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Thickness dependence verification of electrochemically-etched polymer track detectors

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ABSTRACT

Electrochemical etching (ECE) is extremely instrumental for amplifying charged particle tracks in polymer detectors, in particular polycarbonate, for radiation protection dosimetry and other applications. The rationale is high efficiency track enlargement to point observed by the unaided eyes. Many physical and chemical parameters control the ECE efficiency among which polymer thickness and applied voltage, i.e. field strength at a certain frequency, highly affect the detection efficiency and track diameter responses. Alpha particles of ~0.3 to ~3.0 MeV energy with fixed fluences of 10^4 tracks cm^{-2} were studied in 250, 500, 750 and 1000 µm thick polycarbonate under 50 Hz - 32 kV cm^{-1} fixed field strength in order to further verify the Mason and Smythe equations. The flat alpha detection efficiency and track diameter versus thickness responses for alpha energies studied under fixed field strengths are in good agreement with Smythe equation, i.e. all thicknesses can be equally applied if field strength is fixed.

1. Introduction

Electrochemical etching (ECE) of charged particle tracks in polymer track detectors (PTDs) in particular polycarbonate track detectors (PCTDs) has been highly instrumental in a number of wide-scale applications such as radiation protection dosimetry, ion detection and environmental radon monitoring. The ECE is a process in which an alternative high voltage at a certain frequency is applied through two stainless steel electrodes across a PTD of a known thickness sandwiched between two semi-chambers to insulate them from each other while filled with a chemical etchant [1–3]. In this process, a number of physical and chemical parameters affect the characteristic responses of the ECE tracks such as detection efficiency and track diameter. These ECE parameters include charged particle type, energy, fluence and angle of incidence; polymer type, thickness, size, number and size of detectors under ECE; stress applied to the detector (s); applied voltage and frequency; etchant composition, concentration and temperature; and ECE duration [1–7].

The ECE mechanism for track amplification is based on applying a field strength across a PTD which induce a strong field strength at the tip of charged particle track in a PTD causing electric treeing at the track tip for which the Mason equation [8] or Smythe equation [9] have been proposed and studied [1–6,10–13]. In fact, when the electric field strength at the tip of a track exceeds the critical value of dielectric breakdown of the polymer, electrical treeing occurs [8]. The electrical treeing is then expanded around the track as a consequence of the ECE or electromechanical erosion of the polymer at local high field strength regions [14]. The electrical trees are then filled with the etchant forming water trees which in turn cause multiple treeing in the polymer bulk depending on the field strength applied to a PTD of a certain thickness.

Among the above stated ECE parameters, thickness and high voltage; i.e. field strength (voltage/thickness in kV cm^{-1}), at a known frequency applied on a PTD under ECE play crucial roles when other parameters are kept constant [3]. Some ECE studies in particular have focused on verification of the Mason equation and or Smythe equation as regards to different types of charged particle tracks [1–3,10–13]. In particular, Pitt et al. [10] have studied 250–1500 µm thick CR-39 detectors by applying 0.6 kHz - 0.6 to 3.1 kV ECE processing in 5 N NaOH solution at 70 °C to verify the Mason and Smythe models. It was concluded that Mason equation is only valid if the length of the track is close to the detector thickness which can be applied only to particular cases. It was also concluded that since the Mason equation does not contain the detector thickness and has the residual detector thickness "d" in the logarithm, it predicts the virtual independence of the E_{tip} from the detector thickness, as discussed below. This fact contradicts the observations of Pitt and coworkers where their results are in agreement with the Smythe model with a detector response as a linear function of the reciprocal of the detector thickness when the applied voltage was kept constant [10].

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The above studies have applied high frequency – high voltage (HF-HV) generators which seem to usually have capacity or power limitations at least in our HV-HF generating systems to apply directly a constant field strength (kV cm^{-1}) on PTDs of different thicknesses and/or sizes. Recently, mega-size PCTDs of different sizes (e.g. 50 cm × 50 cm or 80 cm × 38 cm) and thicknesses (250, 500, 750 and 1000 μm) have been successfully processed by 50 Hz – HV ECE method which have led to breakthroughs in 4π ion emission understanding in plasma focus devices [7,15,16]. In such applications, both PCTD thickness and its size play crucial roles. Therefore, having a high need to ECE processing of PCTDs of different thicknesses and size in particular large sizes for different applications [7,15,16], availability of PCTDs of different thicknesses and sizes, availability of 50 Hz – HV ECE generators, and the need to verify of the effects of PCTD thickness on detection characteristics, extensive studies on PCTD size and thickness for precise radiation dosimetry and other ion detection applications were performed. The study of the detector size is in progress and will be reported soon. However, it is the purpose of this paper to use PCTDs of different thicknesses in order to:

1. study the effects of applying 50 Hz – HV constant field strengths on PCTD characteristic responses,
2. investigate the effects of PCTD thickness on the efficiency and track diameter characteristics of alpha particles of different energies, and last but not least,
3. verify the Mason and Smythe equations [8,9]; as regards to thickness and field strength dependence in PCTDs of different thicknesses.

2. Theory

When a heavy charged particle passes through a dielectric PTD such as a PCTD, it leaves a trail of damage along its trajectory which resembles a needle pointed on the surface of a dielectric polymer. In chemical etching, a track is formed when the etching rate along the track trajectory is higher than that of the polymer bulk etching rate [17]. In the ECE method, when a PCTD is processed in an ECE chamber when an alternative electrical field strength is applied to the PCTD, a strong field strength is induced at the tip of a track followed by multiple treeing surrounding the track until a track is visualized by the unaided eyes [1–3]. Fig. 1 demonstrates tracks of charged particles in a polymer detector and treeing phenomena at the tip and surrounding of the track volume, while D is the detector thickness, L latent track length, R track radius at the tip and d residual detector thickness. Fig. 1 also shows dyed ECE tracks (DYECETs) superimposed on the track schematics. It should be noted that the DYECETs clearly show the track entrance and expanded treeing around a track which actually form the diameter usually observed under a light microscope. The DYCET method is highly instrumental in terms of showing well the structure of the ECE tracks [18].

It is known that when a field strength (kV cm^{-1}) is applied to a PTD and in turn to a charged particle track which is like a sharp needle on a dielectric material surface, the electrical field strength at the track tip is enhanced to a high field strength of MV cm^{-1}. When this enhanced field strength exceeds a critical value, a treeing phenomenon occurs at the track tip, as formulated in Mason equation [8]:

$$E_{tip} = \frac{2U}{R* \ln[1+(4d/R)]} \quad \text{(Mason Equation)} \tag{1}$$

where E_{tip} is field strength (MV cm^{-1}) at the track tip, U applied voltage (kV) across the detector, R track radius at the tip and d residual detector thickness.

Electrical treeing is in fact expanded in a PTD as a consequence of ECE or electromechanical erosion of the polymer at local high field strength regions [14]. The electrical trees formed are filled with etchant forming water trees which in turn cause multiple treeing in the polymer bulk depending on the field strength applied to a PTD of a certain thickness, as shown in Fig. 1.

Some researchers have used the Mason Eq. (1) in their studies [4,10–13]. The Mason equation in fact does not contain the detector thickness, while it has the residual detector thickness "d" in the logarithm which predicts the virtual independence of the E_{tip} from the detector thickness. The equation is sufficiently accurate when L≫ d, i.e., track length "L" is larger than the residual detector thickness "d" [10]. This situation occurs when a particle has been projected deeply into the detector close to its thickness and nearly reach to the opposite side of it [10,11]. In cases such as alpha particle or neutron-induced recoil tracks in particular in thick PTDs, the ranges are usually very small compared to the PTD thickness and the Mason equation conditions may not fit [10–13].

Some researchers have also used Smythe Eq. (2) in their experiments or simulated studies [10–13]. Pitt et al. [10] verified the Smythe Eq. (2) by studying CR-39 detectors of 250–1500 μm thicknesses processed by 0.6 kHz - 0.6 to 3.1 kV ECE in 5 N NaOH solution. The results however contradict the Mason Eq. (1) while are in agreement with the Smythe model with a detector response which is as a linear increasing function of the reciprocal detector thickness when the applied voltage was kept constant [10].

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

where E_{tip} (MV cm^{-1}) is the field strength at the track tip, E_o (U/D) applied field strength (kV cm^{-1}), R track radius at the track tip and L track length.

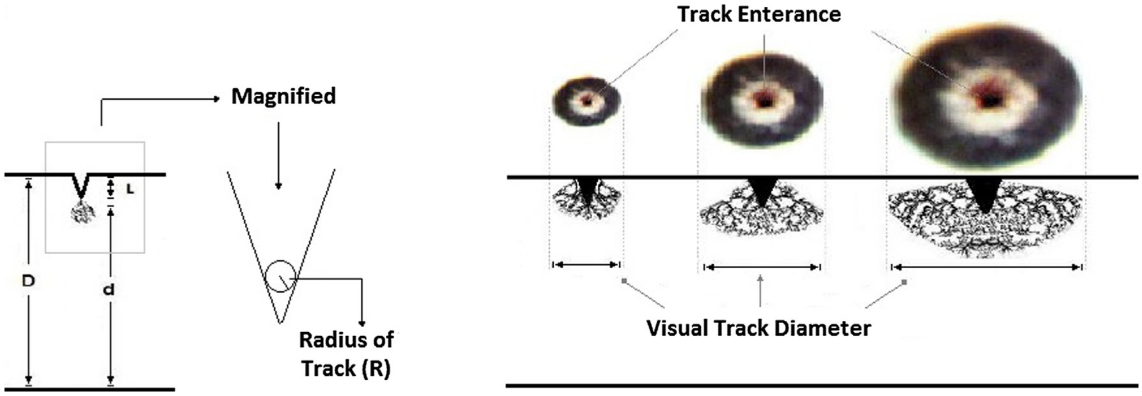

Fig. 1. Track schematic of a charged particle in a PTD with thickness D, latent track length L, track radius at the tip R and residual detector thickness d as well as treeing phenomena at the tip and surrounding the track volume. The DYECETs are superimposed on the track schematics to demonstrate the track entrance and expanded visual track diameter.