Section 4: Material modifications

This section is obviously linked to the preceding one. There, the basic processes governing atomic collisions were analysed; here the interest is focused on the subsequent modifications induced in condensed matter. Radiation is a means, sometimes unique, to induce non-equilibrium states of matter. In this sense, it is an interesting subject of physics by itself. To understand and to control such effects, one clearly need to take properly into account the primary events studied in section 3. But this is by far not sufficient.

The response to these primary events and the permanent modifications that can be induced depend on the nature of the materials. This is already true in the so-called "low-velocity" regime where elastic collisions dominate and the energy is directly transferred to target atoms. The residual modifications induced in this situation depend drastically on the diffusion properties of the implanted species and of the defect formed, on their probability to annihilate, to agglomerate and on their ability to induce stable or metastable phase transitions. The nature of the materials is even more decisive in what concerns the modifications induced in the so-called "high-velocity" regime where inelastic collisions dominate. In this case the ability to induce material modifications is mainly determined by the efficiency and the rapidity of the energy transfer from the target electrons to the target lattice. Very spectacular effects are observed when extremely high densities of energy deposition are reached. In the last few years, impressive progress has been achieved in the understanding and control of material modifications. Numerical simulations are now performed and are becoming able to test the validity of more empirical but rather general approaches (thermal spikes, Coulomb explosion). Non linear and threshold effects as function of deposited energy density are observed and understood.

As radiation induces non-equilibrium states of matter, new materials can be created with novel properties. In industry, many applications of material irradiation have been developed for the production of micro and nano-materials of high technological interest. Moreover, the materials modified by irradiation can be used to study basic problems in many domains of physics; for instance, in solid state physics important information is obtained on phase transitions of vortex lattices in high T_C superconductors or on interactions between magnetic nanoparticles.

Irradiation concerns all classes of materials, ranging from metals to living cells. The present section is thus closely related to chapters 1 and 3 of this book, which are devoted to the impact of nuclear science on biology (and therapy) and on energy. Within this latter field, it is of prime importance for nuclear industry to know the evolution of nuclear fuel and of matrices for nuclear waste transmutation which are submitted to fission fragments. It is also of interest to use ion accelerators to simulate the radiation damage induced by different radiation fields. In another domain, it is important to simulate the wide spectrum of irradiation at which electronic devices are submitted in space and to predict their behaviour. To conclude, it is necessary to understand irradiation induced effects both on the basic and technological grounds.

The studies in the radiation damage field started fifty years ago with the advent of nuclear energy. Most of the interest in this early period has been devoted to the modification of metallic compounds under neutron irradiation. Some time after, the use of implantation for doping semiconductors extended massively. Finally, the formation of new phases by ion irradiation, ion implantation, atomic mixing of multilayers and by dynamic mixing during implantation or deposition, constituted an active research area. Implantation induces a correlated damage and consequently the development of such materials studies, using low energy ion beams, necessarily involves the build-up of a basic understanding of radiation damage processes, particularly those due to the elastic collision effects. On the other hand, the conjunction with significant developments in neighbouring fields (such as the production of metastable alloys by, e.g., laser annealing or mechanical techniques) has led not only to new ideas for tailoring new materials, but also to the introduction of concepts derived from nonequilibrium thermodynamics [1]. The enhanced ability to model a non-equilibrium phase diagram produced by ion irradiation or implantation (the latter adding a source term to the former) is providing predictive power to ion-based techniques. Recent examples have shown how one can, in this way, go so far as to design systems with interesting physical properties that may lead to applications in microelectronics or magnetism [2], [3]. All these research and applications are now mature. Although at present their evolution is largely independent of the nuclear physics research facilities (and will thus not be detailed here). It is only fair to emphasise the crucial role that the latter have played in a recent past.

In the last 15 years, a sizeable scientific community has used facilities shared with nuclear physicists or originally devoted to nuclear science studies. The interest of this community is on the highly excited states of matter induced by swift heavy ion, SHI, high or low energy clusters beams and very low velocity highly charged ions, HCI. In the present section, we focus on these specific ion beams.

4.1 Energy deposition

4.1.1 Radiation-induced excited states of matter

The interaction of charged particles with a target can be analysed considering independently inelastic interactions with target electrons and elastic interactions with screened target nuclei. The former interaction is responsible of the "electronic stopping", $(dE/dx)_e$, that dominates at high velocities, the latter of the "nuclear or atomic stopping", $(dE/dx)_n$ that dominates at low velocities. Ion irradiation may deposit quasi-instantaneously very high energy densities in matter, such feature is certainly not accessible with other irradiation modes as, for instance, high power fast lasers.

4.1.1.1 Inelastic collisions: electronic excitation

Swift heavy ions loose their energy by electronic excitations and the corresponding stopping can reach very high values: some tens of keV/nm. Half of this energy loss is deposited in a range of a few nm around the ion path, the remaining energy is transported far away by the energetic electrons produced. Monte Carlo simulations have been used to describe this energy deposition but there are not direct measurements in the solid state to verify their predictions. The only approach attempted to validate the numerical predictions was to compare the measured electron emission from thin carbon foils to the electron transport calculations based on a master equation in phase space [4] (see section 3.3.1).

High-energy polyatomic beams offer the possibility to reach extreme values of $(dE/dx)_e$. Therefore, they have allowed exploring unknown regions of electronic excitation. Before fragmentation in matter, a C_{60} beam, at only 10 MeV, experiences the maximum $(dE/dx)_e$ reached with a monoatomic beam; at 20 MeV, $(dE/dx)_e$ is 50% higher. Varying the energy and the nature of the cluster, it is possible to explore a large range of $(dE/dx)_e$ and in particular the same stopping power values that are accessible with monoatomic beams but in a much lower velocity regime. This high excitation regime is only obtained in the near surface region of the solid since, mainly due to multiple scattering, the trajectories of the individual constituents of the cluster spread out (see section 3.3.2).

Low energy very Highly Charged Ions, HCI, provided by the new generation Electronic Cyclotron Resonance sources, ECR, or Electron Beam Ion Sources, EBIS, can extract a large number of electrons from surfaces. As the ion appoches the surface, target electrons are captured in high n levels of the projectile and re-emitted by Auger effect. Consequently, the number of electrons extracted can be higher than the charge state of the projectile [5], [6]. This induces a so-called potential track. In the vicinity of the ion impacts, holes are now created in the electronic band structure of the solid instead of electron-hole pairs generated in the case of high velocity projectiles (see section 3.3.3).

4.1.1.2 Elastic collisions

Low energy ions develop displacement cascades in solids. Within these cascades atoms are expelled from their stable site in the target with a kinetic energy ranging from a few 10 to a few 100 eV. Recently [7], an experimental study of the slowing down in crystals of ions in this energy range has been achieved in the Laue Langevin Institute at Grenoble via a gamma ray induced doppler broadening technique. In this technique one uses two features: i) neutrons penetrate deeply into matter and excite nuclei if they are captured, and ii) this capture leads to a newly formed isotope, which deexcites down to the ground state by a sequence of gamma ray emissions. The first emitted gamma ray imparts a recoil to the nucleus and the entire atom will start to move inside the crystal. While the atom is moving through the bulk, the nucleus remains excited for some time (the nuclear state lifetime) and then emits a second gamma ray. A high-precision measurement of the second gamma ray’s line shape provides the Doppler broadening and thus the velocity distribution of the moving isotopes. This distribution is influenced by blocking and channeling effects (see sections 2 and 3). Such effects can be simulated and the comparison with measured line-shapes thus provides information on the interatomic potential governing the ion trajectories.

Non-linear cascades are induced with heavy monoatomic projectiles when the atoms set in motion start to hit other moving atoms. Low energy cluster beams provide new perspectives for studying highly non-linear dense cascades. The effect induced by a cluster exceeds the sum of the effects produced by the atoms bombarding individually the same targets.

4.2 Relaxation of the deposited energy

The structural modifications that follow the energy deposition last typically some picoseconds. Only in organic materials where secondary chemical reactions occur, the time scale of the damage process can be much longer. In this last case, the dynamics of the relaxation of the deposited energy could be experimentally followed. In the other materials, there are no direct experimental techniques to observe the dynamics of the structural modifications. Only numerical simulations or the use of the ejected particles as messengers of the primary steps of the energy deposition gives some insight on short time processes. This situation contrasts with laser irradiation where pump-probes methods allow short time observations.

The relaxation of the highly exited states of matter can induce permanent structural changes. High $(dE/dx)_e$ projectiles can create, above a $(dE/dx)_e$ threshold, a damaged zone all along the particle path generally called latent track. High $(dE/dx)_n$ projectiles develop displacement cascades collapsing in a small size damaged region.

4.2.1 Time resolved measurements

At high $(dE/dx)_e$, the time resolved measurements are presently restricted to water radiolysis [8], [9]. Electrons are very rapidly (< ps) solvated in polar liquids. The solvated electron reacts with the counterpart cations on a ns-µs time scale. The kinetics greatly depends on the heterogeneity of the energy deposition. The decay of the solvated electron is a severe test of the heterogeneous chemical reactions supposed to occur in the ion tracks [10]. On the nanosecond scale, the energy per pulse delivered by heavy ion accelerators is far below the value offered by electron machines. The highest possible intensity is highly desirable in this domain. The increase of the intensity of the GANIL beams associated to an enhancement of the detection sensitivity had recently allowed measuring the decay of the solvated electron with a time resolution of 1 ns. Testing heterogeneous kinetics in model systems, as water, is crucial because secondary chemical reactions probably determine the high $(dE/dx)_e$ behaviour of the organic matter including biological samples.

4.2.2 Numerical simulation

Molecular dynamics, MD, has been used for studying non-linear displacement cascades. A plastic flow of hot liquid towards the surface is predicted when a cascade is centred “inside” the sample while, for a cascade developing nearer to the surface, microexplosions occur [11].

In the electronic deposition regime, a realistic model must explicitly include the target electron system (ab-initio simulations). Presently, this is only feasible for small atomic clusters in vacuum [12]. Bypassing the electron-lattice energy transfer, classical MD calculations are urgently needed to better understand the atomic relaxation of the high-temperature high-pressure tracks induced by swift heavy ions or clusters and slow HCI beams. In solid rare gases a comparison of the sputtering predictions, given by MD, classical thermal spikes without mass transport and, by solving the Navier-Stokes equations has been done [13]. These studies point out the strong coupling between pressure and temperature and reveal the limits of the often-used classical thermal calculations [14].

4.2.3 Electron emission

A few femtoseconds after the passage of the fast ion, the energy thermalises in the electronic system. Measuring the shift and width of Auger lines and convoy electron yields, it has been possible to determine the nuclear track potential of polypropylene and the electron temperature of amorphous carbon in the track centre on a time scale of about 10 fs. These data provide the basic input for thermal spike models and illuminate the relevance of Coulomb explosion in metals and polymers [15].

4.2.4 Electronic and nuclear sputtering in organic and inorganic materials

Ionic and neutral emissions from surfaces represent a signature of the atomic motion short times after the energy deposition [16]. Because it is easier to detect, ionic emission was mostly studied allowing measurements of angular and energy distributions as well as identification of cluster emission. But the ionic fraction represents a very minor part (< 1%) of the total emission. Most of the measurements on neutrals are on total yields. Data on angular distributions and energy distributions are limited. The detection of the neutral clusters is still a challenge. Particle emission (electron, ions and neutrals) is very sensitive to the surface quality (roughness and adsorbed impurities). At present, ultra-high vacuum chambers fitted with surface characterisation set-ups and installed on SHI, slow HCI and clusters beams lines are too scarce.

In polymers exposed to SHI, the angular and velocity distributions of ions coming from extensive fragmentation-rearrangement of the original molecular structure or of ions closer to the original molecular structure are markedly different [17]. These observations nicely show how sputtering can reveal the core and peripheral chemical reactions and the related atom movements occurring in a heavy ion track.

Sputtering was the first evidence that very low HCI induces a severe damage to insulating surfaces (see section 3.3.3). Figure 4.2.1 shows that high yields are observed and, as expected, that the yield is clearly connected to the ion charge state [18].

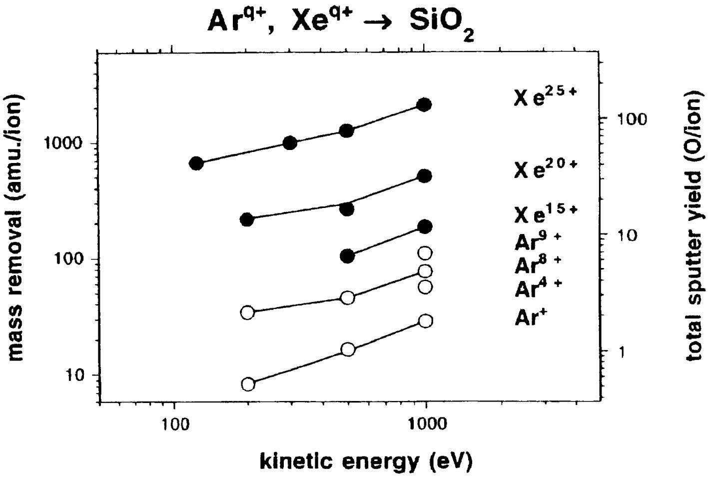

Fig. 4.2.1: Mass removal for SiO_2 in amu. (left scale) or number of sputtered oxygen atoms (right scale) per incident Ar^{q+} (open symbols) and Xe^{q+}(full symbols). For details see [18].

High-energy cluster beams can have extremely high $(dE/dx)_e$ and consequently induce dramatic effects [19]. For organic films, giant craters corresponding to an emission of 10^7 mass units have been observed [20]. These beams also produce a significant amount of large size clusters. In particular, for targets formed by large organic molecules the emission of intact molecules is highly enhanced, with respect to what is obtained with swift monoatomic projectiles.

For gold samples, the non-linear sputtering effects of low energy cluster beams have been analysed [21]. These particles deposit their energy in elastic collisions. Contrary to monoatomic beams, the sputtering yield with these cluster beams is maximum at a velocity substantially lower than the one corresponding to the maximum of nuclear stopping power. A large non-linear sputtering enhancement is observed between cluster and atomic projectiles. When the cluster projectiles have more than three atoms, a square dependence of the sputtering yield is found as a function of the number of constituents.

4.3 Permanent effects induced in solids by strong electronic or atomic perturbations.

The application of sophisticated characterisation methods, like high-resolution transmission microscopy, near field microscopy, defect spectroscopy, and x-ray diffraction (sometimes on-line) resulted in a significant progress in collecting experimental data about track formation and track structures in solids. The mechanisms by which the electronic excitation energy is converted into atomic motion and, finally, into stable structural changes are still under debate. There is now growing evidence that in the late phase (≥0.5 ps) of track formation the matter around the trajectory of a fast heavy ion can be conceived as a high-pressure high-temperature spike.

The attention paid to the effects of SHI on organic materials is rising. Probably, the interest on biological effects and especially on heavy-ion radiotherapy partially explains this trend.

4.3.1 Plastic instability of amorphous materials

The hammering effect of track-generating ions in amorphous materials was one of the most unexpected and remarkable effects of high $(dE/dx)_e$ irradiation. This effect is now much better understood. In these solids, a particle track represents essentially a thermo-elastic inclusion [22], [23]. The consideration of mechanical equilibrium [23] of a fluid track in a solid matrix results in a constitutive equation, which describes the mechanical behaviour of amorphous solids during heavy ion bombardment. Surface deformations and ripples appear at the sample surfaces as a consequence of the bulk deformations [24].

4.3.2 Phase stability under radiation

The investigation of non-equilibrium phases produced by track-generating ions is far from being systematic. In the past, most attention was devoted to amorphisation, which has been often interpreted as melting and freezing of the hot track matter [14].

More recently, the effects of extreme $(dE/dx)_e$ induced by high-energy C_{60} cluster beams have been investigated. For the first time, the amorphisation of some extremely resistant materials as sapphire [25] or silicon [26], [27] has been induced. The damage does not only depend on $(dE/dx)_e$; at given $(dE/dx)_e$, it decreases when increasing the projectile velocity. A very complete analysis of this “velocity effect” has been done on YIG oxide [28].

Investigations of phase transformations between two or more crystalline phases are rare [29], [30], [31]. In yttria the $(dE/dx)_e$ cubic to monoclinic phase transformation becomes easier when the mean crystallite size of the target decreases [32]. The design of high-power fuels, for research reactors, benefits directly from a development of criteria for phase stability under irradiation.

With bilayer or multilayer targets, studies of phase stability and phase formation benefit from usually planar interfaces and, additionally, allow the investigation of diffusional processes (mixing). Some attractive experimental approaches as multilayers with ^{57}Fe isotope enriched layers associated with a detection of the intermixing by Mossbauer spectroscopy have a great potentiality [33]. To progress in the understanding of the relaxation paths of highly excited materials, tailored nanostructured material should play a crucial role in the near future.

In addition to high-resolution electron transmission microscopy, small angle x-rays scattering and, wide angle x-rays scattering should be more applied for the characterisation of the phases formed and their interfaces. An on-line x-ray facility with a large position-sensitive counter is in operation at GANIL (Caen). A 4-circle diffractometer will be installed at the cyclotron of the Ionenstrahllabor of the HMI (Berlin) this year. Neither on-line small-angle scattering apparatus nor grazing angle x-ray diffraction equipment for multilayers studies exists at one of the big European ion accelerators. Cluster beams have largely contributed to the understanding of the track generation. Larger cluster ion accelerators than presently available are considered necessary.

4.3.3 Surface modifications

Surface modifications are related to sputtering and to track formation. Near–field microscopes now allow the imaging of the topographic effects of single ion impacts [34]. Depending on the materials and irradiation conditions craters or hillocks are observed. Protuberances of various shapes, located in the vicinity of the craters, are also seen. Recently transmission electron microscopy in the topographic contrasting mode has been successfully used for analysing the surface irradiation effects [35].

Surface modifications of mica where extensively studied by atomic force microscopy [36]. Figure 4.3.1 shows the radii of the surface tracks versus the restricted energy loss of monoatomic and polyatomic projectile. In the bulk, the restricted energy loss re-scales the results by taking into account the “velocity effect”. This re-scaling can be obtained for monoatomic ions of different velocities but not for cluster irradiations that give smaller radii. This latter discrepancy could be due to an overestimation of the cluster energy loss arising from the difference in the incident charge state of atoms and clusters. This result stresses the importance of charge equilibration (cf. ETACHA-Code, see section 3.3.1) when looking at near surface effects.

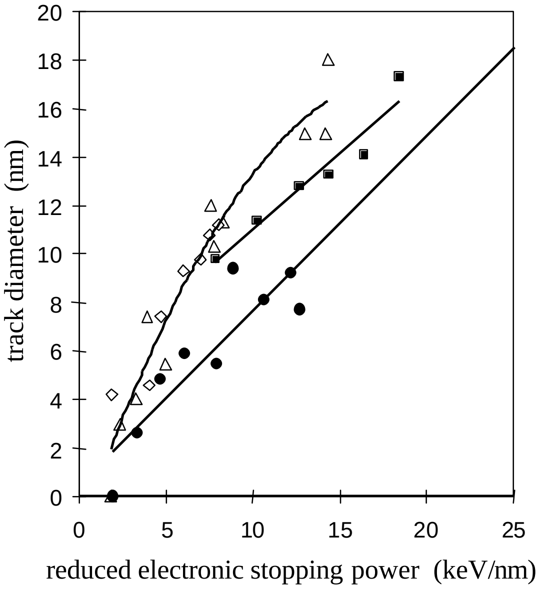

Fig.4.3.1: Track diameter measured by atomic force microscopy [36] as a function of the reduced electronic stopping power calculated with a cut-off energy of δ electrons of 200eV. The open symbols correspond to irradiations with monoatomic ions of different velocities and the black symbols to the cluster irradiations (■ Aluminium clusters, ● Carbon clusters).

4.3.4 Organic materials.

Polymers are one of the simplest organic solids. Besides their use in the applied field, they have been much studied as model systems of the organic matter. Tracks in polymers are complex. Small angle x-rays and neutron scattering measurements visualise the ion tracks as a cylinder of density smaller than the bulk [37]. Infrared spectroscopy informs on the chemical modifications induced by radiation [37], [38]. This technique has revealed that high $(dE/dx)_e$ irradiation induces specific defects. The gas release greatly contributes to the track formation. The gas release analysis shows that the stability of some specific molecules in the chemically reactive core of the tracks largely influences the production yields and consequently the track formation [39].

Closer to life sciences, analysis of the degradation products at high $(dE/dx)_e$ of the elemental constituents of the DNA has been done by Nuclear Magnetic Resonance [40]. As for simple polymers, high $(dE/dx)_e$ irradiation of nucleosides and dinucleosides induce specific modifications. Irradiation of plasmid DNA allows to observed the $(dE/dx)_e$ incidence on the single and double strand-breaks which are supposed to be determinant in radiobiological effects. In addition to standard electrophoresis measurements, transmission electron microscopy was recently used and has allowed the first detection of locally multiple damaged sites formed in DNA after exposure to a heavy-ion beam [41].

4.4 Use of the induced effects

4.4.1 Novel radiation-induced properties of materials

Radiation-induced structural changes are used for obtaining materials with new interesting properties. Slow HCI could be interesting for surface etching in a nanometer scale. Cluster beams are envisaged for the emission, in the gas phase, of intact large organic molecules. However, presently, the latent tracks induced by SHI represent certainly the most important modification in term of applications.

The production of nanopores by chemical etching of ion tracks has turned over to industry. Nanopores are used in many fields, e.g. in medicine for a well-defined drug release, in housings of electronic circuits in motor cars for water-repelling venting holes, and as semi-permeable membranes in miniature fuel cells. At present, these applications are limited to nanopores in polymers but materials resisting to higher temperatures should be developed. The preparation of asymmetric membranes by electro-stopping [42] and of responsive membranes by grafting open new perspectives [43].

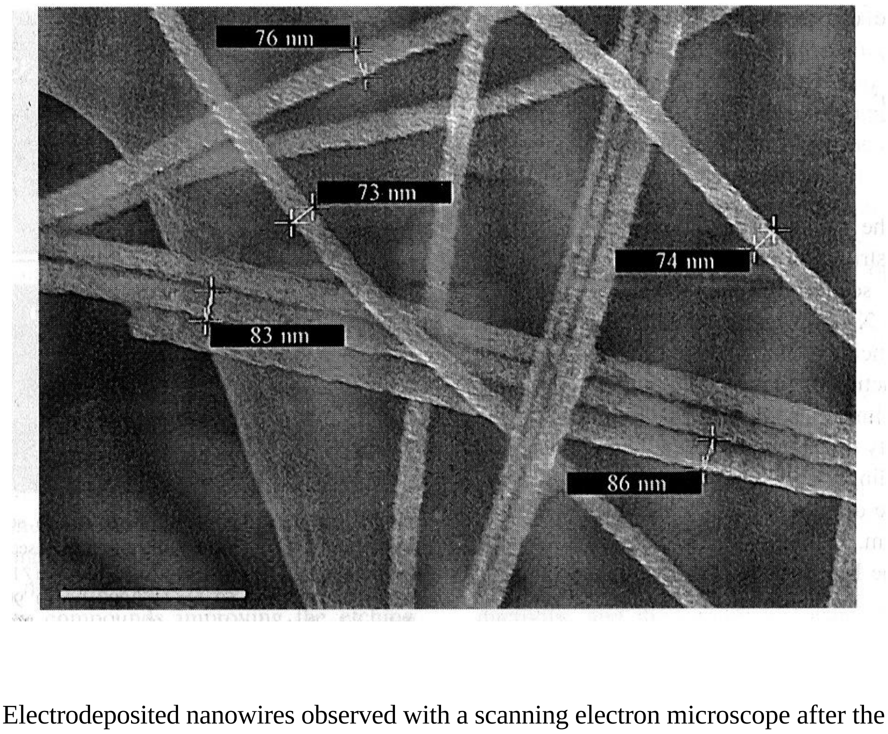

Fig. 4.4.1: Electrodeposited nanowires observed with a scanning electron microscope after the dissolution of the polycarbonate track etch membrane template [45]. The diameter of some nanowires are indicated. Scale bar is 500µm

Replica or template techniques allow the production of cylindrical objects of micrometer-nanometer size on a large variety of materials [44], [45]. Utilising the field effect electrically conducting objects could serve as electron emitters for displays [46]. Recently developed semiconductor growth modes can be exploited to fabricate nanometer-sized semiconductor devices in chemically etched ion tracks. Another possibility is track doping for tailoring the properties of the track [47]. Clearly, the trend is to decrease, as much as possible, the diameter of the cylindrical objects (figure 4.4.1) and to identify the novel properties related to the nanoscopic dimensions of the materials. Nowadays, pore sizes of 15 nm are realistic [45].

Very recently, it has been shown [48] that above a rather low threshold in deposited inelastic energy density (about 5keV/nm), ion irradiation of glasses could induce the controlled nucleation of metallic clusters. One then obtains well-adapted materials for studying individual optical and magnetic properties of nanoclusters with interesting applications in optical switching or filtering.

4.4.2 Basic studies with radiation-induced structured materials

The radiation-induced material modification is a tool for basic studies in other branches of physics. Once more, the latent tracks induced by SHI are the defects that have found a marked interest for basic studies.

Columnar defects induced by fast heavy ions are ideal pinning centres for flux lines in high-T_c-superconductors (HTSC). There, latent tracks have the same geometry than the flux-vortices and same radius as the core of a vortex. This fact has induced a considerable number of studies and hundreds of publications. Sophisticated theories on pinning and melting of the flux line lattice could be tested by the generation of splayed particle tracks [49],[50]. Induced latent tracks in metallic compounds produce magnetic nanostructures and allowed unique studies on nanomagnetism [51].

Some of these experiments would greatly benefit from regular track lattices. The feasibility of the latter is still a time-consuming task. An ion microprobe steering individual ions to pre-set locations is only available at the UNILAC of GSI (Darmstadt) [52].

4.5 Materials under irradiation

Materials are subjected to radiation. It is therefore necessary to understand and predict the induced effects. Very contemporary and important problems exist in the radioactive waste management and in the present and future reactors. In order to handle these questions, it is now crucial to reinforce the community of physicists expert in problems related to irradiation of materials and thus to train young scientists in this domain.

The experimental study of the materials submitted to irradiation are performed in two ways: i) the “real” irradiation conditions are reproduced in the laboratory ii) simulation with beams different from the real exposition gives substantial practical advantages.

4.5.1 “Real” irradiation conditions

The irradiation conditions, in term of ionic species and energies, can be relatively close to the real exposure conditions. This is the case for the study of the fission fragment damage and for the study of SHI effects in electronic components. The flux effect is probably small and acceleration of the irradiation conditions is not very problematic.

Today the problem of radiation-induced malfunctions in integrated systems is very real [52], [53]. This problem is not strictly limited to exposures in space but malfunctions caused in satellite-electronics by a single ion hit are probably the major issue. These bit-flips were named

Single Event Upsets, SEU. Cosmic radiation presents a very large spectrum of ions and energies. It is a real challenge to predict the in flight behaviour of a component starting from a necessary limited number of measurements with accelerator delivered beams. An in-depth understanding of the effects of $(dE/dx)_e$ and of the “velocity effect” is necessary. Microbeams give a valuable contribution to the electronic component studies [54]. They permit the spatial localisation of the ion impacts that induce a SEU (figure 4.5.1) [52] and subsequently the sensitive zones of the circuit (see section 5.3).

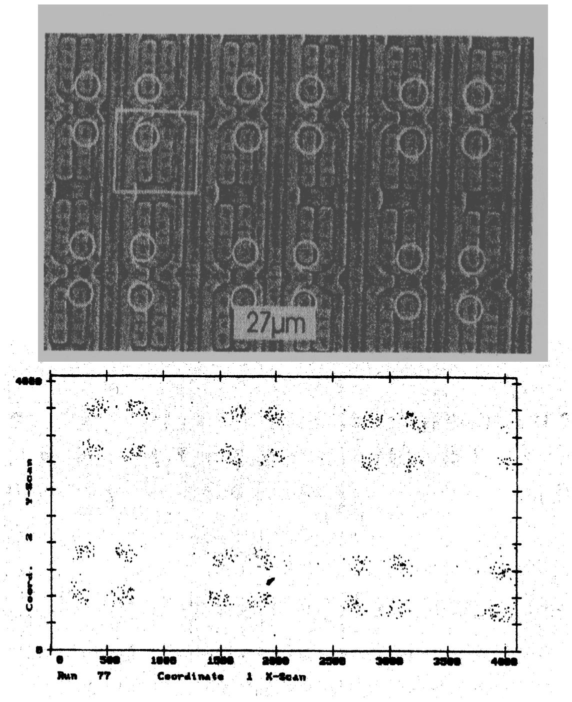

Fig. 4.5.1: Upper part: electron microscopy image of an array of 24 elementary storage cells. Lower part: radiation sensitive sites within a chip area similar to the one of the upper part of the figure. Every point is due to an ion hit leading to an upset. The hits themselves are uniformly distributed [52].

The nuclear fuel is submitted to fission fragments. Moreover, in the case of transmutation of actinides in order to reduce the problem of the nuclear waste management, the matrix hosting the actinides will also be submitted to fission fragments. Track generation by fission fragments could create unaffordable morphological changes of the target. In spite of the numerous studies of latent track formation done (cf. section 4.3.2), it is still difficult to foreseen the behaviour of a given material. Moreover, all the basic studies have been done at room temperature and low fluence; that is very far from the working conditions in a nuclear reactor. Realistic irradiation must be performed. For that, a new beam line is under construction at GANIL allowing high flux irradiation with heavy ions in the 0.5-1 MeV/A range.

4.5.2 Radiation damage simulation

Shortening the irradiation duration and lowering the irradiation cost are the mean reasons for departing from the actual irradiation conditions.

When, in the real situation, the irradiation times are very long, an artificial acceleration of the irradiation is unavoidable. In several cases, the material stability is not only determined by the fluence or the absorbed dose, but also depends on the flux or dose rate. Consequently, the understanding of the flux or the dose rate effects is one of the challenges for the prediction of the stability of materials under irradiation.

The use of small ion accelerators instead of neutron irradiation or very high energy proton irradiation allows a strong reduction of the irradiation time, generates cost benefits and a strong decrease of the radioactivity of the samples. The decrease of the activity of the irradiated samples permits a much better characterisation of the damage at a much lower cost.

The simulation by different particles will never be sufficient to ensure a correct behaviour of a material submitted to a very different radiation field. But it is of great help in selecting promising materials and in understanding the effect of the different parameters such as flux, fluence and temperature.

4.5.2.1 Ion simulation of the fast neutron damage

Ion irradiation is a well-known way to simulate the fast neutron damage to materials. The irradiation conditions must fit the primary knock-on spectrum generated by the neutrons of the reactor. One problem is that the thickness of the irradiated layer is generally much smaller than the thickness of the materials irradiated under real conditions. This is a true limitation since intergranular processes can, to a great extent, control the macroscopic mechanical behaviour. The irradiation over a thickness greater than the grain size implies the use of relatively high-energy accelerators. The other difficulty is that nuclear reactions induce a significant doping of the target by H and He atoms. The simultaneous implantation of these species is often considered necessary. This leads to the use of dual or triple ion beam facilities. The availability of such facilities is one of the crucial issues of the radiation damage simulation.

4.5.2.2 Ion simulation of the material damage in ADS

The new subcritical reactor concepts (ADS for accelerator driven systems) raise new and severe radiation damage problems. Very high-energy protons and neutrons irradiate the structural materials. The atomic displacements are indirectly generated by the spallation products and the nuclear reactions produce a large spectrum of foreigner atoms with very significant concentrations. Several European programs are dedicated to the material problems of sub-critical reactors. This emphasises the importance of the effort needed in this direction.

4.5.2.3 Simulation of the radiation induced corrosion

The contact of metals with water in classical reactors and with liquid metals in ADS, induces a detrimental corrosion. The irradiation of a liquid-solid interface requires a large penetration depth and the use of high-energy accelerators seems essential.

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