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Uniform behavior of insulators irradiated by swift heavy ions

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ABSTRACT

Ion induced R_e track radii are derived from a universal relation $\Theta(r)$ without involving any materials parameter apart from the melting point T_m. The effect is related to the formation of identical ion-induced temperature distributions in track forming insulators for $\langle s_e \rangle = S_e/N$ = constant, where S_e, and N are the electronic stopping power and the atomic density. Based on $\Theta(r)$, an $R_e^2 - \langle s_e \rangle/(T_m - T_{ir})$ plot is applied where the experimental curves coincide for various insulators without adjustable parameters (T_{ir} – temperature of irradiation). The analysis extends to all track-forming insulators studied up until now. The application of the equilibrium value of T_m is justified in thermal spike calculations. The physical meaning of the condition $\langle s_e \rangle = S_e/N$ = constant is discussed. $\Theta(r)$ may be valid in those insulators as well in which tracks are not induced. The Fourier equation is not valid under spike conditions.

1. Introduction

Recently, old ion-induced track data were analyzed again with quite unexpected result [1,2]. It was found that there is a simple relationship between track radii R_e measured in different solids when a simple condition is fulfilled. The explanation of this result led to such conclusions which are irreconcilable with the present ideas about the governing processes.

In the present paper we summarize the most important previous results, extend the analysis of experimental results and discuss some points which have not received sufficient attention previously.

2. Previous results

When a swift heavy ion hits a solid it deposits a large amount of energy in a localized manner, which may induce irreversible changes. One of these possible changes is the formation of amorphous tracks along the trajectory of the projectile. The effect depends on the inelastic energy deposition which is characterized by the electronic stopping power S_e. We found a simple relation between R_e induced in different solids by different ions of different electronic stopping power S_e and different specific ion energy E [1,2]. The only condition is $\langle s_e \rangle = S_e/N$ = constant where N is the number density of atoms. The quantitative relation is valid only for the initial values of R_e which may be changed with time in some solids. A typical result is shown in Fig. 1 [2]. The enveloping curve is given by

$$\Theta(r) = \frac{f\langle s_e \rangle}{3\pi k w^2} \exp\{-r^2/w^2\}, \quad (1)$$

where k is the Boltzmann constant, r is the radial distance from the trajectory, w = 4.5 nm and the efficiency f = 0.4/0.17 at low (E < 2 MeV/nucleon, LO) or high (E > 8 MeV/nucleon, HI) ion velocities which is the consequence of the velocity effect [3].

Track radii can be obtained from the equation $\Theta(R_e) = T_m - T_{ir}$ (T_m and T_{ir} are the melting and irradiation temperatures). $\Theta(r)$ does not contain materials parameters (MPs), does not depend on the experimental parameters, and f has the same values for track forming insulators in the LO and HI ranges leading to different thermal energies $\varepsilon = fS_e$. Thus track radii are given by a universal function and MPs apart T_m have no effect on R_e [1,2]. This result is irreconcilable with the traditional application of the heat flow equation under spike conditions. It was found that the observed relationship between track radii is the consequence of the formation of an identical temperature distribution in irradiated track forming insulators [1].

3. Discussion

Fig. 1 convincingly demonstrates the relationship between track radii showing that T_m alone determines R_e, other MPs are indifferent. This conclusion is valid only for a single value of $\langle s_e \rangle$ which is given in the plot. However, here we show another simple and direct method which is free of this disadvantage. When the universal

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relationship $\Theta(r)$ is valid for an insulator the plot $R_e^2 - \ln(f\langle s_e\rangle/(T_m - T_{ir}))$ is a straight line (T_m-parameter, $f\langle s_e\rangle$-variable, whose slope is w^2. Since $\Theta(r)$ does not contain MPs the lines for various insulators coincide. The plot in Fig. 1 is a special case of this procedure when T_m is a variable and $f\langle s_e\rangle$ = constant.

In this paper, we apply this plot for tracks induced by low velocity ions in TeO_2 [4], by cluster ions in $Y_3Fe_5O_{12}$ [5], and by high velocity projectiles in $NiFe_2O_4$ [6]. There is a good agreement between the theoretical line and the experimental data in Fig. 2. The track data of all track-forming insulators analyzed in Ref. [1,2] also show similar good agreement. The plot confirms the validity of $\Theta(r)$ in a broad range of $\langle s_e\rangle$.

The track data which were used in Fig. 1 were obtained in independent experiments. In this case, one cannot expect that track radii be measured at the same value of $\langle s_e\rangle$. Therefore, when drawing the plot in Fig. 1, the data were evaluated by linear interpolation between neighboring experimental values. This might increase the error of the estimated track radii. In Fig. 2 a new plot is used for the first time which allows the use of the original track data making any interpolation unnecessary. Besides the broad range of the $\langle s_e\rangle$ values this is also a great advantage.

This method can be applied even when systematic studies have not been performed and only a single value of R_e is known. In Fig. 2 we show such data for $ZrSiO_4$ [7], $MgAl_2O_4$ [8], Al_2O_3 [8], $KTiOPO_4$ [9], and Y_2O_3 [10] which were obtained in experiments with LO or HI projectiles. In the case of Al_2O_3 and $MgAl_2O_4$, R_e values have been also measured in a range of S_e but track re-crystallization reduced the initial track sizes. Therefore, we do not use those data. Recently, we analyzed the study of Aruga [11] and derived reliable estimate of S_{et} which is the highest value of S_e without inducing a track [8]. The method does not require the measurement of track sizes only the position of the amorphous–crystalline boundary must be known. Therefore the track re-crystallization has only a minor effect. New measurements by Khalfaoui et al. [12] and Skuratov et al. [13] confirm our estimate for Al_2O_3.

In Fig. 2, the single experimental track data nicely fit to the line derived from the relation $\Theta(r)$ verifying its validity for these solids as well. We emphasize that the good agreement with the relation $\Theta(r)$ was achieved without individual adjustable parameters in a broad range of S_e for a large number of different projectiles having energies in the range 0.02–20 MeV/nucleon and track radii were measured by different methods in different laboratories. Thus the reliability of the conclusions is without doubt.

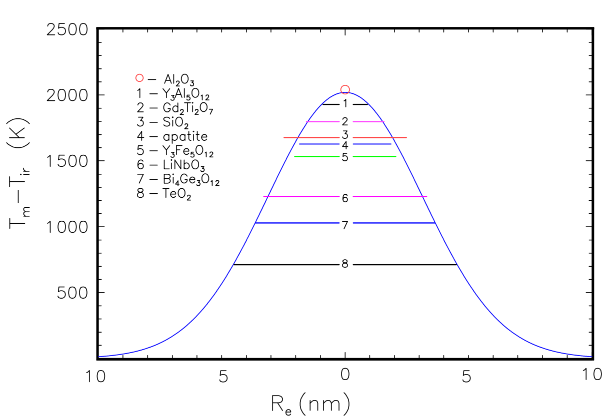

Fig. 1. Variation of the track radii R_e with the melting temperature T_m in various insulators; T_{ir} is the irradiation temperature, k is the Boltzmann constant. The tracks were induced by ion beams with E<2 MeV/nucleon specific energy at $\langle s_e\rangle/3k = 3.42 \times 10^5$ nm^{2}K. The curve $\Theta(r) = T_{pL} \exp\{-r^2/w^2\}$ is a fit with $w = 4.45 \pm 0.18$ nm and $T_{pL} = 2024 \pm 90$ K [2].

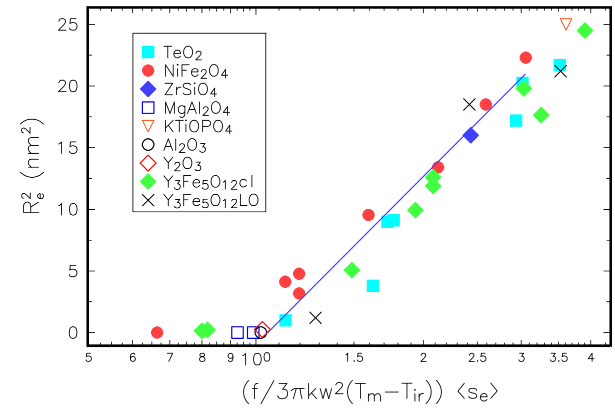

Fig. 2. Variation of the track size with the atomic stopping power $\langle s_e\rangle$; R_e, f, and k are the track radius, the efficiency and the Boltzmann constant, w = 4.5 nm and T_m and T_{ir} are the melting and the irradiation temperatures. $Y_3Fe_5O_{12}$LO and $Y_3Fe_5O_{12}$cl denote irradiation by monoatomic and C cluster ions. The line is drawn according to Eq. (1) with the slope w^2.

Recently we finished reviewing all track data reported up until now. The validity of the $\Theta(r)$ relation for track formation has been verified for 18 insulators including the present results as well [1,2]. In another publication we complete this list with two other solids [14] and there is a number of studies which had to be ignored because they were not suitable for our analysis [14]. After analyzing all experimental track data we conclude that track-forming insulators respond identically to the irradiation by swift heavy ions. Track radii can be derived applying a universal relation $\Theta(r)$ which is free of MPs. The simple relationship between track radii shown in Figs. 1 and 2 is the direct consequence of this feature. Based on this result we assume that such behavior can be found in a large number of irradiated insulators.

The presence of the melting point in the solution of $\Theta(r)$ for R_e demonstrates that thermal processes have an important effect on R_e. We arrived to the same conclusion when analyzed S_{et} in various insulators and a linear dependence on T_m was observed [1]. Actually, S_{et} is proportional to the energy necessary to increase the local temperature from T_{ir} to T_m. Thus it is reasonable to assume that a melt is formed when the local temperature $T > T_m$ and the amorphous track is formed in the fast cooling process of the melt. The ion-induced temperature increase is given by the $\Delta T(r,t)$ function and the time is set to $t = 0$ when it attains its highest value. It is reasonable to assume that R_e is equal to the maximum radius of the melt or the maximum width of the radial temperature distribution $\Delta T(R_e,0)$ at $t = 0$ [1].

Let us denote various MPs as Ω and assume that $\Delta T(r,t,\Omega)$ is valid. It is a reasonable assumption that when $\Delta T = \Delta T(r,t,\Omega)$, the track radius R_e also depends on Ω. When $\Delta T(r,t)$ does not depend on MPs it is evident that R_e depends neither. This must be valid in the opposite direction as well: if MPs have no effect on R_e, then $\Delta T(r,0)$ should not depend on MPs either. When this simple consideration is applied to our case, the result is rather unexpected. When track forming insulators are irradiated by swift heavy ions the induced temperature distributions $\Delta T(r,0)$ are identical when $\langle s_e\rangle$ = constant as they do not contain MPs.

The $\Theta(R_e) = \Delta T(R_e,0) = T_m - T_{ir}$ relation is valid for each track-forming insulator. Therefore, $\Theta(r) = \Delta T(r,0)$ holds for many (melting) temperatures. Thus we claim that the individual $\Delta T(r,0)$ distributions are equal to the universal relation $\Theta(r)$.

Here we refer again to Fig. 2. It is a highly extraordinary situation when the experimental data are compared with a universal function without fitting parameters. In this case, the agreement is a much stronger evidence than usually. Actually, the plot in Fig. 2 verifies that the formation of an identical ion-induced