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LETTER OF INTENT TO THE ISOLDE COMMITTEE

Energetic Radioactive Ion Beam Studies of Hydrogen in Semiconductors

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Introduction

The considerable potential of radioactive isotopes in solid state physics was gradually explored during the last 70 years, after the first radiotracer diffusion experiments have been performed in 1920 [1]. Since these early days, quite a number of "radioactive" solid state physics techniques have been developed, which can be roughly divided into two groups, the well established "nuclear" and the very recently introduced electrical and optical "tracer" techniques. The nuclear techniques like e.g. Emission Channeling (EC) [2], Mössbauer (MS) [3,] or Perturbed Angular Correlation (PAC) Spectroscopy [4] crucially depend on the availability of radioactive isotopes with specific decay properties. These radioactive nuclei are used as probes of their structural or electronic environment in metals or semiconductors, on surfaces and in interfaces. The new "tracer" techniques use radioactive isotopes combined with electrical or optical standard techniques in semiconductor physics like Hall effect (HE) [5], Deep Level Transient Spectroscopy (DLTS) [6,7,8], Capacitance Voltage measurements (CV) [9] or Photoluminescence (PL) Spectroscopy [10, 11] to overcome the chemical "blindness" of the non-radioactive versions. If the radioactive decay causes a chemical transmutation of the impurity the electrical and optical properties of the semiconductor generally change in time with the characteristic time constant of the radioactive decay.

The on-line isotope separator ISOLDE already has a strong impact on the progress of "radioactive" solid state physics. The combination of producing a great variety of isotopically and chemically clean radioactive ion beams of rather high intensities and the possibility to implant the isotopes on-line has attracted a continuously increasing number of materials research projects, particular in the field of semiconductor physics. The installation of a post-accelerator for energetic ion beams at ISOLDE would continue this development by opening up a new generation of "radioactive" solid state physics experiments at ISOLDE, simply due to the advantage of deeper implantations.

In this "Letter of Intent" we propose to investigate the topic "Hydrogen in Semiconductors" with energetic radioactive ion beams. Although we are restricting ourselves to one specific subject, nearly all our statements concerning the advantages of higher implantation energies can be used in general and immediately transferred to other future applications of radioactive ions in solid state physics.

Motivation

The behaviour of hydrogen is one of the most interesting subjects in semiconductors, regarding the scientific as well as the technical point of view. Due to the complex properties of H - there exist at least four different states: H^+, H^-, neutral H^0 and H_2 - not all relevant parameters are yet known for Si and for binary or ternary III-V and II-VI compounds even less information is available [12]. Triggered by the importance of the topic, in the late 80s the first angular correlation (PAC) experiments have been performed at ISOLDE to study H in binary III-V compounds[13] and during the last few years a very comprehensive study on acceptor passivation in III-V compounds could be performed [14,15]. Concerning the microscopic information on the H-passivation mechanism, our results have proven, that PAC can step into the breach, caused by the failure of two of the most powerful microscopic techniques in semiconductors physics, Electron Paramagnetic Resonance (EPR) and Electron Nuclear Double Resonance (ENDOR).

Although our experiments on hydrogen in semiconductors have been very successful until now, the availability of post-accelerated ion beams (up to some MeV in total) would allow us to improve the experimental conditions in an unique way by:

1) Preventing surface problems and enabling experiments inside a diode structure

Due to the present ISOLDE energy of 60 keV the probe atoms are localized some tens of nanometers below the surface after implantation. The close vicinity of the surface to the implanted region, however, can cause severe problems. Defects, produced on the surface, in particular after plasma charging can influence the experimental results in an uncontrolled way. Furthermore, in most cases the implanted probe atoms are localized within the surface depletion region, a fact which hampers experiments in a Schottky diode. Higher implantation energies would be necessary to localize the radioactive isotopes deeper in the bulk, i.e. outside the surface space charge region. The implanted region will than become sensitive to the influence of a Schottky diode and metastable dopant hydrogen complexes could be observed under different Schottky biases. Reversed bias annealing experiments will become feasible, yielding dissociation energies of the H complexes which are not modified by retrapping mechanisms.

2) Monitoring the H depth profile

The H concentration inside a semiconductor is not at all homogenous (see fig.1). Close to the surface the H concentration reaches ~ 10^{19} cm^{-3}. With increasing depth the concentration decreases by some orders of magnitude. The total depth is typically some µm, depending on the background doping. In our present results the PAC probe atoms are localized close to the surface, in the H rich region. Therefore all our results, obtained until now, monitor the first tens of nanometers of the hydrogen profile. Implantation energies up to 10 MeV would allow us to investigate the H passivation mechanism layer by layer and to scan over the whole H profile.

3) Enabling the comparison of PAC with other techniques (DLTS, CV, IR)

Under the present ISOLDE conditions PAC can only be used for investigating the near surface region. On the other hand, electrical techniques like DLTS or CV are suited for bulk investigations and are not sensitive to the surface region. Therefore a direct comparison between microscopic (PAC) and electrical (DLTS, CV) results is very hard. The same holds for comparing results of PAC and infrared measurements (IR). Energies in the order of some MeV would solve this problem by allowing to implant the PAC probe atoms into the DLTS or CV sensitive region or by producing homogeneously doped samples which can be investigated by PAC and IR. Finally, the direct comparison between the results of microscopic and macroscopic techniques would become feasible and the conclusions drawn from these different technical approaches would be reinforced.

4) Increasing the sensitivity

For the Perturbed Angular Correlation in total only 10^{11} to 10^{12} probe atoms are necessary to perform one experiment. Distributed over one cm^{-3}, this corresponds to a sensitivity of 10^{11} to 10^{12} cm^{-3}. In the present experiments, the local probe atom concentration within the implantation profile is in the order of 10^{17} - 10^{18} cm^{-3} and an unnecessary loss of sensitivity is the consequence. By varying the implantation energy between some hundred keV and some MeV however, overlapping implantation profiles could be produced and the resulting local probe atom concentration would be in the order of 10^{15} - 10^{16} cm^{-3}. The increase of sensitivity would reveal H complexes, which are not PAC- or MS- detectable at ISOLDE until now. The possibility to vary the local probe atom concentration between 10^{15} and 10^{19} will permit the study of the Fermi level influence on the H passivation mechanism over a wide range and the observation of metastable H dopant complexes should become possible.

5) Improving tracer techniques

As already mentioned, electrical measurements like DLTS or CV do not work close to the surface. On the other hand, it would be very interesting to use radioactive isotopes, to study the different dopant H complexes and to identify them via the radioactive decay constant. Presently these techniques require a high dose of radioactive isotopes, because a subsequent diffusion step is necessary to force the radioactive impurities into the bulk. This diffusion step itself can cause problems, if the impurities prefer to precipitate or diffuse towards the surface. These problems can be avoided by higher energies, which allow the direct implantation of the isotopes into the DLTS or CV sensitive region.

Conclusion

The installation of a post-accelerator for radioactive isotopes will remarkably enlarge the potential of radioactive isotopes in semiconductor physics. The advantages of higher energies, demonstrated in this "Letter of Intent" on H studies in semiconductors are obvious and can be immediately transferred to similar problems in solid state physics.

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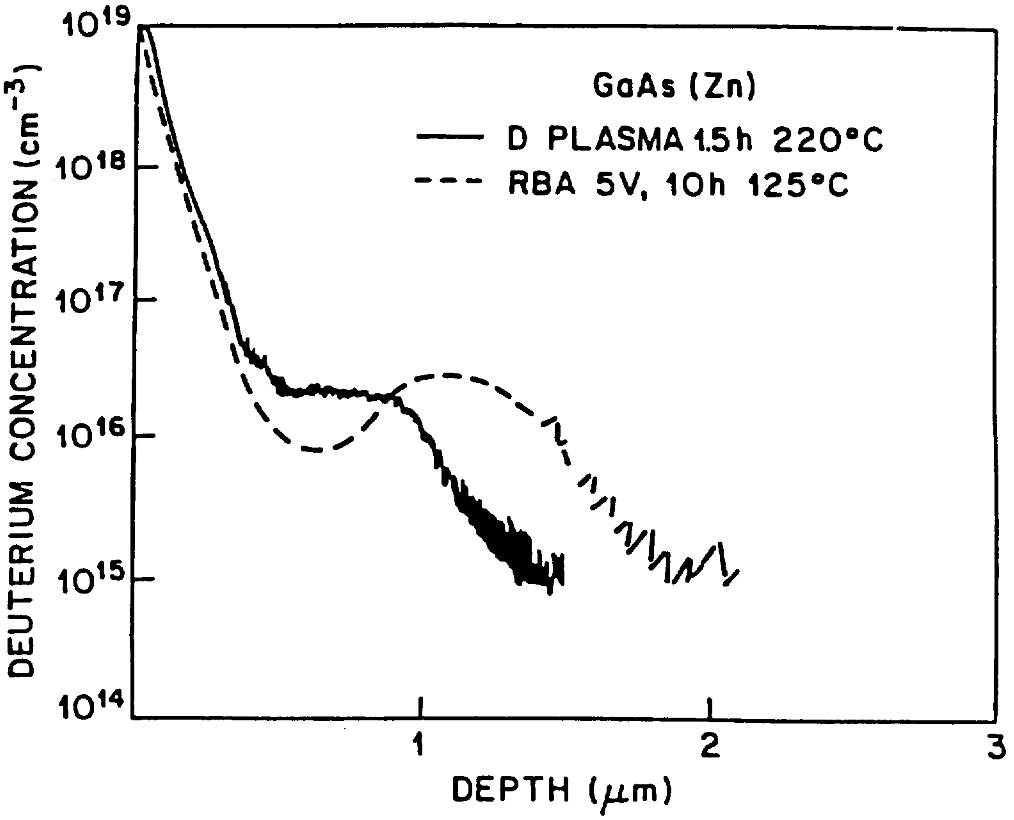

Fig. 1. SIMS profiles of deuterium in p-type GaAs exposed to a D_2 plasma for 1.5 h at 220°C, and reverse bias annealing (V_R = 5 V) for 10 h at 125°C (see ref. [16])