Ion beam interaction with nanomaterial

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***Abstract*— The properties of materials at the nano scale critically depend on their size and shape, thus opening a new exciting area of nanotechnology. Its main thrust is to create novel functional materials with their unique physical, chemical and biological properties and development of different types of novel materials with new characteristics and functions. Ionizing radiation (photon, electron and ion beams) have provided immense possibilities for the desired properties of materials with new characteristics and functions. The aim of ion beam interaction with nanomaterial is to control the nano scale structure of materials to optimize their properties and functionality. A common feature of ionizing radiation is the ability to deposit a huge energy density in the materials when they are incident on materials. At high energy heavy ions of energy > MeV per nucleon, creates an ion track i.e. a cyllindrical zone of radius typically upto 10 nm different from the surrounding, in insulating materials. There are various possibilities of synthesis the nanostructuring by low energy as well as high energy ion beams. The low energy regime is typically below 1 MeV where ion and matter collisions are dominantly elastic and the high energy ion beam region is typically above 1 MeV per nucleon where the energy loss of incident ions in materials is prominently via inelastic collisions. Heavy ions with energy above 1 MeV per nucleon have velocities comparable or more than the Bohr electron velocity and is referred as swift heavy ions**

***Index Terms*— Nanomaterials, Swift heavy ions, Binary scattering, Quasi-equilibrium**

I. Introduction

Ion beams have wide applications in the processing and characterization of materials. These applications depends on the basic interactions between an energetic ion and the atoms of the material. Ion beams interacting with bulk material induce changes on a nanometer scale, for example, localized rearrangement of atoms [1]. Energetic ions interact with materials by collisions with the nuclei and electrons of the atoms that make up the material. In these collisions, energy and momentum is transferred from the projectile particle, which is a moving atom or ion, to the target particles. Each collision leads to a slowing down of the moving projectile and also a deflection of the trajectory that gives the phenomenon of scattering, which is often used synonymously to describe the energy transfer process. Energetic ion beams have been exploited by researchers in different ways in the field of materials science. Its effect on the materials depends on the ion energy, fluence and ion species. The interaction of ion with materials is the deciding factor in the ion beam induced materials modification. The ions lose energy as they traverse through the material which is either spent in displacing atoms by elastic collisions or in exciting or ionizing the atoms by inelastic collision [2]. The former is the dominant process at low energies whereas the inelastic collisions dominate at high energies where the displacements of atoms due to elastic collisions are insignificant. However, even at high energies the displacement of lattice atoms has been known to occur in insulating materials in a cylindrical core along the ion path. The swift heavy ions are also used for on-line monitoring of light elements by elastic recoil detection (ERD) [3]. In this paper, we describe some aspects and also the physical/chemical process of ion beam, specifically swift heavy ion beam interaction with material. The main aim of our effort is to provide the main theory of ion beam scattering with nanomaterial and the ongoing research activities in the forefront of this field.

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II. Energy Transfer in Binary Scattering

The interactions between an energetic ion and target nuclei can be described by collisions between massive point particles. Generally, in ion-solid interactions, it is convenient to treat the scattering interaction between two particles at a time (binary scattering). If energy and momentum are conserved, the collision is termed as elastic. On the other hand, the collision is inelastic if there is a conversion between kinetic energy and potential energy. An example of this is where electrons are excited to higher-lying shells during ion-atom collisions.

Figure1. Schematically illustrates a binary elastic collision. In the collision, energy and momentum are transferred from the projectile particle to the target particle. As the collision is elastic, energy and momentum are conserved:

$$E_1 = E_0 K = E_0 \left\{ \frac{\cos\theta \pm \sqrt{(M_1/M_2)^2 - \sin^2\theta}}{1 + (M_1/M_2)} \right\}^2 \quad (1)$$

$$E_2 = E_0 \Lambda = E_0 \frac{4 M_1 M_2}{(M_1 + M_2)^2} cos^2\phi \quad (2)$$

Here K and Λ are the kinematic factors, which represent the fraction of energy retained by the projectile after collision and the energy transferred to the recoiling target particle, respectively. $K + \Lambda = 1$. For $M1 \leq M2$ only the positive root is valid. Analytic handling of inelastic and elastic binary scattering is most conveniently done in the barycentric, or centre of mass frame [4–7].

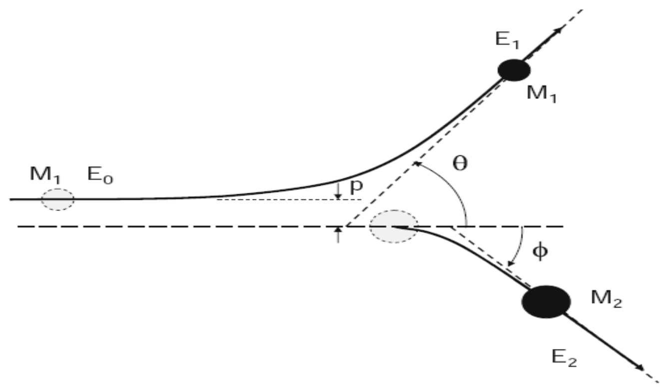

Figure 1. Binary scattering in the laboratory frame. Following convention, the scattered particle is denoted by subscript 1,while the recoiling target particle is denoted by subscript 2.The initial positions of the particles are denoted by grey toned dashed circles

III. ENERGY LOSS AND ANGULAR SCATTERING

Consider an ion passing through a thin film whose thickness increases from a single monolayer to a thick layer but not so thick as to completely stop the ions. When the film is very thin, the ions undergo only one binary collision (single scattering). Eventually, as the film thickness increases, some ions are scattered twice (double scattering), and then three or more times (plural scattering). Multiple scattering is often used to describe the situation where the ions are scattered many times. It must be emphasised that for films with thickness on a scale of nanometers, the mean free path between collisions is comparable to or greater than the thickness of the material. Thus, in traversing a nanometer film, only a small fraction of the ions may actually undergo scattering from a nucleus of an atom in the film. In dealing with ion beam interactions with nanomaterial, it is therefore important to consider that we are often dealing with the transition region between a single, or even no scattering and many scattering events. The energy loss and scattering in thick media have many practical situations. Subsequently, we consider the departures from this situation where single and plural scattering dominate in thin media. The probability of an ion undergoing *n* collisions after penetrating a distance *x* in the target is given by the Poisson distribution [8]:

$$P_n = \frac{(Nx\sigma_A)^n}{n!}\exp(-Nx\sigma_A), \quad n = 1, 2, 3 \ldots$$

where $\sum_{n=0}^{\infty} P_n = 1$. Hence, $P_0 = \exp(-Nx\sigma_A)$, which is the Lambert and Beer law for adsorption of quanta; $P_1 = (Nx\sigma_A)\exp(-Nx\sigma_A)$ corresponds to single scattering and $P_2 = \frac{1}{2}(Nx\sigma_A)^2\exp(-Nx\sigma_A)$ to double scattering, etc. As the projectile passes through the surface, $P_0 = 1$, the possibility for scattering to occur is turned on. It follows that the projectiles penetrate some distance before scattering the mean distance being the mean free path $\lambda = 1/(N\sigma A)$ [9]. Here σA is the cross-section for the particular rocess in question. It should be noted that the different cross-sections for different processes like ion-electron and ion-nucleus scattering imply that the mean free paths are different for the different processes.

IV. ENERGY LOSS AND SCATTERING IN NANOMETER-SCALE MATERIALS

An important difference between material on a nm and µm scale is that the number of atoms encountered by ions becomes small. This can be understood by considering that 1 nm of Si corresponds to 3.7 monolayers, while 1µm corresponds to 3700 monolayers. Ions with energies > 10 eV essentially only interact along their path with a single atom at a time; hence the number of scattering events that can take place in penetrating on a scale of nm is extremely limited. The surface may be considered as a singularity. Above the surface the ion does not undergo any scattering, while as it traverses the surface the scattering processes are abruptly turned on [10]. Deep in the media a statistical quasi-equilibrium is set up and the individual ions approach the statistical average behaviour. The intermediate layer where the quasi-equilibrium is approached represents a transition region. Energy Transfer by Secondary Particle Cascades Materials subjected to ion bombardment are modified not only by the primary ion being incorporated by ion implantation, but also by the kinetic energy deposited by stopping of the primary ion and recoils leading to a whole phenomenon of secondary effects [11]. As discussed above, ions interact by electron and nuclear scattering. Figure 2 schematically illustrates the interrelation of these effects, which stem from ion-electron and ion-nucleus scattering. The energy deposited by the ion is either carried out of the material by recoil and sputtered atoms, X-rays, secondary electrons, photons, etc., or eventually ends up in some form of stored energy and heat.

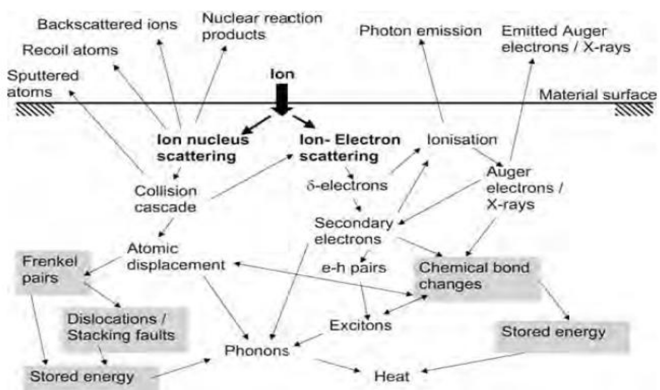

Figure 2. The evolution of the processes taking place in a solid material irradiated with ions. The *grey shaded* processes correspond to long term effects Although, ions can transfer energy during scattering by classical and quantum mechanical processes, it is convenient to consider the scattering as elastic, or, in the case of bound electrons, quasi-elastic, scattering of free particles at rest (Figure 1).This energy is then subsequently deposited in subsequent scattering, as illustrated schematically, that can extend over many generations to form a collision cascade.

V. IONOLUMINESCENCE (IL)

When ion beam is incident on certain materials, it emits photons in UV, visible or IR region. The states in band gap arising due to impurity atoms or the defect states, are populated due to interaction of incident ion and material. The decay of these populated states give photons in different energy regimes from UV to IR. The emitted light is analyzed by suitable detection system such as monochromator, detector, etc., which provides a spectrum of the intensities of different wavelengths. Such a study is referred to as ionoluminescence (IL) and has been extensively used for imaging and analysis of elements and chemical compounds [12]. It is a powerful tool to determine ionic state of impurity atoms. IL spectra provide signatures of the defects inside the material, enabling differentiation of natural specimens from imitations. Since the ion beam especially SHI's can modify the material, resulting in change of ionoluminescence, the on-line studies with ion fluence provide valuable information on modification induced by SHI. The ionoluminescence and PIXE are complimentary techniques. Their combination provides a powerful analytical tool, particularly in geochemistry [13].

VI. OPTICAL WAVEGUIDE FORMATION BY ION IRRADIATIONIN

A. *ORGANIC CRYSTALS*

An optical waveguide is a layer of material whose refractive index is significantly higher than its surrounding so that the light rays remain confined in this region during its transmission through it. The possibility of the formation of such waveguides in some organic crystals have been shown by the irradiation of the organic crystals by 100 MeV Ag ion irradiation. Significant changes in the refractive index (from 1.521 to 1.564) in the irradiated region have been observed [14-15]. The dielectric constant of the irradiated region also increases by about an order of magnitude. The on-line H measurement by ERD technique indicated that these canges are corelated with the loss of H in the irradiated region

VII. CONCLUSION

The Ion beams have vast potential in the field of modification of materials by extremely large energy transferred through the electronic excitation but negligible damage due to elastic collisions. The metal/Si interface can be transformed into silicide in the case of some specific metas by swift heavy ions. Generation of controlled modification in Si and columnar defects in high temperature materials for incorporation of effective pinning centers by high energy heavy ions is providing possibilities for applications in devices. The damage generated by ion beams in organic crystals can be exploited for the formation of optical waveguides. It is clear that the ion beams in materials have several interesting and unique aspects with the possibilities of applications.

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REFERENCE:

[1]. D.Lesueur, Rad. Eff. and Def. in Solids, **126**, (1993) 123 [3] D.K.Avasthi, Nucl. Istr. Meth. **B** (in press).

[2]. D. Kanjilal, S. Chopra, M. M. Narayanan, I. S. Iyer,V. Jha, R. Joshi and S. K. Datta, Nucl. Instr. Meth. **A238**, (1993)

[3]. D.K.Avasthi, Nucl. Istr. Meth. **B** (in press).

[4]. J. Goldstein, D.E. Newbury, D.C. Joy, C.E. Lyman, P. Echlin, E. Lifshin, L.C. Sawyer, J.R. Michael, Scanning Electron Microscopy and X-Ray Microanalysis, Third Edition, Plenum Press, New York, 2003.

[5]. P.B. Hirsch, A. Howie, R. Nicholson, D.W. Pashley,M.J. Whelan, Electron Microscopy of Thin Crystals,Krieger, Malabar, FL, 1977.

[6]. O.L. Krivanek, P.D. Nellist, N. Dellby, M.F. Murfitt,Z. Szilagyi, Ultramicroscopy **96** (2003) 229.

[7]. A.B. El Kareh and J.C.J. El Kareh, Electron Beams,Lenses and Optics, Vol. II, Academic Press, NewYork, 1970.

[8]. P. Sigmund, Particle penetration and radiationeffects, (Springer, Berlin, 2006)

[9]. P. Sigmund, Stopping of heavy ions a theoreticalapproach, (Springer, Berlin, 2004)

[10]. A.D. Marwick and P. Sigmund, Nucl. Instrum.Methods 126 (1974) 317.

[11]. G. Amsel, G. Battistig, A. L'Hoir, Nucl. Instrum.Methods B201 (2003) 325.

[12]. D.N. Jamieson, V. Chan, F.E. Hudson, S.E.Andresen, C. Yang, T. Hopf, S.M. Hearne, C.I.Pakes, S. Prawer, E. Gauja, A.S. Dzurak and R.G.Clark, Nucl. Instrum. Methods B 249 (2006)221–225.

[13]. Y. Zhang and H.J. Whitlow, Modification ofmaterials by MeV ion beams. In Electrostaticaccelerators, (ed) R. Hellborg, (Springer, BerlinHeidelberg New York 2005) pp. 506–529. 13. W.K.Chu, J.W. Mayer and M.-A. Nicolet, Rutherford Backscattering Spectrometry, Academic Press.Orlando, FL (1978).

[14]. Leonard C. Feldman and James W. Mayer,Fundamentals of Surface and Thin Film Analysis,North Holland (1986). 7. A. Ene, I.V. Popescu and T. Badica, Journal of Optoelectronics and Advanced Materials, **8** (2006) 222. [15].D.K. Avasthi, S.K. Hui, E.T. Subramaniyam and B.R. Mehta, Vacuum, **47** (1996) 1061.