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Research Paper**AN APPROACH TO STUDY DAMAGE/TRACKS IN SOLID STATE NUCLEAR TRACK DETECTORS THROUGH TRACK- ANNEALING- INDUCED REPAIR OF DAMAGE IN A STATISTICAL FRAMEWORK**

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Abstract :

Passage of charged particles results in latent tracks/damage in insulating solids that arise from energy loss of charged particles in their interactions with the atoms and electrons of the target medium. Since the energy loss depends on the charged particle parameters viz. charge and energy, the latent tracks can be examined for the purpose of charged particle identification. Mechanism of track formation in insulating solids also called Solid State Nuclear Track Detectors has remained a key area of interest and research. Many track formation mechanisms have been suggested. It is also known that annealing of irradiated samples results in track repair or track erasure besides also that understanding of annealing phenomenon and mechanism in more details is likely to result in more accurate information about the mechanism of track formation, the two processes visualised as being reciprocal processes on the same route. In the present work, track annealing has been studied in a statistical framework and an approach has been developed to compare activation energy of annealing process in different parts of the track with annealing time and temperature as variables. This enables us to compare stability of damage in different parts of the track. Such information, since it enables to look into the track the way it is constituted, is more likely to throw useful information with regard to track formation mechanism.

Keywords :**Introduction:**

One of the most fundamental, complex, intriguing and keenly investigated phenomenon of microscopic physics is the passage of charged particles through matter accompanied with their interactions and the ensuing energy loss. In context of solids, as a result of pioneering work by of Young [1] and Silk and Barnes [2] followed by formidable efforts of the trio of Fleischer, Price and Walker, it became established in early sixties that passage of energetic charged particles through insulating solids caused intense trails of damage called 'Latent Tracks'. The radial dimension of the tracks ($\sim 30\text{--}100\text{ \AA}$) was too small to be observed with optical microscope and hence these tracks were referred to as latent. It also became possible to sufficiently enlarge the tracks using the very simple technique, 'chemical etching', so as to be able to observe them with ordinary optical microscopes [3], [4], [5]. Extent of damage, besides other factors, primarily depended upon the incident charged particle parameters viz. charge and energy and therefore, it could be made possible to employ these tracks as left behind

information or as indelible imprints of the incident ions from the point of view of deriving information about the incident charged particle parameters. The track recording solids were named 'Solid State Nuclear Track Detectors' and thus a new class of charge particle detectors emerged. Ever since, owing to unique features like permanent record of damage, lack of dependence on costly electronics, availability of a variety of detectors with different sensitivity, integrating nature in recording the damage, very simple revelation technique (chemical etching), insensitivity to moderate environmental conditions and well defined effects in more severe environment, SSNTDs have found widespread applications in many important disciplines of science viz. heavy ion physics, nuclear physics, cosmic ray physics, space physics, geochronology, radiation dosimetry, environmental radon mapping, trace element analysis, uranium exploration, microfilters, radiation protection etc. [6], [7], [8], [9], [10], [11], [12], [13].

The general understanding about the nature of damage is that tracks of heavy charged particles in solids are chemically reactive centres of strain and

- a) in inorganic crystals, the damage consists of atomic displacements which manifest as interstitials and vacancies around the path of incident charged particle.
- b) in case of organic polymeric track recorders, the damaged region is characterized by broken chains, reduced molecular weight and presence of new chemical species (free radicals).

This type of visualization of damage is substantiated by the fact that in track annealing, which leads to partial or total repair of the damage at elevated temperatures, the magnitude of activation energies associated with repair of damage has been found to be comparable to that of typical atomic diffusion processes; this is indicative of an atomic nature of damage rather than electronic.

Various mechanisms have been suggested to explain track formation— Direct Atomic Displacement [14], Thermal Spike [15] Total Energy Loss [16] Ion Explosion Spike [5] Restricted Energy Loss [16] Secondary Energy Loss [17] Radius Restricted Energy Loss [18] Primary plus Secondary Damage [19] Lineal Event Density [20].

Track formation in inorganic solids is most satisfactorily explained by ion explosion spike model in which primary ionization is supposed to result in damage and the effect of energy loss by secondary electrons is considered insignificant. For organic track recorders, however, the energy deposited by secondary electrons which are ejected due to the ionization of material by incident energetic charged particles also affects the extent of damage appreciably and hence all the criteria adopted for explaining track formation in polymers incorporate this feature in some form [16]. Restricted energy loss criterion is employed more popularly in context of track formation in organic track detectors.

Present Work:

The present work unfolds a novel approach to compare activation energies at various partial stages of annealing for any temperature-time combinations. It can also be employed to make out a comparison of activation energies in different parts of the same track.

It is known that loss of preferential etching, on account of annealing, first takes place in that part of the track which initially was the most weakly etchable. Hence those parts of the track which are characterized by greater extent of damage pose more resistance to track repair by annealing; it further implies that tracks of lighter ions would be more susceptible to annealing than the heavy ion tracks [21], [22], [23], [10]. Because of the observation that along a track, the damage more easily gets repaired where its extent is small (and vice versa), as a consequence of which the relative ease of repair in different parts of the track would be different, there would be different magnitudes of activation energy during the process of annealing—greater extent of damage in some parts of the track resists healing to a greater extent and extent of damage depends upon incident charged particle parameters too.

Repair of damage due to annealing can be visualized as overcoming of potential barrier by atomic species so as to come to energetically more favourable places. Movement of interstitials to fill vacancies can be understood in a way similar to the one envisaged by Gold [24]. All the barriers are not of same height and thus activation energetics could be generally different. Visualizing the damage as a large assembly of defects which are attempting to overcome the energy barriers under stimulation by thermal energy, the problem can be treated from a statistical viewpoint. At some given annealing temperature T , the extent of repair can be expected to depend upon

- (i) extent of initial damage i.e. at the beginning of the period of observation
- (ii) thermal energy vs activation energy; this factor would govern the thermodynamic probability of the process
- (iii) time of annealing.

Damage strain along the track and the resulting thermodynamic conditions make etching happen faster along the track so that Track Etch Rate (V_T) is more than Bulk Etch Rate (V_B) by a value ' f ' which depends only on the damage along the track.

$$V_T = V_B + f \quad [1]$$

Annealing induced repair of the track/ damage results in decrease of ' f '. Change in the value of ' f ' can be interpreted as the track repair induced by annealing.

Let Δf , change in the value of ' f ', be the extent of repair induced by annealing. It can be written as

$$-\Delta f \propto f (k_B T / E_{act}) \Delta t \quad [2]$$

f represents the initial damage; E_{act} is the activation energy; k_B is Boltzmann constant and Δt is such a short duration of annealing time at annealing temperature T that E_{act} does not change.
or

$$-\Delta f = cf (k_B T / E_{act}) \Delta t \quad [3]$$

c is a constant; it can be assumed to be a characteristic of the detector material and it seems to relate to the resistance that would be posed to a defect during diffusion from the interstitial site to a vacancy. A smaller value of c would imply a smaller Δf and hence a smaller extent of repair for given T , Δt and E_{act} , and a smaller repair despite same thermodynamic probability ($k_B T / E_{act}$) under identical annealing conditions can be interpreted in some way related to opposition posed to the diffusion of interstitial atoms.

$$\frac{\Delta f}{f} = \frac{-ck_B T}{E_{act}} \Delta t \quad [4]$$

$$\int_{f_i}^{f_f} \frac{\Delta f}{f} = \frac{-ck_B T}{E_{act}} (t_f - t_i) \quad [5]$$

$$\ln \frac{f_f}{f_i} = \frac{-ck_B T (t_f - t_i)}{E_{act}} \quad [6]$$

where f_f and f_i refer to final and initial values of f ; t_f and t_i are the corresponding times in such a way that total duration of annealing ($t_f - t_i$) is short enough to ensure a constant E_{act} .

$$\frac{f_f}{f_i} = \exp \left[\frac{-ck_B T (t_f - t_i)}{E_{act}} \right] \quad [7]$$

Since $y = (\Delta f / f) \times 100$, $\Delta f = f_i - f_f$

$$\frac{f_f}{f_i} = 1 - \frac{y}{100} \quad [8]$$

From eq. (7) and (8)

$$E_{act} = \frac{-ck_B T (t_f - t_i)}{\ln \left(1 - \frac{y}{100} \right)} \quad [9]$$

For two different annealing time intervals of the same duration and at the same annealing temperature, if y_1 and y_2 represent the corresponding percentage changes in the values of f (calculated with respect to the value of f at the beginning of the given annealing time interval) and E_{act1} and E_{act2} represent activation energies.

$$\frac{E_{act1}}{E_{act2}} = \frac{\ln \left(1 - \frac{y_2}{100} \right)}{\ln \left(1 - \frac{y_1}{100} \right)} \quad [10]$$

For small values of y eq. (10) becomes

$$\frac{E_{act1}}{E_{act2}} = \frac{y_2}{y_1} \quad [11]$$

So, it is possible to compare activation energies in two different annealing time intervals at same annealing temperature.

Further, for annealing for the same time but at slightly different temperatures, Δf can be written as

$$-\Delta f = c^1 f \frac{k_B T}{E_{act}} t dT \quad [12]$$

(c^1 is a constant)

Integrating eq. (12) and using eq. (8)

$$E_{act} = - \frac{c^1 k_B t (T_f^2 - T_i^2)}{2 \ln \left(1 - \frac{y}{100} \right)} \quad [13]$$

From eq. (13), it is possible to compare activation energies in two different but short temperature intervals for same annealing time.

Finally, it is also possible to compare E_{act} for annealing in different parts of the same track under a given set of annealing temperature-time combination, *e.g.*, change in the value of f corresponding to a very small thickness removal of the bulk material for a given total thickness removed (bulk) is determined; the same procedure is adopted for some other value of the total thickness (bulk) removed. Thus we have values of y_1 and y_2 which characterize the extent of annealing in different regions along the track and it is possible to write

$$\frac{E_{act1}}{E_{act2}} = \frac{y_2}{y_1} \quad [14]$$

Comparison of activation energies following this approach requires experimental annealing results at short intervals of annealing temperature-time combinations over a very wide range. Future annealing experiments in view of requirement of this approach will be able to reveal accurate microscopic information about track annealing kinetics.

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