Defects, irradiation and induced properties

Jean-François BARBOT, Marie-France BEAUFORT, Alain DECLEMY, Maxime VALLET (PhD student)

Former PhDs: Cyril DUPEYRAT, Stéphanie LECLERC, Amy GANDY (UK), Shay REBOH (Br)

Collaborations
Steve E. DONNELLY, Huddersfield University, UK
Paulo F. P. FICHTNER, UFRGS, Porto Alegre, Brasil
Thomas KUPS, Ilmenau University, Germany

CONTEXT

Ion implantation is a key tool for modifying the microstructure of material by introducing defects leading to significant change of its physical properties. In microelectronics industry, ion implantation is the standard method to control the electrical properties by embedding dopants into semiconductors. Defects can also agglomerate that plays a crucial role in the Smart Cut process used to produce thin semiconductor layer transfer (defect engineering). A more recent use of ion implantation lies in the elaboration of diluted magnetic semiconductor (DMS) for spintronics applications. However, if ion implantation is used to tailor the physical properties of semiconductors to achieve specific characteristics, it damages the crystal structure which has to be restored. Then, understanding the damage build up, its recovery and the as-created defects are necessary to improve the performances of the material.

Finally, ion implantation is also used to emulate the damage resulting from neutron irradiation allowing predicting the material behaviour under severe working conditions such as in space environment or in nuclear industry.

Our group is involved since several years in the study of the ion implantation induced damage into semiconductors in a wide range of fluence from point defects up to amorphisation. The strain, the defects evolution up to extended defects (bubbles, cavities, dislocations, stacking faults) and the effect (interaction, organization) on the physical properties (macroscopic behaviour) are investigated. Experimental techniques such as AFM, XRD, TEM, in–situ TEM, Nanoindentation, etc. are carried out in order to characterize the microstructural changes and the physical (mechanical, etc.) properties. In the following are reported the main results obtained after light ion implantation (He, H) into silicon and silicon carbide. Recent results on the microstructural change induced by Fe implantation into SiC are also presented.

HELIUM IMPLANTATION INTO SIC

- Effects of He implantation into SiC [2], [5], [10]
Collaboration : M. Texier, IM2NP, Faculté des Sciences et Techniques, Marseille

Helium implantation-induced surface swelling of 4H-SiC is a well know phenomenon. The swelling is the sum of different contributions (amorphization, void/bubble and the elastic strain) and its evolution drastically depends on the implantation conditions. The scattered intensity (figure 1) is characteristic of a dilatation gradient of the lattice along the surface
normal direction. Upon annealing, the near surface strain progressively relaxes (elastic relaxation) while the maximum strain relaxation stops at a temperature where helium ions agglomerate into platelets. Then platelets evolve into bubble clusters and expel dislocation loops along the strain gradient (plastic relaxation).

At elevated implanted temperatures, two stages of damage production were observed. At high fluence, the dynamic annealing taking place in the near surface region is concomitant with the formation of a thin and deep highly strained region resulting from the accumulation of interstitial atoms. After high temperature annealing the growth of cavities is concomitant with the formation of a high density of stacking faults (figure 2).

Figure 1: X-ray diffraction curves close to the (0004) Bragg reflexion in 4H-SiC implanted at 160keV – RT with helium ions at $1 \times 10^{16}$ cm$^{-2}$ and then annealed at temperature up to 1500°C.

Figure 2: a) TEM image of the microstructure after He implanted 4H-SiC at HT and high fluence showing the damaged layer. b) HRTEM image showing the stacking faults. c) SAED pattern taken at the deep interface.

- **Effects of He implantation on the mechanical properties of 4H-SiC (Matinex prog.) [7]**
  **Collaboration:** C. Tromas, V. Audurier, Institut P'.
  The evolution of mechanical properties of helium-implanted 4H-SiC is studied by nanoindentation tests. The results are analysed in relation with the evolution of the microstructure (mainly determined by XRD and TEM).

- **In-situ TEM investigation of helium bubble evolution in 4H-SiC [12]**
  **Collaboration:** S.E. Donnelly et al., University of Huddersfield. E. Oliviero, CSNSM, Orsay, France. P. Gadaud, Institut P'.
  We use the capabilities of two in-situ TEM ion-irradiation facilities – MIAMI at the University of Huddersfield and JANNuS at Orsay, Paris (**EMIR program**) to understand the bubble/cavities formation under irradiated. Mobility of interstitials is also studied through internal friction.

**DEFECT ENGINEERING IN H AND HE IMPLANTED SILICON (Capes-Cofecub program)**
**Collaboration:** P.F.P. Fichtner, UFRGS, Porto Alegre, Brasil. S. Reboh, CEA-LETI, Grenoble, France. J. Grilhé, Institut P'.
**H-induced subcritical crack propagation and interaction phenomena in [001] Si using He-cracks templates [4] [6]**

H and He ion co-implantation allows the formation of nanocracks within controlled subsurface depths in semiconducting materials. Starting from overpressurized He-cracks, subcritical propagation was activated by diffusional H. Nanocrack interaction can occur by elastic forces, causing tip folding, or by plastic deformation forming extended defects. These observations are discussed and modeled using elasticity and fracture mechanics.

**Orientation of H platelets under local stress in Si [1]**

The orientation of H-platelets is strongly dependent on stress. The stress is induced by the implantation of H (in-plane stress) but can also be previously introduced by local perturbation inside the substrate. Recently, we showed that within specific \{111\} or \{001\} variants determined through the local symmetry of the strain (figure 3). The behavior is understood in terms of elastic interactions and is described via energy minimization calculations, predicting the formation and distribution of each platelet orientation variant. Sub-local organized arrangements of precipitates can be obtained within nanosize domains using local strain fields.

![Figure 3: a) BF TEM image taken after He-plate formation, followed by H2 implantation and annealed at 300 °C. A specific arrangement of \{111\} H platelets is observed with respect to the strain field symmetry axis [001] induced by the He-plate. b) 3D pictograph of the nanostructure](image)

**TRANSITION METAL-IMPLANTED SiC AS A POTENTIAL DILUTED MAGNETIC SEMICONDUCTOR (DMS) [8], [9]**

Collaboration: L. Thomé and A. Debelle, CSNSM-Orsay, France. T. Kups, Ilmenau University, Germany

With the aim of synthesizing so-called DMS, 6H-SiC samples were implanted at elevated temperature with low-energy Fe ions. XRD RBS/C and ALCHEMI are used to study the microstructural changes under annealing up to 1300°C. A different behaviour of Fe atoms and implantation depending on the post-implantation treatment is observed: As-implanted samples exhibit a strong substitution of Fe atoms at the Si-sites (50-100%) and thermal annealing induces strong strain relaxation, damage recovery and substitution rate falling down. Thermal annealing at 900-1100°C induces formation of Fe3Si-like nanoclusters leading...
to a critical temperature $T_c$ up to 500°C while annealing at 1300°C induces a noticeable Fe atom release up to 20% of implanted Fe atoms.

**Current developments**
- He and H co-implantation in Si
- *In-situ* TEM investigation of helium bubble evolution in SiC
- Defects induced by He implantation into $\text{Ti}_3\text{SiC}_2$ MAX phase grown on SiC
- N and transition metals co-implantation in 6H-SiC

**Recent publications**