obtained results for different polymers.

When breakdown chiefly occurs on the pulse front, electric strength should be estimated using breakdown intensity F_{br} , the value of which is determined on the basis of the sample voltage value at the moment of breakdown U_{br} (Fig. 1, a). Fig. 3 shows the dependences $F_{br}(F_{amp})$ for PET and PP films, determined for these polymers at 295 and 343 K. For convenience, the charts in this figure do not show the statistical deviations of F_{br} . It should be noted that variation coefficient F_{br} for these films reached 30%. As seen from the figure, value of F_{br} for the PP film

depends neither on temperature nor on pulse amplitude. On the contrary, PET films at 295 K are characterized by a near-linear increase of F_{br} from 600 to 850 MV/m when F_{amp} increases from 600 to 900 MV/m. When values of F_{amp} are large, the value of F_{br} , apparently, stops increasing and stabilizes at the level of ~ 850 MV/m. The linear pattern of dependence $F_{br}(F_{amp})$ is also observed at a higher temperature. Temperature increase to 343 K results in a smaller slope of the straight line $F_{br}(F_{amp})$.

Analysis of electric test results becomes much more complicated if breakdown on the pulse front does not prevail, e.g., there is a situation observed in case of PET film breakdown at a relatively small test pulse amplitude. Since in this case there is a large number of breakdowns on the pulse plateau or they are absent, a calculation of average value of F_{br} will not adequately determine the polymer dielectric electric strength. In our opinion, in this case it should be characterized not by the value of F_{br} , but by sample lifetime t_{br} . It is difficult to calculate the average value of t_{br} because, in the course of experiments, the accuracy of determination of t_{br} in each test is limited by a finite duration of the time interval where a breakdown is recorded. In the case under consideration, the qualitative nature of dependence $t_{br}(U_{amp})$ can be easily determined by adopting $t_{br} = 100 \mu s$ for each non-broken down sample and by considering this value in calculating the average value of t_{br} .

Fig. 4 shows (in semi-logarithmic coordinates) the t_{br}/Δ ratio vs. U_{amp} calculated for the PET and PP films at 295 and 343 K. Here Δ is pulse leading-edge time at the given amplitude. It should be noted that $t_{br}/\Delta = 1$ corresponds to breakdown transition from the pulse front to the plateau. It is seen that this transition occurs almost in a leap, and it occurs at smaller pulse amplitude values in case of temperature increase. This makes it possible to assert that the pattern of development of electric field-induced processes, which eventually result in a polymer film breakdown, is different on the pulse front and plateau.

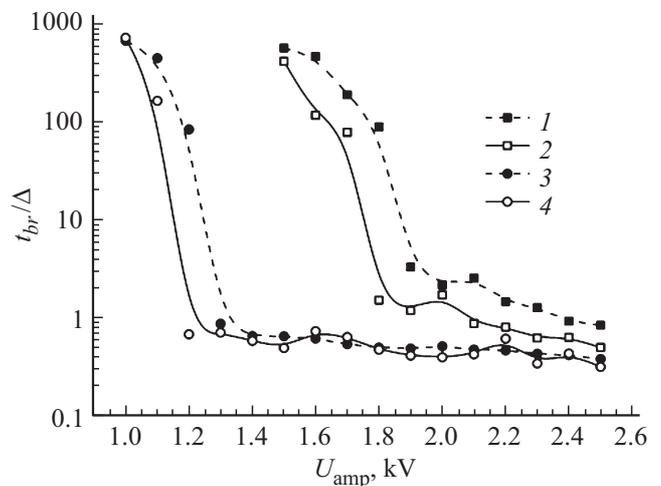


Figure 4. t_{br}/Δ ratio vs. U_{amp} : for the PET film at 295 K (1) and 343 K (2); for the PP film at 295 K (3) and 343 K (4).

When analyzing processes which prepare abrupt structural changes at an electric breakdown of polymer dielectrics, namely, the formation of a breakdown path, the development rate of such processes should be considered as an essential factor which determines the quantity t_{br} . The above-mentioned experimental data makes it possible to conclude that in case of a pulse electric breakdown it must be considerably higher on the pulse front, but not on its plateau.

When discussing the impact of pulse voltage on a polymer dielectric, field-induced ionization of macromolecules will be assumed as the reason of its electric breakdown. The field-induced ionization mechanism of electric breakdown of polymer dielectrics presupposes two interrelated processes that condition the formation of solid-state plasma in a polymer and increase of plasma concentration to the critical value. These are field-induced ionization of macromolecules and thermofluctuation decay of forming molecular ions. Given the short-time development of a pulse breakdown, according to [11], we can restrict ourselves to an analysis of the fastest process, namely, to consideration of field-induced ionization of macromolecules upon an electron tunnel transition from the level of the highest occupied molecular orbital (HOMO) of a macromolecule to the lowest unoccupied orbital (LUMO) of another molecule. It should be noted that such HOMO–LUMO transitions are well-known and determine the operation of organic Zener diodes [16]. The constant of tunnel ionization rate k_{HL} under such transitions is determined as

$$k_{HL} = \nu D_{HL}, \quad (2)$$

where ν is frequency factor, D_{HL} is barrier transparency under a HOMO–LUMO transition. Tunneling in the field direction is most probable, therefore, a simple estimation of the probability of field-induced ionization of molecules can be performed by solving the one-dimensional problem of tunneling through a triangular barrier

$$D_{HL} = \exp\left(-\frac{4\sqrt{2m}\Delta^{3/2}}{3e\hbar F}\right), \quad (3)$$

where m — electron mass, \hbar — Planck constant, F — intensity of the electric field acting on the molecule, Δ — height of potential barrier under a HOMO–LUMO transition. Value of Δ is determined by band gap $E_g = (E_{HOMO} - E_{LUMO})$, (here E_{HOMO} and E_{LUMO} are energies of HOMO and LUMO levels respectively), therefore $\Delta = E_g$. It follows from correlation (3) that the highest macromolecule ionization rate must be achieved on the pulse plateau, but not on its front since electric field intensity there will be the highest. However, this conclusion contradicts the experimental data on rates of breakdown development on the pulse front and plateau.

This contradiction can be avoided by assuming that another process takes place on the pulse front along with tunnel ionization of macromolecules; this process accelerates the ionization of macromolecules and causes

electroluminescence (EL) of polymer dielectrics. It should be noted that EL at a pulse voltage was observed in many polymer films, including PET films [17,18]. Thereat, the most intense luminescence is recorded on the pulse leading and trailing edges, while luminescence on the pulse plateau decays quickly. EL of polymers at a pulse voltage arises in significantly weaker electric fields than fields which enable their pulse breakdown. For instance, luminescence in PET films was recorded already at $F \approx 40$ MV/m [17].

Interrelation between EL and electrical ageing of polymers under direct and alternating voltage has been noted by many authors [19–21]. It is assumed that emission of light in the visible range in this case is due to relaxation of excited states which take place under electron-hole recombination in the bulk (at a direct voltage) or in the polymer's near-electrode regions (at an alternating voltage). Implementation of this EL mechanism, apparently, becomes impossible when polymer dielectric films are exposed to short pulses (not longer than several hundred nanoseconds). This is due to the fact that a region where electrons and holes are present simultaneously and where electron-hole recombination is possible will not form in a polymer film thicker than several microns within such a short time. Indeed, depth of charge penetration into the polymer during the pulse leading edge (on condition that voltage increase rate is constant) is determined by correlation

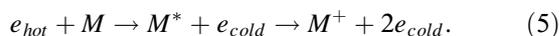
$$l = \frac{1}{2} \mu F_{amp} \Delta, \quad (4)$$

where μ is charge carrier mobility. Adopting that $F_{amp} = 40$ MV/m, $\Delta = 200$ ns and, assuming charge carrier mobility in PET $\mu \approx 10^{-8}$ m²/(V·s) [22], we get $l \approx 40$ nm, i.e. near-electrode regions of a polymer film will indeed accumulate same-sign charges only.

Taking this circumstance into consideration, the authors of [17] conclude that EL in a pulse electric field is caused not by electron-hole recombination, but by shock excitation of luminescent centers by electrons injected from a cathode and accelerated by a high electric field. Despite the fact that free electrons are gradually captured to traps and form a negative volume charge, this charge cannot limit field intensity at the cathode and suppress electron emission. On the contrary, it increases since sample voltage on the pulse leading edge continuously increases. Limitation of cathode field by a volume charge and decrease of emission current become possible only upon transition to the pulse plateau, when sample voltage stops changing. This explains why EL brightness, having reached the peak value, gradually decreases to zero on the pulse plateau.

It can be naturally assumed that, along with excitation of luminescent centers by „hot“ electrons with the energy of 2–3 eV, such electrons, exposed to an electron impact, can excite polymer molecules as well, which will significantly facilitate their subsequent field-induced ionization. It should be noted that the possibility of ionization of electron-excited molecules in a strong electric field is indicated, for instance, in [23,24]. Thus, the mechanism of generation of positive

molecular ions (holes) and electrons can be implemented within a time determined by pulse leading-edge time; the mechanism scheme is as follows:



Here e_{hot} is a „hot“ electron, M — non-excited molecule, M^* — excited molecule, M^+ — positive molecular ion, e_{cold} — „cold“ thermalized electron caused by field-induced ionization of an excited macromolecule or an electron losing energy upon collision with a macromolecule.

As a negative volume charge is accumulated in the near-electron region, field intensity on the boundary of its penetration into the polymer increases. According to [9], field intensity on the charge penetration boundary F_f is determined by correlation

$$F_f \approx F + \frac{eN_t x_f}{2\epsilon\epsilon_0}, \quad (6)$$

where e — electron charge, N_t — trap concentration in polymers, x_f — charge penetration depth, ϵ — polymer permittivity, $\epsilon_0 = 8.85 \cdot 10^{-12}$ F/m. Let us estimate the value of F_f when quantities F are close to the breakdown values. We assume $F = 400$ MV/m, then $x_f \approx 0.4 \mu\text{m}$ according to (4) and, assuming that $N_t \approx 10^{18} \text{ cm}^{-3}$, at $\epsilon = 3$ we get $F_f \approx 1200$ MV/m. The probability of field-induced ionization of non-excited macromolecules in an electric field of such a high intensity becomes rather high [8]. Therefore, field-induced ionization of non-excited molecules can be considered as a factor that accelerates the accumulation of holes and electrons in a polymer dielectric on the electric pulse leading edge.

Breakdown of a polymer dielectric will occur on the pulse leading edge only if charge concentration in the dielectric reaches the critical value which enables self-acceleration of field-induced ionization of macromolecules. Otherwise, charge accumulation will continue on the pulse plateau, but at a decreased rate because the ionization process described in diagram (5) will decelerate considerably or will be suppressed almost completely due to limitation of injection current by the volume charge.

The considered model of development of pulse electric breakdown in polymer films explains the reason for decrease of U_{br} and t_{br} when they are heated. We think that it is related to an abrupt increase of injection current density upon temperature rise and, consequently, an increased number of free electrons capable of gaining (in an electric field) a sufficient energy for molecule excitation.

4. Conclusion

Thus, the performed experimental study of pulse electric strength of PET and PP films 2.5 and $2 \mu\text{m}$ thick under a single exposure to an electric pulse has shown that a breakdown of the films under study is possible both on the pulse front and the plateau, while the probability of breakdown on the front increases as the pulse amplitude

increases. We found an abrupt increase of films' durability upon a transition from a breakdown on the pulse front to a breakdown on the pulse plateau. This result makes it possible to assert that processes that prepare the electric breakdown of films develop faster on the pulse front but not on the pulse plateau. The idea of field-induced ionization of macromolecules was used to explain this peculiarity of pulse breakdown.

It is assumed that, at first, electron injection occurs at relatively low electric field intensities. Injected electrons are accelerated by an electric field and gain an energy sufficient for excitation of molecules but insufficient for their ionization. Excited polymer molecules can ionize at lower electric field intensities than molecules being in the ground state. As a negative volume charge is accumulated in the near-electrode region, electric field intensity on the boundary of its penetration into the polymer will attain values which enable the charge generation also due to field-induced ionization of non-excited molecules. An electric breakdown of a polymer film will occur if both these processes provide attainment of the critical charge concentration within a time not longer than the pulse leading edge time. Otherwise, charge accumulation will continue on the pulse plateau, but at a slower rate due to limitation of field intensity at the cathode by the volume charge and emission current decrease.

The observed decrease of U_{br} and t_{br} at a temperature rise is probably due to an increased density of injection current, which results in an increased concentration of free electrons capable of gaining (in an electric field) sufficient energy for excitation of molecules.

Funding

The research was funded by the Ministry of Science and Higher Education of Russia within the framework of the program of World-class Scientific Center in the field „Advanced digital technologies“ at Saint Petersburg Polytechnic University (agreement dated 17.11.2020 No. 075-15-2020-934).

Conflict of interest

The authors declare that they have no conflict of interest.

References

- [1] L. Zhao, J. Su, C.L. Liu. AIP Advances **10**, 3, 035206 (2020).
- [2] M.P. Wilson, M.J. Given, I.V. Timoshkin, S.J. Mac Gregor, M.A. Sinclair, K.J. Thomas, J.M. Lehr. IEEE Trans. Plasma Sci. **38**, 10, 2611 (2010).
- [3] J. Artbauer. J. Phys. D **29**, 2, 446 (1996).
- [4] I. Kitani, K. Arai. Jpn. J. Appl. Phys. **22**, 5R, 857 (1983).
- [5] Z. Chen, S. Ji, W. Jia, J. Tan, F. Guo, J. Li. W. Chen. IEEE Trans. Plasma Sci. **46**, 11, 4010 (2018).
- [6] L.A. Dissado, J.C. Fothergill. Electrical Degradation and Breakdown in Polymers. The Institution of Engineering and Technology, London (1992). 601 p.

- [7] K.C. Kao. *J. Appl. Phys.* **55**, 3, 752 (1984).
- [8] V.A. Zakrevskii, V.A. Pakhotin, N.T. Sudar. *J. Appl. Phys.* **115**, 23, 234101 (2014).
- [9] V.A. Zakrevsky, V.A. Pakhotin, N.T. Sudar. *Technical Physics* **89**, 1, 120 (2019).
- [10] N.R. Rajopadhye, S.V. Bhoraskar. *J. Mater. Sci. Let.* **5**, 603 (1986).
- [11] V.A. Zakrevsky, V.A. Pakhotin, N.T. Sudar. *Technical Physics* **87**, 2, 249 (2017).
- [12] V.A. Pakhotin, V.A. Zakrevsky, N.T. Sudar. *Technical Physics* **85**, 8, 40 (2015).
- [13] V.M. Rozhkov. *Technical Physics* **73**, 1, 51 (2003).
- [14] S. Boggs. *IEEE Trans. Dielectr. Electr. Insul.* **11**, 1, 90 (2004).
- [15] V.A. Zakrevsky, N.T. Sudar. *Technical Physics* **66**, 4, 105 (1996).
- [16] H. Kleemann, R. Gutierrez, F. Lindner, S. Avdoshenko, P.D. Manrique, B. Lüttssem, K. Leo. *Nano Lett.* **10**, 12, 4929 (2010).
- [17] K. Kaneto, K. Yoshino, K.C. Kao, Y. Inuishi. *Jpn. J. Appl. Phys.* **13**, 6, 1023 (1974).
- [18] K. Kojima, Y. Takai, M. Ieda. *Jpn. J. Appl. Phys.* **21**, 6R, 860 (1982).
- [19] C. Laurent, F. Massines, C. Mayoux. *IEEE Trans. Dielectr. Electr. Insul.* **4**, 5, 585 (1997).
- [20] G. Teyssedre, G. Tardieu, D. Mary, C. Laurent. *J. Phys. D* **34**, 14, 2220 (2001).
- [21] V.A. Zakrevsky, V.A. Pakhotin, N.T. Sudar. *FTT* **61**, 10, 1953 (2019) (in Russian).
- [22] K. Hayashi, K. Yoshino, Y. Inuishi. *Jpn. J. Appl. Phys.* **14**, 1, 39 (1975).
- [23] H.S.W. Massey, E.H.S. Burhop, P.M. Morse. *Phys. Today* **6**, 1, 15 (1953).
- [24] V.A. Polyansky, I.L. Pankrat'eva. *J. Electrostatics* **70**, 2, 201 (2012).