THE IMPACT OF PET INTERFACES IN THE DIELECTRIC STRENGTH OF MULTILAYERED ELECTRICAL INSULATION UNDER HIGH INTENSITY FIELDS

Konstantinos Theodosiou[*] — Ioannis Gialas[*] — Isidoros Vitellas[**] — Dimosthenis Agoris

The influence of PET interfaces in, polymeric insulation, dielectric strength is examined by this paper. PET (Polyethylene terephthalate) films of different thickness are put together forming a planar sample of a typical thickness of $200\mu m$ and subjected to AC ramp voltage, until the dielectric breakdown. Experiments were executed for investigating the role of the position of the first, the second and the last interface in the sample, as well as the influence of interface number n. All the experiments were executed with the same voltage rising step, the breakdown AC voltage V_b was measured and the dielectric strength F_b was calculated. It was shown that interfaces act as deep trapping centers for electrons giving rise to the sample dielectric strength for sort time experiments. The more the number of interfaces, the higher the dielectric strength. Moreover the thinner the first film, the higher the dielectric strength for the sample. It was also found that the position of the second interface does not play an important role in the process and the position of the last interface is significant only in case that samples have the same first interface position. The results were tested using finite elements simulation.

K e y w o r d s: PET, polymeric insulation, dielectric breakdown, dielectric strength, finite elements simulation

1 INTRODUCTION

Polymer sheets are commonly used for the insulation of electric equipment (cables, motor winding etc). Interfaces between polymer-metal and polymer-polymer often influence the whole performance of such electric systems. The importance of investigating these kinds of interfaces, has always been identified as very crucial. Even today many aspects of the role of interfaces in the aging and breakdown of that kind of equipment, are not well explained, despite the effort that has been done in the area from many researchers.

Many models have been introduced [1, 3, 4, 5, 6, 7] attempting to explain, macroscopically or microscopically, the charge transport in polymeric insulators. Especially the role of electrode-polymer interface in this process was the subject of large amount of research, mainly because of its importance in the electron tunneling from the metal to the polymer [8, 10, 11, 12] and the creation of the space charge layer. As the necessity of HV equipment with higher electric strength has lead to the use of polymers sheets and barriers, the role of interfaces became more significant. Polymer-polymer, polymer-mica, polymer-oil, have been investigated, especially their position and type [13, 14, 15], what kind of space charge they accumulate [1, 16, 17, 18, 20] and in what as well as the way that all these aspects affect breakdown strength. Agoris et al [15] have studied the role of the first interface position, thickness and type of barrier in the breakdown characteristics of LDPE (Low density polyethylene) samples, and proved that an optimum position exist for the first interface. Chen et al [21], have investigated the role of interface of the same material (LDPE-LDPE) showing that it acts as a potential barrier to electrons while allowing positive carriers pass easily. In spite of a great number of papers devoted to the role of interfaces in the breakdown characteristics of polymeric insulators, many aspects are not yet well known.

The objective of this paper is to focus on the role of polymer-polymer (PET) interfaces that exist in various electrical equipment under high AC fields, studying experimental results of breakdown measurements. Despite the fact that interfaces in high electrically stressed materials, cause accumulation of space charge and in long term can lead to the failure of the material, in short term experimental conditions, they can improve the dielectric strength. The number as well as the position of the first, the second and the last (back) polymer-polymer interfaces are investigated. In the following section the description of the samples and the experimental procedure is presented. Then the experimental results and theoretical relations are discussed and followed by a few concluding remarks.

2 EXPERIMENTAL PROCEDURE AND SAMPLES

Specimens of PET films (pure PET from Insula Trade S.A. GR) were chosen because of its wide use and relatively simple structure. Films with thickness of 25, 50, 75, 125 and $200\,\mu m$ (named K, A, B, C and D respectively) in square form with dimensions $120 \times 120\,\text{mm}^2$ were put in layers in order to form a sample of $200\,\mu m$ (electrode

[*] University of the Aegean, 82100 Chios, Greece. E-mail: k.theodosiou@aegean.gr

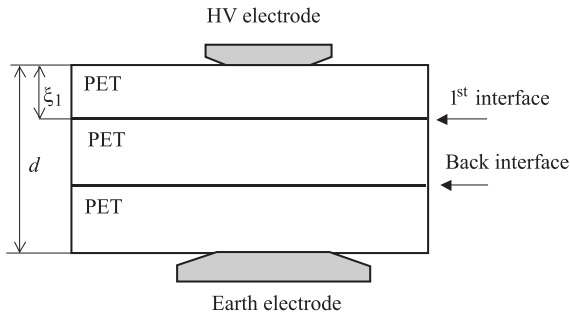[**] University of Patras, 26500 Rio, Patras, Greece

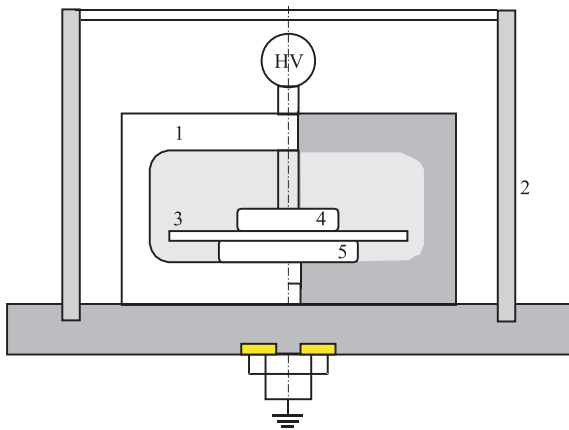**Fig. 1.** Schematic diagram of the sample with PET interfaces.

Fig. 2. Experimental cell filled with power transformer's oil. 1) Inner cell and electrodes base 2) Oil can 3) PET film sample 4) High voltage electrode 5) Earth electrode.
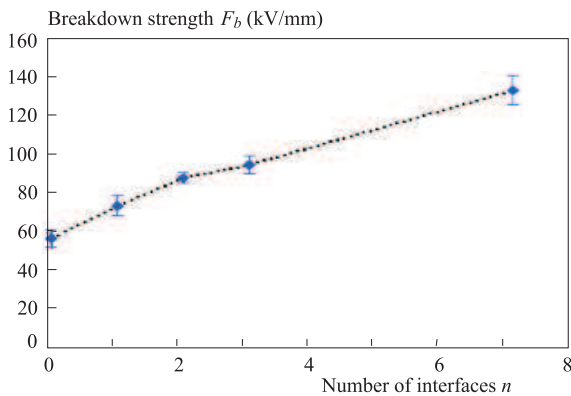

Fig. 3. Average Breakdown Electric field strength in sample versus number of interfaces n. Each point represent the average breakdown strength for various film combinations that have same number of interfaces.

spacing). Fig. 1 represents a schematic diagram of the sample containing four PET films (three interfaces). The position of the first interface is actually the thickness of the first (upper) film and is denoted with ξ_1.

The combinations of films that used are shown in Table 1. The first letter represents the film attached to the upper electrode.

Table 1. Film combinations for $200\,\mu$m electrode spacing.

Number of interfaces n	Film combinations
1	BC,CB
2	BBA,KAC,KCA,AKC,BAB,ABB,ACK
3	AAAA,KBBK,KBKB,BBKK,BKKB,KKBB
7	8K

These electrodes were constructed in vacuum conditions with instant evaporation of a suitable amount of copper, avoiding air enclosure between the samples surface and electrodes. Because of the short time duration of the copper evaporation, no damage occurred on the specimen surfaces, while a good contact was maintained between specimen and evaporated electrodes, as verified by systematic sampling in samples cross sections with the aid of a microscope.

A special experimental test cell was used, filled with power transformer oil and equipped with stainless steel electrodes with rounding edges, as shown in Fig. 2. The diameters of the main electrodes were equal to the corresponding copper electrodes of the samples. The procedure for putting a sample in the test cell was the following: the electrodes base (1) was taken out of the test cell, the electrodes surfaces (4–5) were cleaned from the oil, the sample (3) was placed and fixed between the main electrodes and finally the base (1) was assembled in the bottom of the test cell and connected to an AC power supply. The layers of the sample were gradually assembled under constant pressure in order to avoid trapped air layers inside them. The dielectric strength of the oil (higher than $60\,$kV/mm) was measured regularly and was replaced when it was necessary.

More information about the experimental apparatus are given in [22, 23].

2.1 Breakdown measurements

The power supply used for the experiment was an AC 50 Hz, 100 kV, 100 mA. The voltage applied to the specimen increased from zero at a constant rate of 3 kV/sec, to the breakdown voltage. When breakdown occurred, the voltage supply was interrupted automatically, with the current limiting protection system, adjusted at 6 mA. The breakdown voltage was monitored using a digital voltmeter with memory and the maximum value in each specimen was recorded. For each film combination a group of specimens, each one consisting of twenty samples was used, the breakdown voltage V_b was measured and the dielectric strength F_b of each sample was calculated. Inspection that was taking place immediately after breakdown, have shown spots in the upper electrode perimeter.
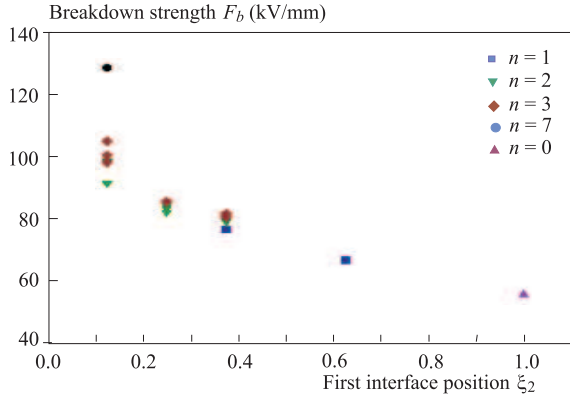
Breakdown strength F_b (kV/mm)

Fig. 4. Average breakdown Electric field strength sample versus position (ξ_1/d) of the first (upper) interface in respect to the high voltage electrode. It must be noted that the dielectric strength for specimen with no interfaces is $57.4kV$
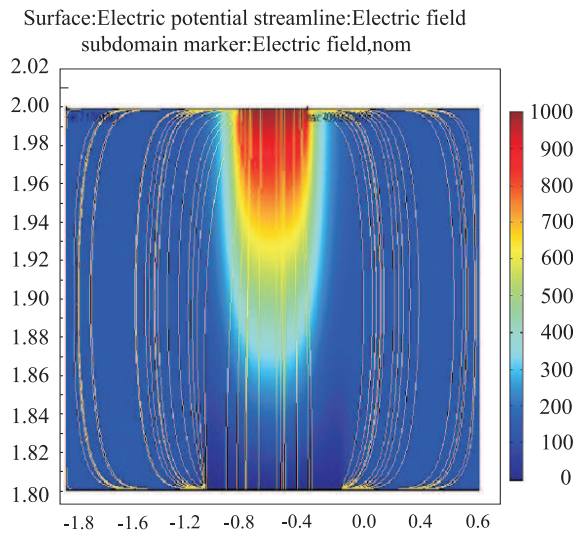
Surface:Electric potential streamline:Electric field subdomain marker:Electric field,nom

Fig. 5. Electric field in a sample without space charge. Yellow lines represent electric field's F_l lines and the point marker its maximum (electrode's edge). The background colors saw the variations of electric potential.

3 RESULTS AND DISCUSSION

Figure 3 represents the first set of breakdown measurements (F_b) in samples with same electrode spacing $d = 200\,\mu$m and different number of interfaces (n) between electrodes. Each point in the graph represents the average of different combinations that have the same number of interfaces. Twenty samples with the same configuration were used for each combination. The bottom line refers to the case of only one film ($n = 0$) between electrodes. It is obvious that the mean value of dielectric strength increases as the number of interfaces also increases. For example we have the following values $57.4, 87.5$ and 130.9 kV/mm of F_b for $n = 0(D), 3(4 \times A)$ and $7(8 \times K)$ respectively. The interface between two dielectric films is determined by a charge density σ that is

given [2] by the formula

$$\sigma = \left(\varepsilon_{r2} - \varepsilon_{r1}\frac{\kappa_2}{\kappa_1}\right)E_2 = \left(-\varepsilon_{r1} + \varepsilon_{r2}\frac{\kappa_1}{\kappa_2}\right)E_1 \quad (1)$$

where κ_1 and κ_2 are the conductivities of two materials forming the interface, ε_{r1}, ε_{r1} the relative permittivities of the same materials and E_1, E_2 the electric field inside them. Because of the fact that we have the same material at both sides of the interface and $\varepsilon_{r1}/\varepsilon_{r2} = \kappa_1/\kappa_2$, σ should be zero. Clearly this expectation is not consistent with experimental results [17, 20, 21]. This seeming inconsistency can be explained by the fact that the system is not linear because of changes in conductivity due to local electric field variations and hence to the electric stress. Another important fact is that interfaces act as deep traps due to changes in lamelas orientation, broken bonds, chain folds, air bubbles etc [6, 7, 21, 22]. In present work of Chen et al [21], measurements in LPDE interfaces indicated that electrons are trapped in the interface while positive charges pass through easily. The result of this space charge accumulation is that the local electric field $F_l(t)$ is a result of the applied electric field and internal field due to space charge. In our previous work [22, 23], we have derived the following relations:

$$F_l(t) = F_a(t) - F_i(t) = \alpha\frac{V}{d} - F_i(t) \quad (2)$$

where $F_a(t)$ is the applied electric field, V is the applied voltage, d is the polymer thickness (electrode spacing), $F_i(t)$ the internal electric field created by the trapped electrons and α the local overstress factor which depends on the local morphology (local asperities, microvoids with special orientation ect). This field tends to retard the oncoming groups of injected electrons and its intensity is given by

$$F_i(t) = \frac{Q(t)}{\epsilon\epsilon_0}\left(1 - \frac{\xi}{d}\right) \quad (3)$$

with $Q(t)$ the total trapped charge per unit area and ξ the interface position in the specimen. A very important fact that is worth mentioning here is that in AC fields, when the electrodes polarity changes (in half period time), the minus sign in (2) becomes plus instantly and the local electric field reaches its maximum.

In order to evaluate theoretically the trapped charge $Q(t)$, we consider the electron trapping rate [9]

$$\frac{dn_f(t)}{dt} = \frac{\sigma J(t)}{e}[N_t - n_f(t)] \quad (4)$$

where $n_f(t)$ and N_t the concentrations of the filled and the total traps respectively and σ the effective capture cross section of the traps. $J(t)$ is the injected current density due to Fowler-Nordheim tunneling

$$J(t) = CF_l^2(t)\exp\left(-\beta/F_l(t)\right) \quad (5)$$

Surface:Electric potential streamline:Electric field
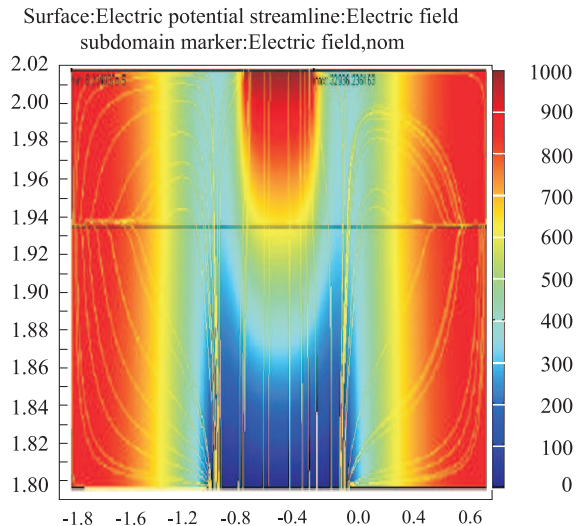subdomain marker:Electric field,nom

Fig. 6. Electric field in a sample with space charge in the surface between the two samples (black line). The field's lines have changed and the maximum Electric field has decreased.
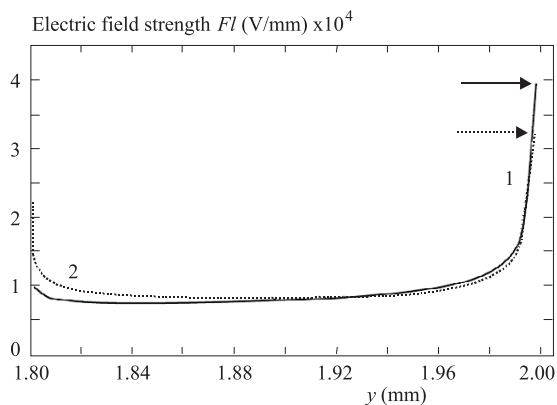
Electric field strength *Fl* (V/mm) x10^4

Fig. 7. Electric field strength inside the sample (from one electrode edge to the other) . Line 1 (full line) shows the strength of the sample without space charge and the line 2 (dotted line) the strength with the presence of a space charge layer. The field strength in the upper electrode has decreased and in the earth electrode has increased (see the arrows).

with

$$C = \frac{e^3}{16\pi^2\hbar\Phi_e}, \quad \beta = \frac{4(2m_e)^{1/2}}{3\hbar e}(\Phi_e)^{3/2} \quad (6)$$

where e and m_e the charge and the effective mass of electron respectively, $\hbar$ the Planck constant, Φ_e the effective potential barrier in eV and $F_l(t)$ the intensity of the local electric field.

¿From relation (4), we can derive from the initial condition $n_f(t) = 0$ for $t = 0$ that

$$n_f(t) = N_t\Big[1 - \exp\Big(-\frac{\sigma}{e}\int_0^t J(t)\mathrm{d}t\Big)\Big] \quad (7)$$

The total trapped charge will be then

$$Q(t) = \int_0^d n_f\mathrm{d}x = edN_t\Big[1 - \exp\Big(-\frac{\sigma}{e}\int_0^t J(t)\mathrm{d}t\Big)\Big]. \quad (8)$$

From relations (2), (3) and (8), it is obvious that the intensity of the local electric field is controlled by many parameters. At the moment we will comment on two parameters, the position of the interface ξ and the total trapped charge $Q(t)$ play a very significant role. As ξ decreases and $Q(t)$ increases, the intensity of the internal electric field increases and hence the local electric field decreases. In a sort term breakdown experiment, interfaces act as continuous traps and retard the oncoming injected electrons. More interfaces result in the increase of the $Q(t)$ due to higher N_t. If we also consider that in interfaces, electric field refraction is taking place, a lengthening of the conducting path, may be accounted as a reason for higher electric strength in samples with more interfaces.

At the same time, some samples with fewer interfaces have higher dielectric strength. In order to elucidate this feature, we made additional measurements attempting to evaluate the role of position of the first interface (or the thickness of the upper film) in the sample, as shown in Fig. 4. We chose the parameter ξ_1/d to denote the position of the first interface ξ_1 with respect to the total sample thickness d. For example, samples KAC and KCA with $n = 2$ have F_b values 93.43 and 100.5 kV/mm, significantly higher than those of samples BBKK and BKKB (83.67 and 82.65 kV/mm respectively). Results for $n = 2$ and 3 with the same value of $\xi_1/d = 0.125$ are presented table 2. It is evident that as the position of the first interface ξ_i decreases, the sample's dielectric strength increases, as it was predicted from relations (2) and (3). Using FEMLAB 3.1 ®simulation package we obtained for BC and CB configuration ($n = 1$) a maximum field strength of 32936.3 V/mm and 35857.7 V/mm respectively. This result is consistent with the experimental breakdown measurement results. We have to note here that the electric field strength dependance from the position of the interface seems to follow a rather complicated form, giving, alike the case of the well known barrier effect, a maximun in a specific position. Experiments and a detailed discussion on this effect is presented in a forthcoming paper of the authors. A second possible explanation is that the thinner film has a higher dielectric strength [22,23], and the penetration of the samples always starts from the HV electrode.

In the next paragraph we will evaluate the variation of the intensity of the local electric field by differentiating relation (2)

$$\frac{\mathrm{d}F_l(t)}{\mathrm{d}t} = (\alpha/d)\frac{\mathrm{d}V(t)}{\mathrm{d}t} - \frac{\mathrm{d}F_i(t)}{\mathrm{d}t} \quad (9)$$

(The term $(\alpha/d)\frac{\mathrm{d}V(t)}{\mathrm{d}t}$ is an experimental quantity and always positive). For an applied voltage with rising rate (λ kV/s), the former relation gives

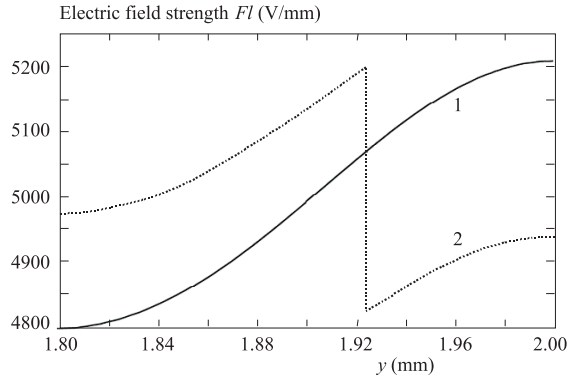$$\frac{\mathrm{d}F_l(t)}{\mathrm{d}t} = \rho_a - \rho_i \quad (10)$$

Fig. 8. Electric field strength inside the sample's center. Line 1 (full line) shows the strength of the sample without space charge and the line 2 (dotted line) the strength with the presence of a space charge layer (the vertical part of the dotted line in the position of the space charge layer is due to the fact that this layer has zero thickness). The average field strength has decreased.
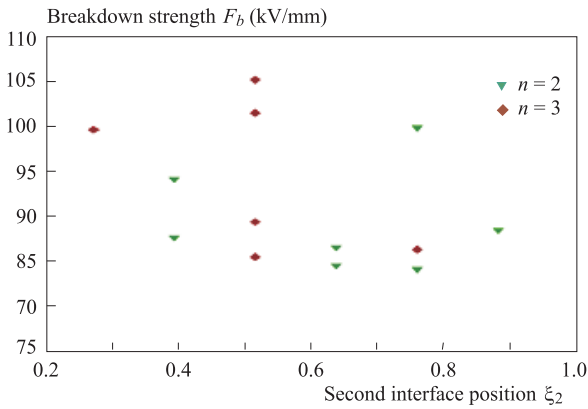

Fig. 9. Average breakdown Electric field strength sample F_b versus second interface position (ξ_2/d).
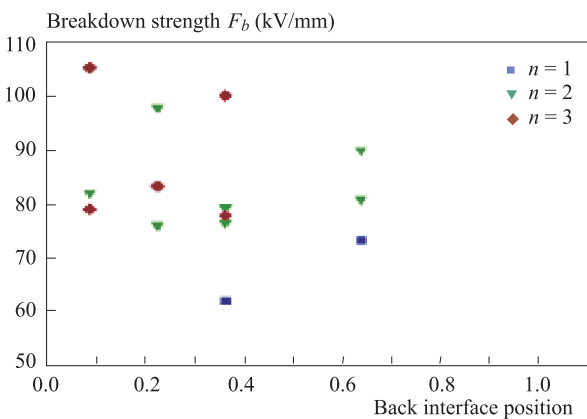

Fig. 10. Average breakdown Electric field strength sample F_b versus last (back) interface position. It must be noted that the dielectric strength for specimen with no interfaces is $57.4 kV$.

with

$$\rho_a = (\alpha/d)\lambda, \quad \rho_i = \frac{\mathrm{d}F_i(t)}{\mathrm{d}t} = \frac{1}{\epsilon\epsilon_0}\Big(1 - \frac{\xi}{d}\Big)\frac{\mathrm{d}Q(t)}{\mathrm{d}t} \quad (11)$$

and by differentiating relation (8), ρ_i can be expressed as

$$\rho_i = \frac{\sigma J(t)dN_t}{\epsilon\epsilon_0}\Big(1 - \frac{\xi}{d}\Big)\exp\Big(-\frac{\sigma}{e}\int_0^t J(t)\mathrm{d}t\Big) \quad (12)$$

It is obvious from (12) that ρ_i is controlled by many parameters such as carrier mobility, the distribution of the traps and their capture cross section, the dielectric permitivity *etc*. It can be seen from (10) that there are three possible ways to describe the $J - F_l$ or $I - V$ relation.

(i) $\rho_a > \rho_i$ then F_l increases and consequently J (relation (5)) also increases.

(ii) $\rho_a = \rho_i$ thus F_l becomes time independent and J becomes saturated, as a result of constant ρ_i.

(iii) $\rho_a < \rho_i$ and J after reaching a peak value, decreases with F_a increasing. This will happen if N_t or σ or both are large.

Figures 5 and 6 show the electric field F_l and its maximum without and with the presence of space charge respectively. The change is obvious while the internal (space charge) field F_i becomes comparable with the applied field F_a. The FEMLAB 3.1 simulation package was used with the values: $V = 1000$ Volt, $\frac{\xi}{d} = 0.375$ $\varepsilon = 3$ and $Q = 1 \times 10^{-8}$ Cb. These values correspond to an internal field F_i value equal to the one tenth of the external applied field V/d. The chosen Q is of the same order with the trapped charge measured by Chen et al [21]). The decrease of the maximum strength (upper electrode edge) was 19.3% as it is shown in figure 7. From the other hand the strength in the earth electrode edge increases. The strength of the average electric field also decreases (Fig. 8).

In our experiments, the position of the other interfaces seems to be insignificant as it can be seen in fig. 9 for the second interface position. The same conclusion appears in fig. 10 for the last, in respect to the earth electrode, interface, except in the case we have the same first interface position. Then the closer the back (last) interface to the earth electrode, the higher the dielectric strength (see Table 2). This is an indication that electron injection is also taking place in that electrode, but at a significantly lower rate.

It is very important to notice that the dielectric strength of the samples in general, deteriorates in the long term at the presence of interfaces mainly due to partial discharges in the trapped air between them. Charge recombination (a free electron and a positive macroion pair) [24] is also significant in interfaces especially in AC fields. This process involves the release of energy in the order of almost 6 eV that can directly lead to macromolecule dissociation, bond breaking and hence chemical and mechanical damage.

Table 2. Film combinations with the same ξ/d. In that case, specimens with the last interface closer to the earth electrode have the higher dielectric strength.

Number of interfaces **n**	Film combinations	Breakdown strength (kv/mm)
2	KAC	93.43
	KCA	100.5
	KKBB	100.21
3	KBKB	102.5
	KBBK	107.1

4 CONCLUSIONS

The role of interfaces in the dielectric strength of samples of sandwiched PET films has been examined. Samples with standard thickness of $200\,\mu m$ were subjected to AC 50 Hz ramping voltage until the dielectric's breakdown. The bigger the number of interfaces the higher the breakdown electric field strength. This fact was explained mainly as a result of the space charge accumulation in the interfaces and in the resulting electric field that opposes the external applied field. Another reason could be the lengthening of the conduction path between the two electrodes. An important factor affecting dielectric strength is the position of the interfaces. Samples with the first interface closer to the HV electrode had a significant higher dielectric strength, because of the more intense internal field and the higher strength of the first film itself. The position of the other interfaces had no effect in the dielectric characteristics of the samples. The role of the last interface position was significant only in the case that samples have had first interface at the same position. This was attributed to the fact that electron injection is much lower in the earth electrode than that of the HV electrode.

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Konstantinos Theodosiou is a lecturer in the University of the Aegean, Chios, Greece. He has born on 1967 in Greece and has obtained an MPhys, an MSc in Electronic Engineering and a Phd in the field of Electrical Insulation. His research interests include degradation and breakdown of insulating materials, polymer physics, electromagnetics.

Ioannis Gialas is an Associate Professor in the University of the Aegean, Chios, Greece. He has born on 1960 in Greece and has obtained an MPhys, an MSc in Physics and a PhD in the field of Experimental High Energy Physics. His research interests are in the area of experimental High Energy Physics and electromagnetics.

Isidoros Vitellas is Director of the High Voltage Laboratory in DEH (Public Power Corporation) Athens, Greece. He has born on 1954 in Greece and has obtained an Diploma in Electrical Engineering and a PhD in the same field. His research interests include electrical power generation and transfer, degradation and breakdown of insulating materials, electromagnetics.

Dimosthenis Agoris is an Associate Professor in the Department of Electrical Engineering and Computer Technology, University of Patras, Rio, Patras, Greece and Director of the High Voltage Laboratory in the same Department. He has born on 1952 in Greece and has obtained an Diploma in Electrical Engineering and a PhD in the same field. His research interests include Electrostatics, Electromagnetics, electrical power generation and transfer, degradation and breakdown of insulating materials.