

Parameters characterizing the charge state of dielectrics

BOŻENA ŁOWKIS*

Wrocław University of Science and Technology, Faculty of Electrical Engineering,
8 Janiszewskiego St., 50-377 Wrocław, Poland

This paper presents three physical sources of the electric field in dielectrics: excess free volume charges with the distribution $q_v(x,y,z)$, free surface charges with the distribution $q_s(x,y,z)$ and frozen polarization state in the dielectric. They have a deciding influence on the parameters of the electret, in particular they determine the total lifetime of the electret and technical components made of it. The indeterminacy related to the mutual proportions of the spatial and surface charges was discussed: one can find an infinite number of distributions of surface $q_{se}(x,y,z)$ and spatial $q_{ve}(x,y,z)$ charges leading to the same distribution of the electric field $E(x,y,z)$. A general case of electret was considered, where a coexistence of relaxation decay of frozen polarization and Maxwellian relaxation dependent on volume conductivity of the dielectric is assumed. An attempt to interpret the charge lifetime in real electrets was made.

Keywords: *dielectric; polymer; electrets; charge; lifetime*

1. Introduction

The lifetime of electric charge τ is one of the basic parameters characterizing electret materials. Electrets fabricated from different polymer foils have different lifetimes, which depend on electrical conductivity and concentration as well as energy of localized trap-states in the material. Systematic studies of electret properties of some foils made from polyolefins series (e.g. PE, PTFE, PCV) showed that foil electrets made of completely symmetrical polyolefins are characterized by the highest charge stability. The degree of branching of polymer chains and size of crystallites has a slightly smaller influence on electrets stability. The more branched the polymer, the less durable polymers made of it.

Possible applications of electret materials are directly related to the lifetime of electric charge. The charge lifetime in contemporary polymer electrets is relatively long, reaching about 10^3 years to 10^5 years [1, 2], depending on the type of material, manufacturing method and the conditions of use (effect of air moisture, temperature, etc.). The topics related to the lifetime of electric charge

have been considered in numerous scientific publications. We believe that works [1–8] are particularly relevant to this field and useful to understand and model this phenomenon. In the literature [1], the electret lifetime was estimated based on the isothermal charge decay, the charge decay in non-isothermal conditions and the thermally stimulated current. The experimental results indicate that two relaxation processes can be observed, one due to the decay of the heterocharge and the other due to the decay of the homocharge.

In my previous work [2], we have presented a few applications of electrets with the charge implanted from an external source, such as medicine and health protection. Basic characteristics of the formed electrets, especially an average location of electric charge and space charge distribution, are discussed. The isothermal and non-isothermal methods of assessment of the electrets charge lifetime have been employed. Finally, the effect of the manufacturing process parameters, electrization state and environmental conditions on the stability of filtration fibers and filtration quality is analyzed.

Molinie [3] presented a broad survey of the existing models accounting for surface potential decay. Molinie made a claim that several

*E-mail: bozena.lowkis@pwr.edu.pl

polarization or transport processes may be involved in the charge decay. The work of Tabti et al. [4] took advantage of a specific surface potential decay (SPD) formulation to characterize the dielectric behavior of fibrous electrets that were negatively-charged from a triode-type electrode system. The experiments were performed in a typical ambient temperature, at a wide range of the relative humidity.

Thakur et al. [5] described an experimental evaluation where a series of fibrous electrets was prepared by applying electrostatic charge to a polypropylene nonwoven fabric using corona charging process. The charge decay was examined over a wide range of charging parameters. It turned out that the charge decay characteristics were well approximated by a double exponential function composed of two exponentials with very different characteristics. This result might suggest, analogously to the conclusion in the literature [1], that two charges of different nature were present in the electrets. The authors claimed that one of those charges was a result of ions deposited on the surface of the electret while the other came from internal polarization.

Sessler et al. [6] suggest that the charge transport in electron-beam irradiated insulators can be analyzed using different theoretical models. Those models are based upon various assumptions concerning generation, drift, trapping and recombination of the charge carriers. The authors focus on two models that gained particular popularity. The first one, macroscopic, uses the concept of radiation-induced conductivity (RIC) generated by the injected electrons. The second one, microscopic, directly describes the carrier generation and recombination in the insulator.

Plopeanu et al. [7] describe the influence of several factors on the surface potential decay characteristics of the electret filter media. The results show that the surface charge decay is a function of the relative humidity, the temperature and the electric potential of the electrode grid.

A survey of thermal techniques to estimate the charge distribution in the thickness direction

of the polymer electrets is presented by Singh [8]. The author includes a comprehensive review of thermal data, as well.

All of the aforementioned papers are mostly concerned with the experimental evaluation of the charge decay in electrets. We believe, however, that due to the charge storing properties and wide applications of electrets, a theoretical analysis of this process is of great importance. The goal of this paper is to introduce a formal framework to describe electric field sources in a specific type of dielectric.

2. Sources of the electric field in electrets

Electret is a dielectric that generates an external electric field in its surroundings. Theoretically, the field should remain constant over time. In real electrets it decays with time. A source of the field in electrets is an accumulated electric charge or a permanent polarization “frozen” in the dielectric [2]. Both effects can be expressed in a formal way by appropriate distributions of electric charge. The intrinsic charges, shifted during polarization of the dielectric, are called bound charges and their volume and surface density are denoted as q'_v and q'_s , respectively. Besides, there are also so called excessive charges of the densities q_v and q_s , introduced into the dielectric from outside. Finally, free charges in the dielectric may also be a source of field provided that their total density at a given point is different from zero. The charges of the two last groups are commonly called free charges. The total charge of an electret is a sum of free and bound charges with the densities:

$$q_{ve} = q_v + q'_v \quad (1)$$

$$q_{se} = q_s + q'_s \quad (2)$$

A real electric field around an electret can be assessed by taking into account both spatial – $q_{ve}(x,y,z)$ and surface – $q_{se}(x,y,z)$ charge distributions. It means that one can assign two corresponding charge distributions to every electret: spatial

and surface. However, some uncertainties may occur due to mutual proportion of the spatial and surface charge. If only the value of external electric field $E(x,y,z)$ is known without any detailed data concerning surface and bulk of the electret, then the problem is indeterminate. There is an infinite number of surface $q_{sc}(x,y,z)$ and spatial $q_{ve}(x,y,z)$ charge distributions that give the same distribution of electric field $E(x,y,z)$. In case of the most common electrets in a form of flat parallel plates, each of them, after neglecting the boundary effects, can be described by equivalent surface charges with densities q_{sa} and q_{sb} on both sides a and b of the sample [2, 9]. The densities may be determined from a measurement but it is impossible to assess if they have the character of equivalent values or correspond to actual, physically existing charges. It is the indeterminacy of the first kind. It can be presumed that there is also the indeterminacy of the second kind. Even assuming that the surface charges q_{sa} and q_{sb} obtained from the measurement are physically feasible, i.e. $q_{ve} = 0$, it cannot be resolved whether q_s has a character of free charge or is a formal expression of frozen polarization state $P(x,y,z)$ in the dielectric.

It can be assumed that three physical sources of electric field decide about electret parameters in real conditions:

- free volume charges with the distribution $q_v(x,y,z)$;
- free surface charges with the distribution $q_s(x,y,z)$;
- frozen polarization state in the dielectric, described by $P(x,y,z)$ or equivalent charges with densities q'_v and q'_s .

The idea of introducing these three kinds of sources stems from the fact that they are caused by various mechanisms and their lifetimes may significantly differ [10]. This has a deciding influence on the total lifetime of the electret and technical components made of it. Thus, there is a tendency to distinguish the nature of charge in the electret and to intentionally tailor it in order to obtain assumed parameters, i.e. appropriate electric field and sufficiently long lifetime of electret total charge.

The simplest way of identifying the kind of charge in the electret is to distinguish between homo- and heterocharge. It is possible only when the conditions of electret forming are known and the sign of generated equivalent surface charge can be compared to the sign of the charge on the electrode during the forming process. The reasoning can be extended to the intrinsic charge whose sign can be compared with the direction of electric field during the forming process.

The heterocharge has a polarization origin, whereas the homocharge is connected with the process of injection of excess carriers. In real electrets, both types of carriers exist simultaneously and one of them may determine the character of the whole sample, both in terms of the absolute value and the total lifetime τ . The quality of a component made from modern polymer electrets is mainly determined by the homocharge and its stability in time. The meaning of electret lifetime can be then understood as the relaxation time of homocharge at room temperature.

3. General case of electret

Considering a general case of electret, in which co-existence of the following phenomena is assumed:

- relaxation decay of frozen polarization, according to the equation:

$$P(t) = P_0 e^{\left[\frac{-t}{\tau_p}\right]} \quad (3)$$

- Maxwellian relaxation dependent on volume conductivity of a dielectric σ_v , as stated by the relationship:

$$\tau_M = \epsilon_0 \epsilon \sigma_v^{-1} \quad (4)$$

It is possible to obtain a total density of charge on an electret surface [11]:

$$q_{se}(t) = q_{sp}(0) \frac{\beta}{\beta - 1} e^{\frac{-t}{\tau_p}} - \left[q_{sp}(0) \frac{\beta}{\beta - 1} - q_{se}(0) \right] e^{\frac{-t}{\tau_M}} \quad (5)$$

where $q_{se}(t)$ is a total charge density on electret surface, $q_{sp}(0)$ is an initial value of heterocharge, τ_p is relaxation time of heterocharge, $\beta = \frac{\tau_M}{\tau_p}$.

The changes of electret surface charge in time observed during experiments can be presented as a superposition of the change in heterocharge q_{sp} with relaxation time dependent on polarization processes, and homocharge with relaxation time τ_M , dependent on dielectric conductivity [12].

A significant amount of information can be obtained from equation 5.

Let the Maxwellian relaxation time τ_M of free charge be much larger than the time of relaxation polarization τ_p . Then, $\beta = \frac{\tau_M}{\tau_p} \gg 1$.

Such a case occurs in dielectrics in which sufficiently long-lasting relaxation polarization cannot be created and whose electric conductivity is very low (e.g. polystyrene, PTFE). Then, from equation 5, it follows:

$$q_{se}(t) = q_{sp}(0)e^{-\frac{t}{\tau_p}} - q_{sM}(0)e^{-\frac{t}{\tau_M}} \quad (6)$$

After the time $t > \tau_p$, the first component of equation 6 disappears, and the total charge of the electret varies according to the relationship:

$$q_{se}(t) = -q_{sM}(0)e^{-\frac{t}{\tau_M}} \quad (7)$$

The lifetime of the electret is determined by the electric conductivity of a material the electret is made of. However, the considered case of Maxwellian relaxation $\beta = \frac{\tau_M}{\tau_p} \gg 1$ is a bit simplified from a physical point of view.

During electret polarization, slow relaxation polarization is created inside, and excess charge is injected. After electret forming, the slow relaxation polarization decays but the excess charge does not change much, since $\tau_M \gg \tau_p$. The lifetime of free charge is then determined only by material conductivity and shortcircuit conditions.

The second case corresponds to the situation when the relaxation time τ_p is much larger than τ_M , corresponding to the free charge. This condition is fulfilled when the electret has significantly higher electric conductivity but the slow relaxation

polarization is maintained for a long time. Then, $\beta = \frac{\tau_M}{\tau_p} \ll 1$ and from equation 5, the following relationship is obtained:

$$q_{se}(t) = -\beta q_{sp}(0)e^{-\frac{t}{\tau_p}} + [\beta q_{sp}(0) + q_{se}(0)]e^{-\frac{t}{\tau_M}} \quad (8)$$

Since $\tau_M \ll \tau_p$, then after some time, electret charge will be changing according to the equation:

$$q_{se}(t) = -\beta q_{sp}(0)e^{-\frac{t}{\tau_p}} \quad (9)$$

and its lifetime will be equal to τ_p , i.e. equal to the duration of slow relaxation polarization. The case of $\beta = \frac{\tau_M}{\tau_p} \ll 1$ is characteristic of specific electret effect. The observed permanent charge corresponds in this case to dynamic equilibrium between bound and free charges. According to phenomenological theory, the lifetime of the electret is determined either by the time of relaxation polarization or by the time of Maxwellian relaxation. Therefore, electrets can be made only from dielectrics in which relaxation polarization is maintained for a long time or whose electric conductivity is very low.

4. Lifetime

The durability of electret charge plays an essential role in the assessment of usefulness of the material for practical applications [2]. It is defined by so called lifetime τ . The lifetime τ is a physical quantity that can be determined only when the charge decay occurs according to a simple analytical relationship. A mathematical model for assessment of the total lifetime of an electret is based on a commonly known Arrhenius equation:

$$q_s(t, T) = q_s(0, T)e^{-\left[\frac{t}{\tau(T)}\right]} \quad (10)$$

where $q_s(t, T)$ denotes surface charge dependent on time t and temperature T . The real decay of electret charge can be only roughly described by the above relationship. However, the equation is considered as a definition of electret lifetime τ . The studies on charge durability and departure of the simple exponential decay enable interpretation of basic physical processes responsible for accelerated aging of electrets. Of course,

in practical applications, electrets with long lifetime are of interest. In such a case, estimation of lifetime in normal atmospheric conditions by directly measuring the changes in surface charge density is practically impossible within a reasonable timeframe. Raising the temperature can accelerate the depolarization process. Using thermostimulated depolarization seems to be particularly promising for determining electret lifetime [1, 2, 12]. Thermally stimulated depolarization enhances the ability to move the spatial charge and dipoles “frozen” in electret, which allows a significant shortening of the experiment time.

5. Conclusions

The presented considerations can be used to analyze the phenomena occurring in electrets but they do not allow quantitative assessment of the processes taking place in real structures. In real electrets, lifetime is much longer than it follows from Maxwellian relaxation determined by dielectric conductivity. It seems that interpretation of this phenomenon is connected with the following mechanisms:

- existence of frozen slow relaxation polarization in the dielectric, regardless whether the explanation of this phenomenon is known;
- creation of spatial charge distributions in the dielectric, both from intrinsic electric charge and excess charge injected from outside;
- existence of neutralizing effect of dielectric conductivity, leading to compensation of electric field in the electret.

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