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Defects studies in high-energy ion implanted semiconductors

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1 Introduction

Defects in semiconductors (impurities and lattice defects) have been extensively investigated in the past 3-4 decades by various experimental techniques. There are at least three reasons why these studies should be continued. First and foremost the physics of defects has been found to be very rich and has increased considerably our understanding of real, imperfect crystals as opposed to ideal, perfect crystals. Secondly, the profound understanding of the physics of some defects in silicon has led to improvements and novel developments of technological processes, e.g. today the terminology "defect engineering" is used for a controlled utilization of defects in material synthesis. Thirdly, compared to the best-studied material, silicon, our knowledge regarding defects in other semiconductors is rather limited.

In the following we restrict the discussion of the major advances in defect investigations, which we envisage for the proposed post-accelerator of the PS-Booster-ISOLDE facility, to silicon since also for this well-studied material we expect novel, rewarding experimental possibilities. We intend to study Si, Ge and SiGe grown by MBE while other compound semiconductors will be studied with similar techniques by other ISOLDE solid state groups.

2 The study of defects

The basic characterization of defects in semiconductors involves the knowledge of their geometrical structure, electronic configuration, electrical activity related to band-gap states and dynamical properties which characterize mutual defect interactions and interactions with the lattice. We concentrate here on the obvious improvements offered by a high energy (1-10 MeV) radioactive ion-beam. Such a beam can provide samples for extended studies by means of presently well established techniques, such as Mossbauer Spectroscopy (MS), Deep Level Transient Spectroscopy (DLTS) and possibly Electron Paramagnetic Resonance (EPR).

Mossbauer spectroscopy on radioactive probe atoms, which decay to a Mossbauer isotope provides atomic scale informations on the defect structure, electronic configuration and dynamics. MS also enables studies of defect-defect interactions. DLTS allows to characterize the electronic gap states as well as the dynamics of the responsible defect. As stated below, the availability of a high energy radioactive ion beam is of fundamental importance for the successfull use of the DLTS using radioactive impurities (DLTS-RI) technique. EPR can address informations about the defect local structure, its dynamical properties, its interaction with other defects and with the lattice. MS and DLTS are highly sensitive, i.e. the concentration limits are 10^{12}-10^{14} cm^{-3} in the implanted volume equivalent to a total number of 10^{8}-10^{10} implanted radioactive ions. The sensitivity in standard EPR measurements depends on the particular defect, typical values for the minimum number of detectable spins are 10^{11}-10^{12}.

3 DLTS-RI

The DLTS provides informations about the activation energy, the capture cross section and the concentration of deep-level defects in semiconductors. These informations, together with the complementary informations provided by the other spectroscopic techniques MS and EPR, represent a complete characterization of the basic defect properties. However the DLTS technique is "chemically blind" therefore the correlation with MS and EPR results could be ambiguous. The use of radioactive isotopes combined with DLTS measurements [1, 2] overcomes this problem and allows, besides the standard DLTS parameters, the determination of the chemical nature of the signal through its decay. This results in an easier and unique correlation to other results. The use of DLTS-RI will allow also to study the influence of the recoil energy on the configuration of the daughter defect. Recently, the first recoil-produced Frenkel pair in a semiconductor has been observed by ^{119}Sn MS in InSb [1]

So far DLTS-RI has been performed on radioactive isotopes introduced by implantation and subsequent in-diffusion. The ISOLDE facility has been used [2, 3] to create the starting region for the diffusion of the radioactive isotopes upon annealing at high temperatures. This method represents an important improvement compared to diffusion from radioactive thin films deposited on Si for example, because it overcomes diffusion barrier effect of the surface and because the high specific activity and purity allow studies of elements with low solubility. It works well for fast diffusors. However, this approach is limited by the fact that the depth control is very poor. Furthermore several post-implantation steps are required preventing the use of radioisotopes with half-life shorter than one day. The availability in the future of high energy beams (> 1 MeV) will allow to work on prefabricated diodes. The radioactive impurities will be implanted directly into the depletion layers of the diodes which, after annealing at 800-900 °C, keep their electrical characteristics. This technique is fully established for a number of stable isotopes in our laboratories in Aarhus. In summary:

1. The use of prefabricated diodes and the small number of post-implantation steps will allow the use of relatively fast decaying nuclei.
2. High energy allows layer implantation resulting in lower concentration for the same minimum number of implanted isotopes.
3. An almost monoenergetic source will produce a well defined implanted profile allowing diffusion studies.
4. Complications due to the surface will be avoided with the use of high energy implantation.
5. Dual implantation will allow the study of defect interaction and particular complexes.

As a specific example which demands the post-accelerator facility ($\sim 3 - 4 MeV$) we propose to study the Sn-vacancy complexes which are formed either in the decay of the Sb-vacancy (E-center) or directly in Sn doped samples. In both cases electron-irradiation is used to create vacancies. EPR studies [4, 5] have shown that the local symmetry of the two defects is different. Sb and Sn related DLTS signals have been identified [6], however, particularly for the case of Sn, a unique correlation between the chemical nature of the defect and gap levels has not been established. DLTS-RI will provide this identification and MS informations on possibly different defect configurations [7].

4 Technical remarks

With respect to the technical installation of the post accelerator we have the following remarks. A location of the EBIS source as the first piece of equipment, upstream the present HV platform would be appreciated as an energy of 1 MeV could be obtained directly with say 4^+ ions and the platform operated at 250 kV. Also, when the RFQ is installed, a short beamline for implantations on-line Mossbauer spectroscopy and DLTS should be foreseen since we expect to obtain the necessary energies (1-10 MeV) to be reached with the RFQ only.

5 Conclusions

We conclude that the application of high energy ion beams will provide substantial widening of the radioisotope techniques presently available in the study of semiconductor defects. In particular the combination of different spectroscopic techniques, such as MS, DLTS-RI and EPR will provide novel informations on static (morphological, electrical) and dynamical properties.

6 References

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