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Development of a new approach to simulate a particle track under electrochemical etching in polymeric detectors

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ABSTRACT

A numerical approach based on image processing was developed to simulate a particle track in a typical polymeric detector, e.g., polycarbonate, under electrochemical etching. The physical parameters such as applied voltage, detector thickness, track length, the radii of curvature at the tip of track, and the incidence angle of the particle were considered, and then the boundary condition of the problem was defined. A numerical method was developed to solve Laplace equation, and then the distribution of the applied voltage was obtained through the polymer volume. Subsequently, the electric field strengths in the detector elements were computed. In each step of the computation, an image processing technique was applied to convert the computed values to grayscale images. The results showed that a numerical solution to Laplace equation is dedicatedly an attractive approach to provide us the accurate values of electric field strength through the polymeric detector volume as well as the track area. According to the results, for a particular condition of the detector thickness equal to 445 μm, track length of 21 μm, the radii of 2.5 μm at track tip, the incidence angle of 90°, and the applied voltage of 2080 V, after computing Laplace equation for an extremely high population of 4000 × 4000 elements of detector, the average field strength at the tip of track was computed equal to 0.31 MV cm^{-1} which is in the range of dielectric strength for polymers. The results by our computation confirm Smythe's model for estimating the ECE-tracks.

1. Introduction

The process of chemical etching (Young, 1958) and alternatively electrochemical etching (Tommasino, 1970) are frequently used to enlarge latent tracks in solid state nuclear track detectors (SSNTDs), i.e. the typical polymers such as polycarbonate, CR-39, etc. (AL-Najjar et al., 1979; Durrani, 2001). During the etching of a polymeric detector, the surface of detector is smoothly removed by a conventional chemical agent. However, the etching rate along the particle trajectory is higher than that in the track-free areas. This phenomenon causes some conical forms inside the detector which are called tracks.

The process mentioned above is totally changed if an electric voltage difference is applied between two surfaces of detector (Durrani et al., 1987). The process of electrochemical etching (ECE) is a well established approach used widely in routine neutron and Rn dosimetries, and other fields of research on charge particle detection; however, compare to the standard chemical etching (CE), ECE has occasionally the disadvantage of destroying any information content in the latent track concerning the particle's LET. Thus, because of the insufficient information on the mechanisms governing ECE, the method is apparently not very well suited for research work. Due to the wide applications of ECE-tracks, it is important to study the theory and underlying mechanisms governing the formation of ECE-tracks in SSNTDs.

The process of electrochemical etching is based on the phenomenon of electric treeing in insulators (Karamdoust et al., 1988). During this phenomenon, the electric field strength at the end of particle trajectory exceeds the critical value of the dielectric breakdown of a typical polymer. To calculate the electric field strength from the equation $E = -\nabla V$, Laplace equation should be solved to obtain the voltage difference under the specific boundary condition. (Banoushi et al., 2007; Sun et al., 2008). As we have stated in two recent studies (Banoushi et al., 2007; Sun et al., 2008), an analytical approach for solving Laplace equation at the end of

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particle's trajectory is almost impossible due to the complexity of boundary condition. Therefore, some researchers have attempted to propose simplified models of the problem. In 1970, Tommasino (1970) used a simplified equation based on Mason's model in dielectrics (Mason, 1951) to explain the phenomenon of particle tracks formation in SSNTDs. Other researchers (AL-Najjar et al., 1979; Sohrabi et al., 1981) also used this equation in their studies. Subsequently, in 1988, Pitt et al. (1988) suggested another simplified equation based on Smythe's model (Smythe, 1939) as a better descriptive equation to explain the problem. Although, the problem can be partly solved by using the mentioned simplified models, however, these models are not accurately able to explain numerous unknown mechanisms of ECE in nuclear tracks for a general condition. For instance, Smythe's equation is sufficiently accurate only for the cases in which the tracks are formed near the detector surface. In contrary, Mason's equation can be relatively accurate only if the range of particle in detector is comparable with the thickness of detector (deep tracks) (Durrani et al., 1987; Karamdoust et al., 1988).

In our recent experimental work (Banoushi et al., 2007), we suggested that solving Laplace equation numerically is a certain approach to obtain the accurate electric field strength at the tip of an ECE-track in a general condition. For this purpose, in our previous research work (Sun et al., 2008), we have developed a new numerical computation algorithm to calculate the electric field strength at the tip of an ECE-track.

In this work, we attempt to develop an algorithm based on image processing techniques to visualize the electrical condition of typical SSNTDs containing latent tracks under electrochemical etching. By numerical solution of Laplace equation, it will be shown how the applied voltage in ECE is distributed through the detector volume. On the other hand, the approach based on applying image processing techniques to convert the computed voltage and field strength values to the grayscale images will provide informative visual features of this exciting phenomenon.

2. Theoretical model

2.1. Algorithm

The main steps of the simulation have been simply shown in Fig. 1. For running the computation, a computer with an adequate CPU and the RAM greater than 1 GB is required. The program written in Matlab for this study includes six sub-programs. Variables in the program are the applied voltage in ECE ($V_{\max}$), and the geometrical parameters of a single track in a typical SSNTD (e.g. polycarbonate) such as the detector thickness (D); track angle (θ, the incidence angle of charged particle to the detector surface), track length (L); the curvature radius at the tip of track (R); and the number of detector elements used for computation ($M \times N$). For the purpose of comparing the computation results with those from the previous experimental works, the parameters of a real track were chosen as $D = 445$ μm, $V = 2080$ V, $L = 21$ μm, $R = 2.5$ μm and $\theta = 90°$ (Karamdoust et al., 1988). For a region containing 4000×4000 elements of the detector volume including the ECE-track, if the detector thickness is $D = 445$ μm, the width of each pixel is calculated equal to 111.25 nm. It is worth to explain that since the parameter of radii at the tip of track (R) is normally restricted only to the range of microns, choosing the sufficient amount of pixels around the tip of track is greatly important to elevate the accuracy of compotation around the tip of track.

2.2. Geometry of detector elements

The aim in the first step of the simulation is to generate the geometry of track in two dimensions. As shown in Fig. 1, the input data of this program, as given in Section 2.1, are the real values of an ECE-track, and the output of program (in this step) is the matrix of generated elements of the detector including the two dimensional track. The mentioned matrix contains the initial voltage values at the detector elements of the track region. To generate the geometry of track, we attempt to define a particular boundary condition as shown in Fig. 2 (Sun et al., 2008). This figure shows the main geometry of an ECE-track along the particle trajectory (OC) with the angle θ. As the first step, an $M \times N$ area including the track under evaluation is assumed. In this step, the program should be able to identify whether an assumed element (j, i) belongs to the track region. For this purpose, two regions ABM_1M_2 and the circle (C, R) are considered as shown in Fig. 2.

Using Fig. 2 to specify track boundaries, the calculations are done as follow:

$$\text{The centre of track's aperture } (O) = \begin{pmatrix} x_o = \dfrac{x_1 + x_2}{2} \\ y_o = \dfrac{y_1 + y_2}{2} \end{pmatrix} \tag{1}$$

$$\text{The centre of track's tip circle} = \begin{pmatrix} x_c = x_o + H\cos\theta \\ y_c = y_o + H\sin\theta \end{pmatrix} \tag{2}$$

where $H = L - R$.

Considering two dimensional profile of the assumed track in Fig. 2, track walls ($\overline{AM_1}$ and $\overline{BM_2}$) are identified as:

$$\begin{pmatrix} L_{m1} = \sqrt{L_1^2 + R^2} \\ L_{m2} = \sqrt{L_2^2 + R^2} \end{pmatrix} \tag{3}$$

Moreover:

$$\begin{pmatrix} L_1 = \sqrt{(x_c - x_1)^2 + (y_c - y_1)^2} \\ L_2 = \sqrt{(x_c - x_2)^2 + (y_c - y_2)^2} \end{pmatrix} \tag{4}$$

According to Fig. 2, two points M_1 *and* M_2 are two tangent points of track walls ($\overline{AM_1}$ and $\overline{BM_2}$) on the circle located at track tip; thus the coordinates of the points can be calculated as:

$$M_1 : \begin{pmatrix} x_{m1} = x_1 + L_{m1}\cos(\alpha_1 + \beta_1) \\ y_{m1} = y_1 + L_{m1}\sin(\alpha_1 + \beta_1) \end{pmatrix} \tag{5}$$

$$M_2 : \begin{pmatrix} x_{m_2} = x_2 + L_{m_2}\cos\gamma \\ y_{m_2} = y_2 + L_{m_2}\sin\gamma \end{pmatrix} \tag{6}$$

where $\gamma = (\pi - \alpha_2 - \beta_2)$. As mentioned before, two regions restricted by the assumed track can be defined as follows.

2.2.1. Region 1

This region is restricted by four lines (track walls) as shown in Fig. 3. The quadrilateral ABM_1M_2 can be specified by four equations given below:

$$\begin{aligned} &\overline{AB} : y = y_1 \\ &\overline{AM_1} : x = \frac{y - y_1}{m_2} + x_1 \\ &\overline{BM_2} : x = \frac{y - y_2}{m_3} + x_2 \\ &\overline{M_1M_2} : y = y_{m_1} + m_4(x - x_{m_1}) \end{aligned} \tag{7}$$

where m_2, m_3, and m_4 are the gradient of the lines, i.e. $-\tan(\alpha_1 + \beta_1)$, $\tan\gamma$, and $\tan\delta$, respectively.