

# SPACE CHARGE DISTRIBUTION IN PHOTOVOLTAIC CELL INSULATION

Vladimír Ďurman — Milan Perný — Vladimír Šály — Marek Pípa \*

Near-electrode processes were studied in the thermoplastic polyurethane (TPU) insulation intended for encapsulation of photovoltaic cells. The analysis came out from the dielectric measurements in the region of very low frequency. The measurements showed that the observed phenomena is related to the electrode polarization. This type of polarization always influences the space charge distribution in material and also enhances the electric field near the electrodes. For practice, it is important to decide if the electric field enhancement is dangerous for proper operation of photovoltaic cell. Using the parameters obtained from dielectric measurements, the electric field distribution was calculated in the TPU foil. It was found that electric field increased more than 10-times in comparison with the initial value.

**Key words:** polarization mechanism, electric field distribution, solar cell encapsulation, electrical conduction

## 1 INTRODUCTION

The majority of countries realise the need of a more consequent focus on renewable energy sources that represent an environmentally acceptable solution compliant with idea of permanent and sustainable development. Solar energy, one of the non-conventional sources of energy, is the subject of great interest [1].

In insulation practice, polarization processes with long relaxation times appear mainly in polymer dielectrics and in layered dielectric structures. By investigating the system properties, we mostly treat the phenomena originating at the layer interfaces. The basic interface in any system is the electrode-dielectric interface. It is connected with the electrode polarization. Monitoring of this process is useful at the ageing tests of materials. On the other hand, the process deforms the electric field inside the insulating materials. A significant increase of electric field appears near the electrodes, which must be considered in operating voltage dimensioning [2].

## 2 ELECTRODE POLARIZATION

The dielectric properties of materials are commonly characterized by semi empirical functions of the complex permittivity  $\varepsilon^*$ . In the range of very low frequencies a complex modulus  $m^* = 1/\varepsilon^*$  is preferably used. As for the complex permittivity, recently the universal dielectric response of Jonscher is preferred [3] but in the papers on dielectrics the Havriliak-Negami function is used in many cases. For a simple model of polymer dielectrics it is sufficient to use the famous Cole-Cole formula. The mentioned function can be written as follows

$$C_0\varepsilon^*(\omega) = C_0 \left( \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + (i\omega\tau_0)^{1-\alpha}} - i \frac{\sigma_0}{\varepsilon_0\omega} \right). \quad (1)$$

Here  $\omega$  is the angular frequency,  $\varepsilon_\infty$  is the optical permittivity of the dielectric,  $C_0$  is the geometric or vacuum capacitance,  $\Delta\varepsilon$  is the permittivity increment,  $\tau_0$  is the relaxation time,  $\alpha$  is the shape parameter,  $\varepsilon_0$  is the vacuum permittivity and  $\sigma_0$  is conductivity. In practice the complex permittivity is divided into its real ( $\varepsilon'$ ) and imaginary ( $\varepsilon''$ ) parts.

A two-layer dielectric is mainly created at the electrode surface in the system with blocking and non-injecting electrodes. The free cations in the dielectric are accumulated near the negative electrode, creating a positive charge. A similar process runs near the positive electrode. The steady state of accumulation is given by the balance of concentration gradient and the Coulombic (electric) force. The cations in the dielectrics and the negative charge at the electrode create the so-called double layer. The layer is characterized by the Debye length

$$L_D = \frac{1}{q} \left( \frac{\varepsilon_0 \varepsilon_R k T}{n_0} \right)^{\frac{1}{2}}, \quad (2)$$

where  $q$  is the ionic charge,  $\varepsilon_R$  is the relative permittivity of material in absence of free charges,  $n_0$  is the free ion concentration,  $k$  is Boltzmanns constant and  $T$  is temperature. In the case of non-polar material the value of  $\varepsilon_R$  equals to  $\varepsilon_\infty$ .

In some previous works [4] it was found that the electrode polarization could be represented by a simple Debye model, *ie*, the model according to (1) with zero value of parameter  $\alpha$ . By using label  $L$  for the electrode distance and  $\sigma_0$  for the material conductivity we can write for the permittivity increment  $\Delta\varepsilon$  of electrode polarization

$$\Delta\varepsilon = \left( \frac{L}{2L_D} - 1 \right) \varepsilon_R. \quad (3)$$

For relaxation time  $\tau_0$  the next equation is valid

$$\tau_0 = \frac{L}{2L_D} \frac{\varepsilon_0 \varepsilon_R}{\sigma_0}. \quad (4)$$

\* Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Ilkovičova 3, 812 19 Bratislava, Slovakia, vladimir.durman@stuba.sk

### 3 ELECTRIC FIELD AND CONDUCTION

The charge carrier movement in an insulating material is described by the well-known system of differential equations [5]. The equations in a one-dimensional model have the shape

$$j_+ = q\mu_+pE - qD_+\frac{\partial p}{\partial x}, \quad (5)$$

$$j_- = q\mu_-nE + qD_-\frac{\partial n}{\partial x}, \quad (6)$$

$$\frac{\partial E}{\partial x} = \frac{q}{\varepsilon}(p - n), \quad (7)$$

$$j = \varepsilon \frac{\partial E}{\partial t} + j_+ + j_-, \quad (8)$$

where  $j$  is current density,  $q$  is charge,  $\mu$  is mobility,  $D$  is diffusion coefficient,  $E$  is electric field,  $\varepsilon$  is permittivity,  $p$  is concentration of positive charge carriers,  $n$  is concentration of negative charge carriers,  $x$  is space coordinate and  $t$  is time. The index  $\pm$  belongs to the parameters of the positive (negative) charge carriers. Solution of the above system of equations is complicated due to a large number of variables and unknown material parameters. Some simplifications are often used to reach the solution in an easier way. In the case of electric field treatment in TPU foil we adopted the solution according to [6]. Here we are dealing with a solution in the steady state with no time-depending variables. This is in accordance with the DC operation of TPU foils. The proposed model is symmetrical (both the positive and negative charge carriers have the same physical parameters). The author in [6] rewrote the above equations into the form where the only space variable was conductivity  $\sigma$ . He obtained the final formula as

$$\sigma = \sigma_0 + \sigma_1 \cosh\left(\frac{x - L/2}{l}\right), \quad (9)$$

where  $\sigma_0$  is the physical conductivity,  $L$  is the distance of electrodes and  $l$  is an empirical constant which must be determined experimentally. For parameter  $\sigma_1$  the next equation is valid

$$\sigma_1 = \frac{\sigma_b - \sigma_0}{\cosh\left(\frac{L}{2l}\right)}, \quad (10)$$

where  $\sigma_b$  is the boundary conductivity which depends on the electrode properties. When treating the interface phenomena we find mostly the blocking or partially blocking electrode. The basic relation between the current density and the electric field is

$$E = \frac{j}{\sigma}, \quad (11)$$

and after integration from 0 to  $L$  we get

$$j = \frac{U \sqrt{\sigma_0^2 - \sigma_1^2}}{4l \operatorname{artanh}\left(\sqrt{\frac{\sigma_0 - \sigma_1}{\sigma_0 + \sigma_1}} \tanh \frac{L}{4l}\right)}, \quad (12)$$

where  $U$  is the voltage on the electrodes. By combining equations (7), (9) and (11) we find the space charge density

$$\rho = -\frac{\varepsilon \sigma_1 j}{l \sigma^2} \sinh\left(\frac{x - L/2}{l}\right). \quad (13)$$

Equations (9–13) are suitable for calculating the electric field and current density under condition that some additional parameters are known from experiment. Details of the calculation procedure will be given in the following chapters.

### 4 EXPERIMENT

The aim of experiment was investigation of a special material used for encapsulation and insulation of solar cell structures, namely of thermoplastic polyurethane (TPU). It is a polar, three-component system formatted by the soft segments (polyesters, polyethers, and their combination). The thickness of the foil specimen was 0.47 mm. During the measurements, the temperature was stabilized by the thermostat TETTEX, type 2965. We used the standard three-electrode system with the electrode diameter of 5 cm. Two types of measurements were performed:

- Complex capacitance measurements in the range from 0.001 Hz to 1 kHz. Here we used a complex capacitance meter constructed at our laboratory particularly for the range of very low frequencies. The voltage on the specimens during measurements was 5 V.
- Absorption current measurement at 50 V using electrometer Keithley 4517A. At the complex capacitance measurements we found two polarization processes: the process with a shorter relaxation time, which was already known, and the electrode process with high permittivity increment. The processes were separated and their parameters were found by using an optimization procedure [7].

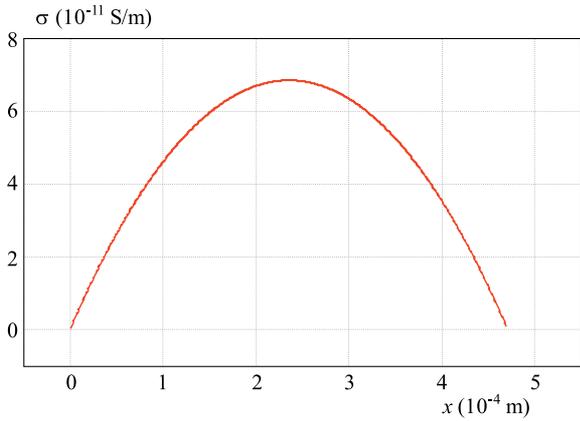
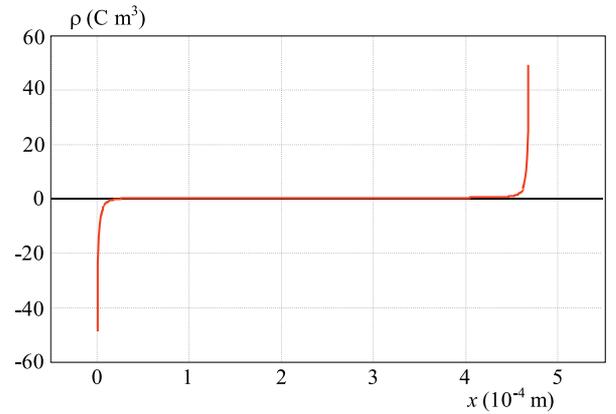
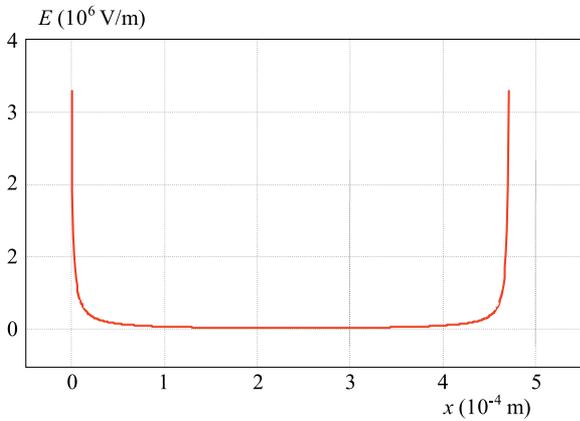
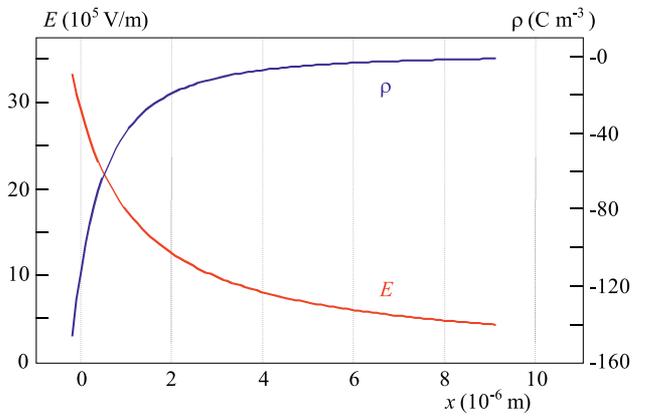
The calculated parameters are listed in Tab. 1. The parameters lettering matches the lettering in (1). In this table index EP means the electrode process and index RP means the relaxation process with the shorter relaxation time. At the absorption current measurement we found a value of  $2.3 \times 10^{-9}$  A in the steady state after 1500 s. The electric field mean value was  $1.06 \times 10^5$  Vm $^{-1}$ .

### 5 ELECTRIC FIELD CALCULATIONS

The procedure for electric field calculation is based on the solution expressed by equations (11–13). We come out from (12). From experiment we know the values of distance  $L$ , current density  $j$ , voltage  $U$  and conductivity  $\sigma_0$ . In addition, we can calculate the Debye length from (3) or (4). To find the complete solution, we must

**Table 1.** Summary of the calculated parameters

$T$ (°C)	$\varepsilon_\infty$ (—)	$\Delta\varepsilon_{RP}$ (—)	$\tau_{RP}$ (s)	$\alpha_{RP}$ (—)	$\Delta\varepsilon_{EP}$ (—)	$\tau_{EP}$ (s)	$\sigma_0$ (nS/m)
35	6.5	32	0.164	0.11	534	7.4	1.7
42	6.4	31	0.086	0.09	512	5.2	3.2
50	6.3	31	0.053	0.09	810	4.4	5.1
56	6.3	31	0.035	0.08	849	3.7	7.5
62	6.2	32	0.028	0.10	1180	3.1	10.2
68	6.1	35	0.023	0.12	1828	2.7	13.5
75	6.0	33	0.015	0.11	1905	2.3	19.3

**Fig. 1.** Conductivity in TPU foil**Fig. 2.** Space charge density in TPU foil**Fig. 3.** Electric field in TPU foil**Fig. 4.** Electric field and space charge density near the anode

calculate the two unknown constants: the boundary conductivity  $\sigma_b$ , and the empirical constant  $l$ . This was done in the following way. First, a set of pairs  $(\sigma_b, l)$  was found which fulfil (12). Here the interval for  $\sigma_b$  was chosen so as to cover the values of a few orders smaller than the value  $\sigma_0$  (partially blocking electrodes). Second, for each pair from the above set the curve of  $\rho$  inside the electrode spacing was calculated using (13). The Debye length can be calculated as the inverse of the concentration gradient in log-lin co-ordinates. In our case the required gradient was calculated from the previously mentioned space charge  $\rho$ . Then, for the final solution we simply choose that pair

$(\sigma_b, l)$  for which the Debye length equals to the one obtained from the complex capacitance measurements. The optimized values of the constants in our experiment were:  $l = 6.05 \times 10^{-4}$  m,  $\sigma_b = 7.52 \times 10^{13}$  S m<sup>-1</sup>. The corresponding curves of  $\sigma$ ,  $\rho$  and  $E$  are in Figs. 1 to 3. In these figures the anode electrode is placed at  $x = 0$  and the cathode at  $x = 4.7 \times 10^{-4}$  m. The detail distribution near the anode is in Fig. 4. Calculations proved that the highest deformation of the electric field appeared in the vicinity of electrodes. The maximum value of the electric field is determined by the boundary conductivity  $\sigma_b$ .

## 6 CONCLUSIONS

The electrode processes in plastic materials invoke the accumulation of space charge which influences the electric field inside the system. Therefore we must check these phenomena for proper dimensioning of any insulation system. In our paper it was demonstrated how to use the existing knowledge on the space charge distribution for the electric field estimation. It is important to combine the space charge theory with the results of dielectric measurements in the very low frequency range. In this particular case we found that the electric field at the electrode can reach a value 30 times higher than in the bulk of the material. The space charge region has the thickness of a few  $\mu\text{m}$ . The insulating material is stressed only locally, so deterioration due to enhanced stress will appear during long-time operation. More precise information on the ageing process can be obtained by accelerated aging tests performed at higher electric fields.

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**Vladimír Ďurman** born in Nové Mesto nad Váhom, Slovakia, in 1946, graduated from the Faculty of Electrical Engineering, Slovak Technical University, Bratislava, in electrotechnology in 1968, and received the CSc (PhD) degree in electrotechnology from the same university in 1979. At present he is a research worker at the Institute of Power and Applied Electrical Engineering, Slovak Technical University in Bratislava. He is engaged in the research of dielectrics and dielectric properties of materials.

**Milan Perný** was born in Slovakia in 1985. He graduated from the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava in 2009 in materials science. He works in materials science, photovoltaics and renewable energy sources. At present he works at the Institute of Power and Applied Electrical Engineering, Slovak Technical University in Bratislava. Main interests of his research include DC and AC diagnostic methods in the field of homojunction and heterojunction solar cells.

**Vladimír Šály** was born in Slovakia in 1956. He graduated from the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava in electrotechnology and in 1985 he received the scientific degree PhD. from the same university. Since 2003 he has been employed as Associated Professor at SUT FEI. He works in materials science, especially in dielectric and semiconductor structures and photovoltaic renewable energy sources.

**Marek Pípa** (Ing, PhD) was born in 1978 in Nové Zámky. He studied Power engineering at Faculty of electrical engineering and information technology of Slovak university of technology in Bratislava. After obtaining master degree with honor in 2004 he started PhD studies in the field of Power engineering at the same faculty. Since 2008, when finished doctoral studies and now is an assistant professor at the Institute of electrical power engineering of his alma mater. He is expert for renewable power sources and deputy head of the high-voltage testing laboratory working on high-voltage technique and renewable energy sources.