Annealing of preexisting defects in silicon single crystals by ion irradiation

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Few years ago, a new phenomenon called SHIBIEC (Swift Heavy Ion Induced Epitaxial Crystallization) was discovered to occur in some solids irradiated with swift ions [1]. Very recently, SNEEL (Synergy between Nuclear S_n and Electronic S_e Energy Losses) effects were put forward in SiC and MgO irradiated with a dual ion beam [2].

SHIBIEC does not occur il all solids. It was mainly observed in materials that are weakly damaged by S_e. SHIBIEC occurs at RT (or above) for $S_e > S_e^{threshold}$ depending on the investigated material. SHIBIEC leads to a strong healing of defects only in materials that are not totally amorphous.

In this latter case, SHIBIEC leads to a decrease of the thickness of the amorphous layer. Molecular dynamics simulations showed that swift ion irradiation induces recovery of radiation damage via a thermal spike phenomenon.

Electronic excitation at a-c interfaces act as seeds for recrystallization.

SNEEL does not occur in all solids. It was mainly observed in materials that are weakly damaged by S_e. SNEEL occurs at RT (or above) for $S_e > S_e^{threshold}$ depending on the investigated material.

SNEEL leads to a strong healing of defects even in materials which are totally amorphized by S_n.

SHIBIEC and SNEEL present a crucial interest for fundamental studies dealing with ion-solid interactions. More work is required to understand underlying processes.

Also, SHIBIEC and SNEEL present a crucial interest industrial applications where synergistic S_n/S_e effects may lead to a strong reduction of the damage production in materials submitted to severe irradiations (i.e. nuclear devices).

Due to the early interest for the development of the ion implantation doping process in Si previous studies were mainly focused on the irradiation with ions having energies in the range of a few hundreds of keV to a few MeV, i.e., in a slowing down regime where the nuclear energy loss is dominant. These investigations showed that Si is quite easily damaged at or below room temperature RT with all ions and that, depending on the ion fluence, the resulting damage takes the form of partial or total amorphization of the bombarded layer. Since this disorder is detrimental to device performance, many attempts were made to recover the original crystallinity. One of the important methods is the solid phase epitaxy (SPE) technique, which is based on the recrystallization of the implantation-induced amorphous layer by epitaxial growth from the crystalline substrate achieved by heating the material at temperatures as high as 1450 °C. Another method is based on the ion-beam induced epitaxial crystallization (IBIEC) process, where the amorphous layer is further bombarded with ion species having energies such that their ion projected range is quite deeper than that of the preimplanted ions but with a slowing down still dominated by nuclear collisions. In contrast to the huge effort performed in the field of ion implantation and irradiation at low energy, very few studies were devoted to the effects of ion bombardment of silicon at higher energies, i.e., in a slowing down regime essentially due to electronic excitations and ionizations, despite the fact that the latter are well known to induce various types of atomic rearrangements in solids. In view of all these effects and also for the potential use of Si in hostile environments it was quite crucial to investigate the behavior of this material under ion irradiation at different energies in order to examine the role of the nuclear collisions and that of the electronic excitations and also to study the possible interference between these two phenomena. For this purpose, Si will be irradiated separately with low energy ions and high energy ions and also successively with both ions.

Energetic ions induce damage in the silicon and at higher fluences, a phase transformation from crystalline Si (c-Si) to amorphous Si (a-Si) can occur. Damage induced by ion irradiation in Si depends on fluence flux, energy of the ion, mass of the ion, target temperature,
tilt angle of the target, etc.. Understanding the amorphization process is still an active area of research and various mechanisms have been put forward. A few decades ago, Morehead and Crowder proposed that the amporphization initially occurs in the cylindrical region around each ion path [3] and a continuous amorphization can be explained assuming that there will be sufficient overlap of the amorphized cylindrical cascades and this mechanism was known as heterogeneous amorphization. Swanson et al.[4] and Holland et al.[5] introduced a homogeneous model according to which amorphization was a phase transition induced by an accumulation of sufficient number of defects in crystalline silicon [9].

Previous studies using MeV Au ion implantation in silicon dealt with determination of range, straggling and lateral spread of Au ions as a function of energy, incident angle and temperature [7–9].The values of measured projected range (Rp) and the straggling of MeV Au ions in silicon were found to be consistently larger than the values predicted by TRIM [10] for both the low current implantation (0.02–0.04 μAcm^{-2}) [8] and high current implantation (0.5–2.0 μAcm^{-2}) [11]. In the present work, we intend to study of amorphization caused by 1.345 MeV Au^{2+} ion implantation in Si(1 00) single crystals at various fluences between 10^{13} at/cm^2 and 10^{15} at/cm^2 and at low currents while the substrate will be kept at room temperature. Low current implantation was chosen to avoid dynamic annealing of damage. The fluences will be measured by RBS. The values of the projected range (Rp) and the straggling of MeV Au ions in silicon will be also measured. For such a low energy damage is mainly attributed to energy transfer to the atomic structure, which result in target atoms directly displaced from their lattice sites and defects being produced via atomic collision cascades. The amorphization induced by implantation will be studied using Rutherford backscattering spectroscopy in channeling geometry (RBS/C).

Ion channeling technique is a well-established modern tool for determination structural properties (e.g. structural defects) of few-micrometer surface layers in crystalline materials. Experimental results obtained with this technique are usually in the form of backscattering spectra and angular scans. Interpretation of such data is usually not straightforward. In defect analysis the major drawback of the channeling technique is the difficulty in extracting quantitative information from backscattering/ channeling spectra. As long as the main research interest was focused on monoelemental single crystals the simplified channelling data analysis based on the two-beam approximation [12] was usually considered to be sufficiently accurate.

The new challenge for the technique emerged with growing technological importance of compound crystals and heterostructures grown using contemporary epitaxial techniques. In these cases the simple methods cannot be applied because of the complicated relations of the physical processes involved in channeling in multielemental crystals. Here Monte Carlo computer simulations seem to be indispensable.

During a particle–solid interaction, two distinct energy transfer processes occur: atomic collision cascades and electronic excitation on the atomic and electronic structures, respectively. In a defective structure, which is normally the case in many applications, the effects of ionization due to electronic energy loss are largely unknown. Ionization effects due to the energy loss to target electrons can anneal pre-existing defects, and therefore may effectively modify or alter microstructure evolution.

Previous investigations indicated that ionization effects due to the energy loss to target electrons can anneal pre-existing defects, and therefore may effectively modify or alter microstructure evolution.

In order to check the occurrence of such a phenomenon, we will select some Si crystals irradiated with 1.345 MeV Au^{2+} ions at various fluences between 10^{13} at/cm^2 and 10^{15} at/cm^2 , and we will irradiate these samples with 21 MeV Co ions at fluences between 10^{13} at/cm^2 si 10^{15} at/cm^2.
Previous studies [1,2] have demonstrated that swift heavy ion irradiation with electronic energy deposition ranging from 10 to 33 keV/nm leads to some damage annealing.
We already started by implanting 1.345 MeV Au^{2+} ions into silicon (100) single crystals.
The implantation was performed at room temperature at the ion-implantation beam line at the 3.0 MV Tandetron Cockcroft-Walton accelerator of IFIN-HH. The implantation beam line has a raster scanner to scan the beam on the sample for providing uniform implantation over a predefined area.The implantation was performed at an angle of 7^0 between the sample surface normal and the incident ion beam in an attempt to minimize channeling effects during the implantation. The predefined fluence on

the samples was 10^{15} ions/ cm^{-2}. The RBS and RBS/C measurements were carried out using the above mentioned accelerator facility with 2.0 MeV He^{2+} ions. The results are presented in Figs.1,2.
The implanted fluence was measured by RBS and a result of $1.25x10^{15}$ at/cm^2 was obtained. Disorder depth profile extracted from RBS/C spectrum is displayed in Fig. 2. Complete amorphization is observed, since the disorder fraction reaches the random level (i.e., $f_D = 1$) over a thickness of approximately 400 nm.
In a preliminary measurement, we irradiated with 10 MeV Co^{3+} ions at a fluence of $3x10^{14}$ at/cm^2 Si crystals previously implanted with 1.345 MeV Au^{1+} ions at various fluences between 10^{13} and 10^{15} at/cm^2. The Au and Co implanted samples were investigated by Rutherford backscattering spectrometry in channeling geometry; the damage profiles were extracted using the two-beam approximation. An RBS/C spectrum recorded after 10 MeV Co ion irradiation do not exhibit any significant damage. Two RBS/C spectra recorded after Co irradiation are shown in Fig.3. The corresponding disorder profiles are displayed in Fig.4. One obtaines a significant reduction of the amplitude of the damaged region for the sample implanted with Au at a fluence of $1x10^{13}$ at/cm^2 revealig a clear recrystallization effect. For the sample implanted with Au at a fluence of $3x10^{13}$ at/cm^2 one obtaines a significant reduction of the damaged region. The samples are further investigated by X-ray diffraction (XRD) and transmission electron microscopy (TEM).

Beam request: 14 days (42 shifts) at the 3 MV Tandetron accelerator.

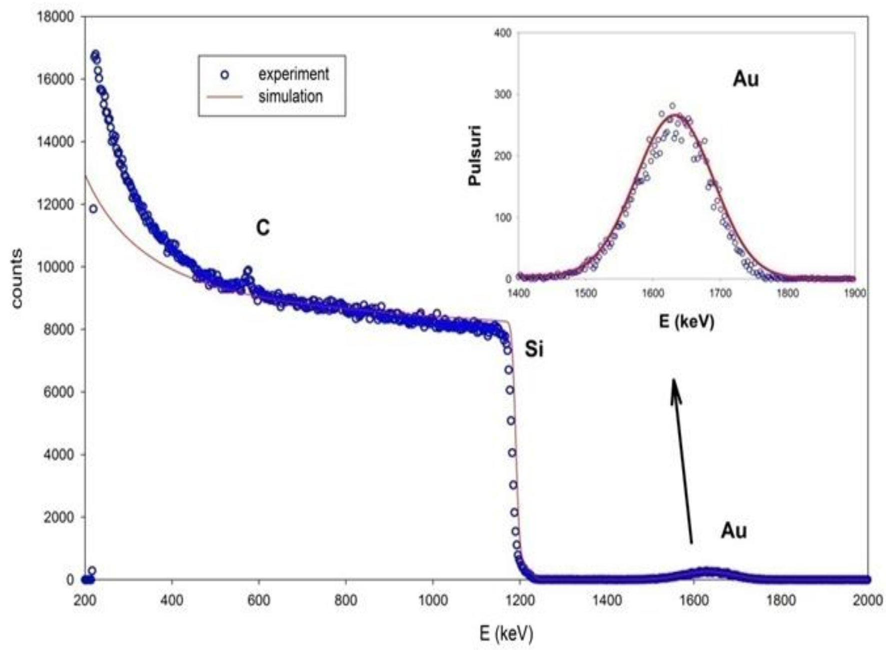

Fig. 1: *2 MeV $^4He^{++}$ for 1.345 MeV Au-implanted Si (100) for Au -implanted specimens at $1.25x10^{15}$ at/cm^2 , collected charge was 264 μC , with the detector at 165^0 and 145^0*

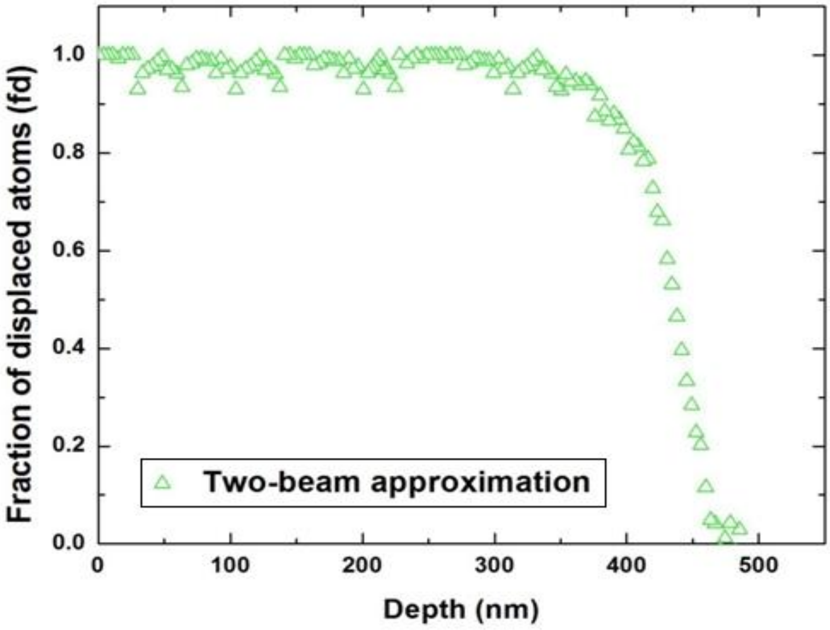

Fig. 2: *Depth distributions of the damage accumulated in a Si crystal, implanted at RT with 1.345 MeV Au ions at a fluence of 1.25x10^{15} at/cm^2, extracted from the analysis of RBS/C spectra, using the TBA procedure*

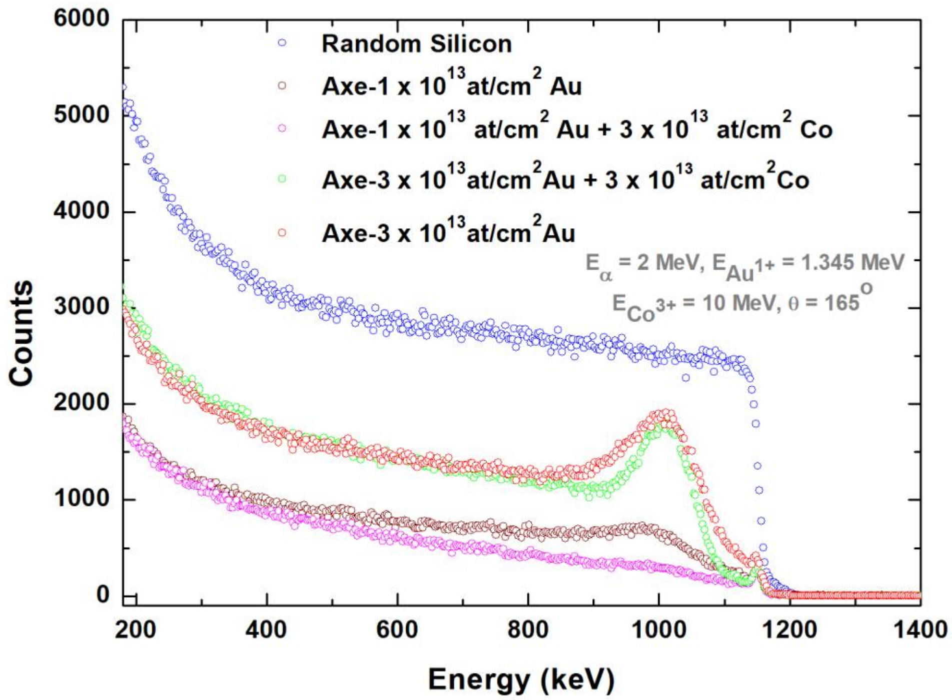

Fig. 3: *RBS spectra recorded in random and channeling orientations on Si crystals, implanted with 1.345 MeV Au^{1+} ions, then irradiated with 10 MeV Co^{3+} ions*

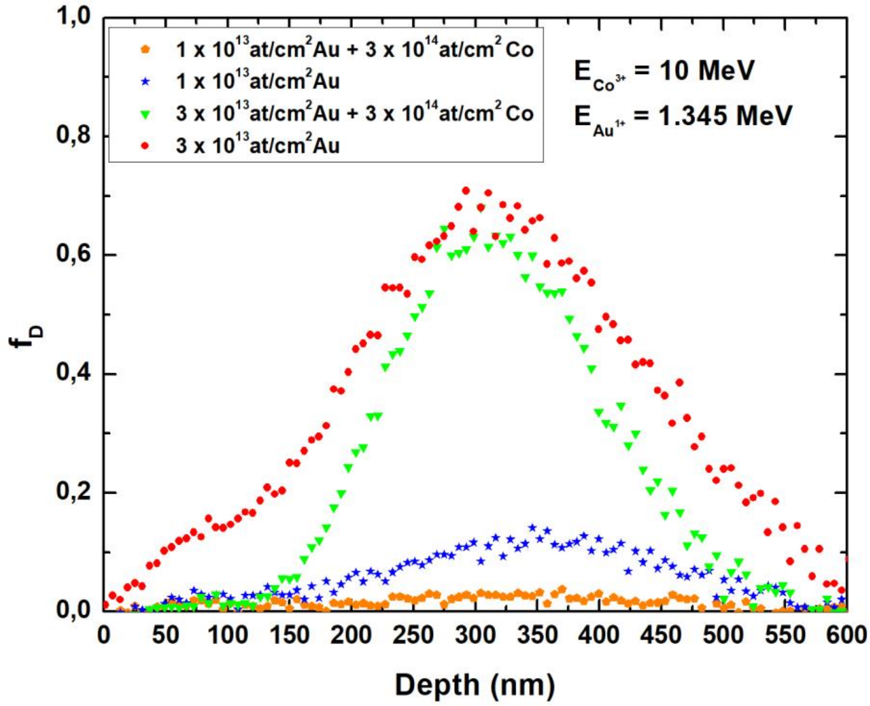

Fig. 4: *Damage profiles in the Si crystals, implanted at RT with 1.345 MeV Au^{1+} ions and with 10 MeV Co^{3+} ions*

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