APPLICATION OF ION CHANNELING TO RADIATION DAMAGE STUDIES*

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ABSTRACT

A brief summary of the ion channeling technique is presented as it applies to the study of radiation damage. Primary emphasis is given to recent advances which allow quantitative depth profiling studies of intrinsic defects in metals.

I. INTRODUCTION

Ion channeling has been used to study implantation damage in semiconductors, metals and insulators, and also to study impurities in association with the defects.¹⁻⁶ During ion channeling energetic particles undergo correlated collisions with the atomic rows or planes in a single crystal. This results in a spatial redistribution so that there is a large reduction in the particle probability density near the rows or planes and an increase near the channel center. Thus close encounter events, such as ion back-scattering, are reduced approximately 1 to 2 orders of magnitude for channeled particles with lattice atoms in perfect lattice sites², whereas there is a much higher interaction probability with displaced atoms.

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In this summary we primarily discuss those aspects of the technique which relate to the usefulness of channeling for high temperature radiation damage studies in metals. The majority of ion channeling studies have been applied to implantation damage in semiconductors. In contrast, little quantitative work on implantation or other radiation damage studies in metals ^{has} ~~have~~ been carried out, although recent progress in the understanding of ion channeling now allows such studies to be performed.

II. ION CHANNELING ANALYSIS

Ion channeling is primarily sensitive to individually displaced atoms, such as interstitials, or to perturbations in the atomic rows or planes, such as may occur around dislocations or at voids in a crystal. The direct scattering of channeled particles by displaced atoms and the dechanneling of particles into random directions are monitored by ion backscattering. By energy analysis of the backscattered particles the depth of the interaction in the crystal can be determined. The channeling signal can be considered to consist of two components: (1) the direct scattering and; (2) the dechanneled component. For implantation damage in metals the direct scattering component is to first order negligibly small under many conditions and the dechanneled signal at a given depth z is approximately given by²⁻⁴

$$\chi_D(z) \approx \chi_V(z) + [1 - \chi_V(z)] \left\{ 1 - \exp[-\sigma \int_0^z n(z') dz'] \right\}, \quad (1)$$

where χ_D is the dechanneling in the damaged crystal, χ_V is the dechanneling signal in a virgin crystal (in both cases normalized by the random scattering fraction at that depth), σ the cross section for dechanneling by the defects and n the density of defects. Thus under these assumptions the density of defects at a given depth z is given by

$$n(z) = \frac{\partial}{\partial z} \left\{ \frac{1}{\sigma} \ln \left[\frac{1 - \chi_V(z)}{1 - \chi_D(z)} \right] \right\}, \quad (2)$$

where the channeling parameter in brackets in Eq. 2 can be easily measured from the damaged and virgin crystals.

The physics of the process is contained within the cross section, σ , which may be calculated or, alternatively, measured provided the total density of defects is known in a given calibration sample. If a variety of defects of different σ result in comparable dechanneling signals simultaneously, then the channeling analysis will only give a qualitative indicator of the total damage present. However, if the radiation damage condition, together with the choice of channeling parameters, is such that a single type of defect dominates the dechanneling and the above analysis applies, then quantitative studies of the damage density with depth resolutions $\sim 100 \text{ \AA}$ can be carried out. In such studies it is always valuable to perform selected transmission electron microscopy (TEM) analyses on the samples to provide information on the larger defects present and to give further self-consistency to the interpretation of the channeling results.

III. APPLICATION OF ION CHANNELING

The dechanneling cross section σ depends on the nature of the defect and can exhibit quite different functional dependences on channeling parameters such as the energy of the incident beam for different types of defects.²⁻⁵ For example, the dechanneling for dislocation lines increases as the square root of energy, for stacking faults or voids is approximately independent of energy and for randomly distributed point defects such as interstitials decreases linearly with energy. Also, for the case where interstitial-like defects dominate, the direct scattering component becomes large and a different analysis may be applied; this is more frequently the case for semiconductors.¹ Thus, in addition to qualitative checks by transmission electron microscopy, measurements of the dechanneling at a given depth as a function of energy, for example, provide for a self-consistent check on the interpretation of the results. Also, by combining channeling measurements with TEM measurements for cases where independent determination of the density of defects can be made, the cross sections for such defects as dislocations have been measured and have been shown to give good agreement with simple theoretical estimates.³

Given preliminary measurements to sufficiently characterize the system and determine the applicability of the above analysis, then Eq. 2 can be used to obtain the depth profile of the disorder. High concentrations of disorder are required, for example, $\sim 10^9$ - 10^{10} dislocation/cm², and good depth resolutions, ~ 100 Å.

can be obtained. In this way the technique is highly complementary to transmission electron microscopy, where a survey of the nature of the defects can be readily obtained, but it is quite tedious to obtain quantitative depth information in general and, for the densities of defects which can be measured by channeling, is nearly impossible due to overlapping strain contrast.

As an example of the application of the technique we consider heavy ion implantation damage in Al.² By TEM one can show that a dense network of dislocations are formed by implantation to relatively high fluences (10^{15} - $10^{17}/\text{cm}^2$), and from the energy dependence of the dechanneling consistency is found for dechanneling dominated by strain-like regions, as occur for dislocations. Figure 1 shows the channeling-ion backscattering spectra, both for a major axial and a major planar direction in Al. Implantation conditions correspond to a fluence of $7 \times 10^{15}/\text{cm}^2$ 150 keV Ni ions at room temperature.

Figure 2 shows results of analysis of the Al spectra by Eq. 2 to obtain the depth distribution of the density of disorder. Also shown is the Ni profile obtained from the ion backscattering measurements. Planar channeling analysis is found to be quite useful here, although it is only recently that it has been applied to such studies. The depth distribution of the disorder relative to that of the implanted ions is quite similar to that predicted theoretically for the depth distribution of the primary damage energy production by the implanted ions. Also there is an

indication of a somewhat lower density of defects near the surface, probably due to the competition of the surface as a sink for the primary defects which are produced.

IV. SUMMARY OF TECHNIQUE ADVANTAGES AND LIMITATIONS

The channeling technique is particularly useful for studies of high densities of defects where complementary techniques such as transmission electron microscopy may be difficult to apply quantitatively. Under conditions where a single type of defect dominates the dechanneling, the channeling technique can be quite quantitative. In addition, the depth distribution of defects can generally be determined in such cases without layer removal techniques. The functional dependence of the dechanneling varies with defect type, so that self-consistent checks can be made to further verify the nature of the defect probed. Sufficient sensitivity exists to both primary and high temperature secondary defects in metals such that a wide variety of radiation damage conditions may be studied. Also, there is an advantage that the ion channeling and backscattering analysis allows the solute depth distribution within the matrix to be monitored, which in many cases may be related to the defect flow and annihilation and the resulting damage distribution. In addition, by lattice location measurements information about the structure of solute-defect centers can also be obtained.⁶

Some of the disadvantages of the channeling technique are that single crystals are required and, as typically used, the lateral resolution is poor (~ 1 mm). In addition, the technique probes relatively shallow depths (≤ 10 μ m) and requires careful analysis for interpretation of the results. It is not a survey technique and can most profitably be applied when the dechanneling cross section and number density of defects is such that dechanneling by a given class of defects dominates over other defects present.

The channeling technique has recently been demonstrated to hold promise for application to radiation damage studies in metals, but relatively little work of a quantitative nature has been carried out so far. The technique is well suited to the high damage levels which might be anticipated in fusion reactor environments. One area of possible application would be studies of the mechanisms and kinetics of the secondary defect production and evolution as a function of fundamental parameters such as flux, temperature and solute concentrations. Finally, the channeling technique is most valuable when used in conjunction with other defect-specific techniques such as transmission electron microscopy.

References

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Figure Captions

- Fig. 1 The 2 MeV He ion backscattering spectra for $\langle 110 \rangle$ axial and $\{111\}$ planar channeling in Al before and after 7×10^{15} Ni/cm² implantation.
- Fig. 2 The disorder and Ni depth profiles obtained from the spectra of Fig. 1.