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Verification of Mason and Smythe equations for electrical treeing breakdown at the tip of charged particle tracks in ECE polycarbonate detectors

Ayoub Banoushi[a], Mohammad Reza Kardan[b,*], Mehdi Sohrabi[b,1], Ali Mostofizadeh[c], Xiudong Sun[c]

[a]*Nuclear Science and Technology Research Institute (NSTRI), Reactor and Accelerator Research and Development School, Tehran, Iran*
[b]*Nuclear Science and Technology Research Institute (NSTRI), Radiation Application Research School, Tehran, Iran*
[c]*Department of Physics, Harbin Institute of Technology, Harbin 150001, China*

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Abstract

There are two different equations to describe enhancement of field strength at the track tip in ECE polycarbonate detectors: Mason and Smythe equations. In order to evaluate the equations, PC detectors with different thicknesses were exposed to 1 MeV alpha and/or fast neutron. The response of the detectors was studied as a function of applied voltage and average field strength. The ratio of critical voltages for different detectors was estimated experimentally and compared with calculated values. The experimental results are in good agreement with Smythe's equation. The results show that the track density and mean track diameter in the different detectors have the same behaviour, when the macroscopic field strength increases, and also that the field strength at the tip of tracks is proportional to macroscopic field strength.

Keywords: Polycarbonate; Electrochemical etching; Treeing; Track; Field strength; Mason's equation; Smythe's equation; SSNTD

1. Introduction

The electrochemical etching (ECE) of charged particle tracks in polymeric solid state nuclear track detectors (SSNTDs) is an established and widely used tool for the visualization of latent nuclear tracks. In view of the growing use of ECE in some fields, it is important to understand the underlying mechanisms and the theory governing the production of the ECE tracks in SSNTDs. The process of ECE is based on the phenomenon of treeing observed in dielectric insulators. This phenomenon happens due to a high increase of field strength at the tip of the track.

Tommasino (1970) introduced ECE of fission fragments and used Mason's equation (Mason, 1951) to justify the increase of field strength at the tip of a track. Other researchers (Sohrabi, 1981; AL-Najjar et al., 1979) used this equation in their studies. Pitt et al. (1988) suggested Smythe's equation (Smythe, 1939) as a better descriptive equation to govern the behaviour of ECE tracks. Also, Karamdoust and Durrani (1988) tried to verify these equations in CR-39 experimentally.

In this work, some experiments were arranged to verify Mason and Smythe equations for electrical treeing breakdown at the tip of charged particle tracks in ECE polycarbonate (PC) detectors.

2. Theory

When a polymeric detector, like PC, is etched in a chemical reagent, the effect of chemical etchant is more preferentially on latent tracks than other parts, so that a conical volume of latent track full of etchant will be formed. If an alternative voltage is then applied across the detector, the electric field is enhanced at the tip of the track, which can be at proper applied conditions enough to exceed the dielectric strength of the material to trigger sparks causing the treeing phenomenon, which originated at the sharpest point of the track tip.

To evaluate the field strength at the tip of this conical geometry, the following (Laplace) equation should be solved at the

* Corresponding author. Tel.: +98 21 88634023; fax: +98 21 88009502.
E-mail address: mkardan@aeoi.org.ir (M. Reza Kardan).
[1] Present address. International Atomic Energy Agency, Vienna, Austria.

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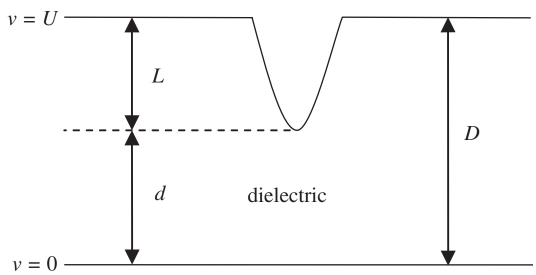

Fig. 1. The track geometry and boundary conditions.

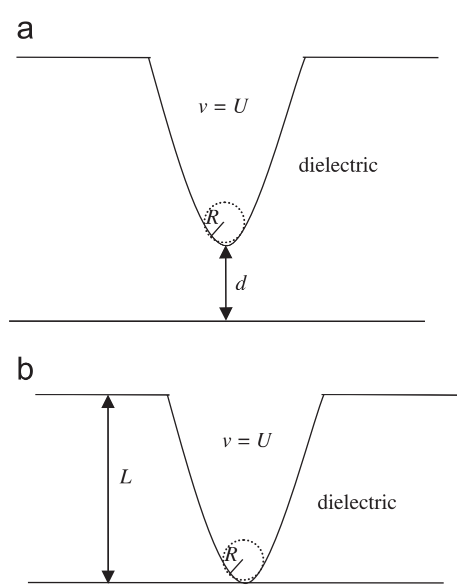

Fig. 2. Track geometry used in (a) Mason's equation, (b) Smythe's equation.

track tip region:

$$\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}+\frac{\partial^2 U}{\partial z^2}=0, \tag{1}$$

where U is voltage in the track tip region. The boundary conditions are shown in Fig. 1. The electrical field strength (E) may be obtained by

$$E=-\nabla v. \tag{2}$$

Due to the complexity of boundary condition in this case, Eq. (1) cannot be solved analytically, thus some simplified assumptions have been considered.

Tommasino (1970) used Mason's equation to calculate the field strength at the tip of tracks. Mason had introduced the following equation to find the field strength for a semi-infinite hyperboloid by a conductive plate at the opposite side (Fig. 2a):

$$E_{\text{tip}}=U.\frac{2}{R.\ln[1+4d/R]}, \tag{3}$$

where U is applied voltage; d is distance from the plate to the track tip (residual detector thickness); R is the curvature radius at the track tip.

This equation can accurately find the field strength at the track tip, if the track depth in the polymer, L, is much larger than d.

Some other researchers have preferred Smythe's equation to calculate the field strength. They have assumed that the track model is a spheroidal boss projected from a conductive plate into a dielectric material which is comparable to an ellipsoid, as shown in Fig. 2b. In this model, the field strength can be calculated using the following equation:

$$E_{\text{tip}}=E_0.\frac{2L/R}{\ln(4L/R)-2}, \tag{4}$$

where D is the detector thickness and $E_0=U/D$ is the macroscopic field strength. This equation is sufficiently accurate when $d\gg R$.

Treeing phenomenon will be initiated, if the field strength exceeds a critical value (E_{cr}). Although E_{cr} depends on the type of polymer, it is not related to the thickness. If D_1 and D_2 are the thicknesses of detector Nos. 1 and 2, the following equation can be written:

$$E_{\text{cr}_1}=E_{\text{cr}_2}, \tag{5}$$

where E_{cr_1} and E_{cr_2} are the critical field strengths of detector Nos. 1 and 2 with different thicknesses. If the incident charged particles and all ECE conditions, unless applied voltage, are the same, then the track parameters such as L and R will be similar, so that, using Eqs. (3) and (5)

$$U_{\text{cr}_1}/U_{\text{cr}_2}=\ln(1+4d_1/R)/\ln(1+4d_2/R) \tag{6}$$

while, using Eqs. (4) and (5)

$$U_{\text{cr}_1}/U_{\text{cr}_2}=D_1/D_2. \tag{7}$$

In these equations, U_{cr_1} and U_{cr_2} are the critical voltages for two different thicknesses.

Comparing the calculated values of the rational critical voltages, using Eqs. (6) and (7), with experimental result can be a good method to answer this problem: which Eq. ((6) or (7)) will estimate the ratio of the critical voltages for PC detectors?

3. Experimental method

Lexan PC detectors with 125, 250, 375 and 500 μm thicknesses have been examined. The detectors were cut into pieces of 2.5 cm × 2.5 cm size from the larger sheets which were masked on both sides. The detectors were irradiated, similarly, either by collimated beams of 1 MeV alpha particles or by fast neutron-induced recoils. The alpha source was an 241Am and neutron source was 241Am-Be. The voltage amplitude was variable, while the frequency was constant at 2 kHz, in all experiments. The ECE was carried out for 3 h, using an optimized solution of KOH (15%), C_2H_5OH (40%) and H_2O (45%)-PEW.

4. Results and discussion

As mentioned above, the detectors were exposed to alpha particles. After finishing ECE time, the density and diameter