© 2026 IJRTI | Volume 11, Issue 3 March 2026 | ISSN: 2456-3315

Analysis and Effects of Various Models of Low and High Energy Ion Beams Irradiation and Mixing on Materials

Anil K. Das *[1]
[1]St. John's College, M.G. Road, Agra, Uttar Pradesh-282002, India.
*Email: anildas001@yahoo.co.in

Abstract

Various Models are proposed by different scientists across the world to explain the formation of different tracks in different materials. These tracks area and depth changes with Ion energy, fluence and material. This paper studies and compares the various phenomena involved in high energy and low energy irradiation based on different proposed models.

Key words: low energy ion beam mixing, electronic energy loss nuclear energy loss, high energy ion beam mixing, Ballistic Process, Thermal spike diffusion, Radiation enhanced Diffusion, Thermal Spike model, Coulomb Explosion model,

Ion beam mixing

Depending on how much energy the ions lose to the target, the ion beam mixing procedure can be split into two categories: (i) electronic energy loss or inelastic collision with the target's atoms' electrons, S_e (ii) nuclear energy loss occurs when an elastic collision with the target's atoms' nuclei occurs, S_n. As a result, the loss of nuclear and electronic energy in the target atoms adds up to the overall energy loss [1]-

$$\left(\frac{dE}{dx}\right)_{total} = \left(\frac{dE}{dx}\right)_{nuclear} + \left(\frac{dE}{dx}\right)_{electronic}$$

Figure 1, created using the software SRIM (Stopping and Range of Ions in Matter), depicts the energy loss of Ag ions in Indium [2]. It was developed by J.P. Biersack and J.F. Ziegler.

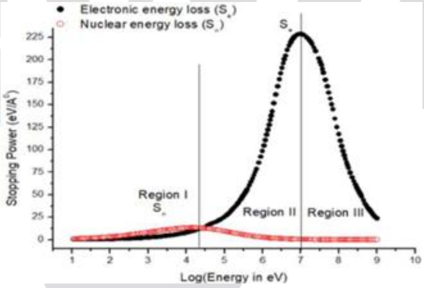

Fig 1. Loss of energy of Ag ions in Indium

The area of energy loss is split into two sections: nuclear energy loss (region I) and electronic energy loss (region II). Swift Heavy Ions (SHI) are high-energy ions with orbital velocities that are greater than or comparable to Bohr's orbital velocity. On the other hand, low energy ions are those with energies between a few keV and a few MeV.

The phenomena of ion beam mixing can becategorized as:

(A) Low energy ion beam mixing

When an ion of a few hundred keV bombards a target material, energy is primarily lost to the target atoms by elastic impact. This elastic collision causes the transfer of energy necessary to move atoms from their initial positions, eventually leading to a displacement cascade. Nuclear energy loss is another name for this kind of energy loss. Mixing occurs when two separate atoms' border atoms are displaced. On the basis of time scale, we can divide the effect of nuclear energy loss into two main categories: prompt processes (ballistic process), which take place within a few picoseconds, and delayed processes (thermal spike diffusion and radiation enhanced diffusion), which take place within several nanoseconds or longer.

(i) Mixing due to Ballistic Process

Ballistic Process is any collision phase that lasts for between 0.1 and 1 picosecond. During this period, the ion energy that was initially delivered to the initially colliding atom is lost by subsequent recoils [3]. Ballistic mixing may lead to recoil mixing and collision cascade mixing [4]. In recoil mixing, one atom can be shifted from its initial position after receiving a sizable amount of energy from an incident ion. However, there might be low energy, uncorrelated atomic displacements in the event of cascade mixing. The kinetic energy of the many atoms participating in cascade mixing along the ion path is far smaller than the energy of the incident ion.

(ii) Thermal spike diffusion

The term "thermal spike" refers to a very tiny volume within the target where the majority of the atoms are in motion for a brief period of time and the remaining material is thought to be liquid [5]. Thermal spike is caused by the dissipation of energy left over from the collision cascade in 10^{-13} seconds. The thermal spike's temperature can increase by up to 1000K. The principal mechanism for thermal energy dissipation is κl [5]. We chose the ion and its energy for the situation of low energy ion beam mixing so that it loses the majority of its energy at the interface of two material layers. In this instance, the flux is 10^{16} ions/cm^2 or higher [6].

(iii) Radiation enhanced Diffusion

The temperature rises and the atoms are actively moved when an ion bombards the target atoms. The term "radiation enhanced diffusion" (RED) refers to this phenomena. During ion radiation, the generation and annihilation of the vacancy at the target are in a dynamic equilibrium. According to Cheng et al., "average cohesive energy of the alloy is related to the transition temperature (temperature above which there is enhancement of mixing) between ballistic mixing regime and RED" [7].

(B) Swift Heavy Ion (SHI) Beam Mixing

Low energy ion beam mixing is totally unrelated to this mixing. Figure 1 makes it abundantly evident that S_e, the electronic energy loss, plays a role in the ion beam mixing process. The thermal spike model and the Coulomb explosion model are the two models that have been put out to explain SHI ion beam mixing.

(i) Thermal Spike model

The target is represented in this model as two connected subsystems, the lattice and the electrons [5]. Electron-electron interaction transfers ion energy to the electron subsystem, causing the temperature to rise to 10^5 K in time 10^{-15} sec. As a result, electron-phonon coupling transfers the energy of electrons to the lattice system. This causes the temperature of a cylindrical zone of about 10 nm in diameter to rise, reaching a molten state for a few picoseconds before being rapidly thermally quenched, which produces amorphization along the ion route (fig 2).

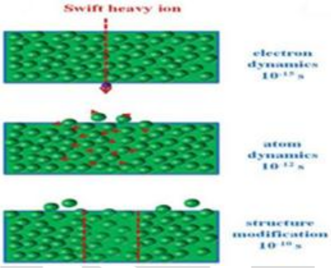

Fig 2 Thermal Spike Model for the formation of track by SHI [9]

Two coupled equations govern the energy transfer process from ion to electronic and electronic to lattice subsystem in terms of cylindrical symmetry [8]:

$$\rho C(T)\,\frac{\partial T}{\partial t} = \nabla(K(T)\nabla T) + g(T_e - T)$$

$$Ce\,\frac{\partial T_e}{\partial t} = \nabla(K_e \nabla T_e) - g(T_e - T) + A(r,t)$$

Where T_e, K_e, C_e, T, K(T), C(T), are temperature, thermal conductivity and specific heat of electronic and atomic subsystem respectively. ρ is specific mass of the lattice and A(r,t) stands for energy deposited in the electronic system by an incident ion and g is electron phonon coupling factor and depends on the velocity of the sound in material, κ of the material and temperature T as follow;

$$g = \pi^4\,\frac{(k_B n_e s)^2}{18\kappa T}$$

k_B and n_e are Boltzmann constant and electron density respectively.
The time taken by the ions to increase the temperature of the electronic system is ~ 10^{-15} sec. Then, over the course of 10^{-12} seconds, the electron–phonon interaction causes the lattice temperature to rise to 10^4 K. The melting point of the lattice in the cylindrical periphery may be exceeded at a specific S_e (threshold) lattice temperature. After that, depending on the material, the temperature of the lattice and the electronic system rapidly drops at a rate of 10^5 K/sec. The diffusion of the atoms near the boundary causes the mixing of the two layers.

(ii) Coulomb Explosion model

As shown in fig. 3, an ion beam passes through a target material, causing a cylindrical zone to become ionised and electrons to be ejected a greater distance.

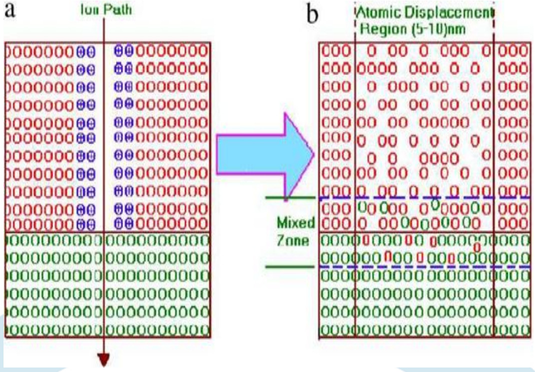

Fig 3 (a) Passage of Ion Beam and coulomb Explosion Schematic (b) Mixed zone is formed as a consequence of Mixing [10].

Between the positive atoms of the target, coulomb repulsion takes place. When neutralisation time exceeds 0.01 ps, a Coulomb explosion occurs, causing two layers to mix in the target. However, Coulomb explosion is not allowed if the target atoms' binding forces are stronger than Coulomb repulsion. For insulators, this concept has received extensive study. The energy of the ion beam is taken away by the electrons in the case of conductors like metals, which heats up the entire target and quickly neutralises ionised regions.

Conclusions:

The whole phenomenon can be explained by following figures.

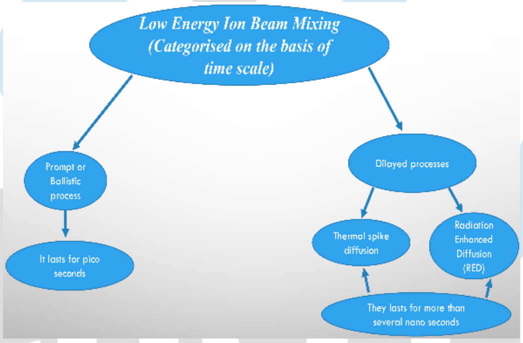

Fig 4. Low energy Ion Beam Mixing categorisation

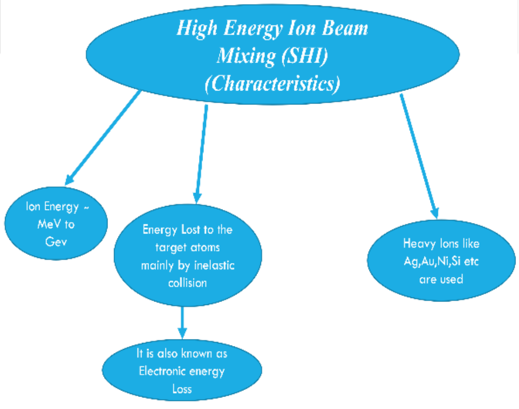

Fig 5. High energy Ion Beam Mixing characteristics

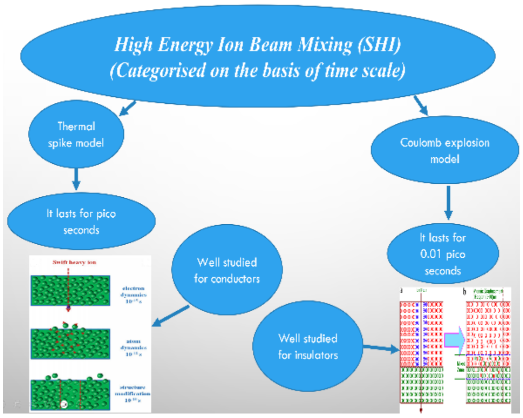

Fig 6. High energy Ion Beam Mixing categorisation

References

(1) D.K. Avasthi, G.K. Mehta, swift heavy ions for materials and nanostructuring, Springer Science and Business Media, 2011.
(2) www.srim.org.
(3) W. Bolse, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 80 (1993) 137.
(4) W. Bolse, Materials Science and Engineering: R: Reports 12 (1994) vii.
(5) M. Alurralde, A. Caro, M. Victoria, Journal of Nuclear Materials 183 (1991) 33.
(6) T. Devolder, Physical Review B 62 (2000) 5794.
(7) Y. T. Cheng, X.A. Zhao, T. Banwell, T. Workman, M.A. Nicolet, W. Johnson, Journal of Applied Physics 60 (1986) 2615.
(8) H.W. Tom, G. Aumiller, C. Brito-Cruz, Physical Review letters 60 (1988) 1438.
(9) Z. Wang, C. Dufour, E. Paumier, M. Toulemonde, Journal of Physics: Condensed Matter 6 (1994) 6733.
(10) Xu, Yang & Meehan, Kathleen & Guido, L. & Lu, Guoquan & Wyatt, Chris & Love, Nancy (2005)