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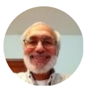

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ION CHANNELING STUDY OF RADIATION INDUCED DEFECTS IN A BENT SILICON CRYSTAL *

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High energy proton channeling (12–120 GeV) and low energy helium ion channeling (1.5–4 MeV) have been used to study the effects of radiation damage induced in silicon by high energy (400 GeV) proton irradiation. It is shown that radiation fluence up to $10^{17}/cm^2$ does not preclude deflection of high energy charged particle beams in elastically bent silicon crystals. Evidence of macroscopic segregation of residual defects in the strain field of a deformed crystal is demonstrated.

1. Introduction

Deflection of high energy ion beams by channeling in elastically bent single crystals [1,2] has stimulated suggestions about the possible application of this effect in high energy physics studies [3]. Since the suggested applications frequently involve much more intense ion beams than those used in the initial bending studies, radiation damage produced by the high energy ions becomes an important question. As part of a systematic study of ion beam bending in single crystals we have studied production of radiation damage in silicon crystals by high energy (400 GeV/c) proton beams and the effect of ion induced disorder on channeled particle trajectories through bent crystals. The purpose of this paper is to report on an attempt to assess the effect of radiation damage on dechanneling and deflection of high energy protons (12–180 GeV) and to use channeling of low energy (1.5–4 MeV) ^{4}He ions to measure the amount and dynamics of radiation damage in a bent single crystal. We note the observation of apparent macroscopic segregation of ion induced defects in a bent single crystal and point out some ramifications of strain field induced defect segregation for crystal defect, ion implantation and other studies.

2. High energy proton channeling study

A systematic study has been carried out of the deflection protons channeled between low index planes in elastically bent silicon crystals [4]. Deflection of protons of 12–180 GeV/c energy from the Fermi National Accelerator Laboratory was measured in position-sensitive drift-chamber detectors. Emergent particle direction distributions such as that shown in fig. 1 were observed. Details of the measurement and analysis are described in ref. 4 and will not be repeated here. From distributions such as that shown in fig. 1, deflection probability and the path length in which particle dechanneling takes place (dechanneling length) can be determined. Deflection measurements were carried out for particles channeled between Si(111) planes in a silicon crystal 2 cm long (in the beam direction) before and after irradiation with 1×10^{17} 400 GeV protons/cm^2. The irradiation took place over a one week period and heating of the crystal during the irradiation was estimated to be less than 20°C. It was found that the probability for deflection of particles was not appreciably reduced by the irradiation. The dechanneling length was calculated from analysis of emergent particle angular distributions and compared to those obtained for the pre-irradiated crystal. The results are shown in fig. 2.

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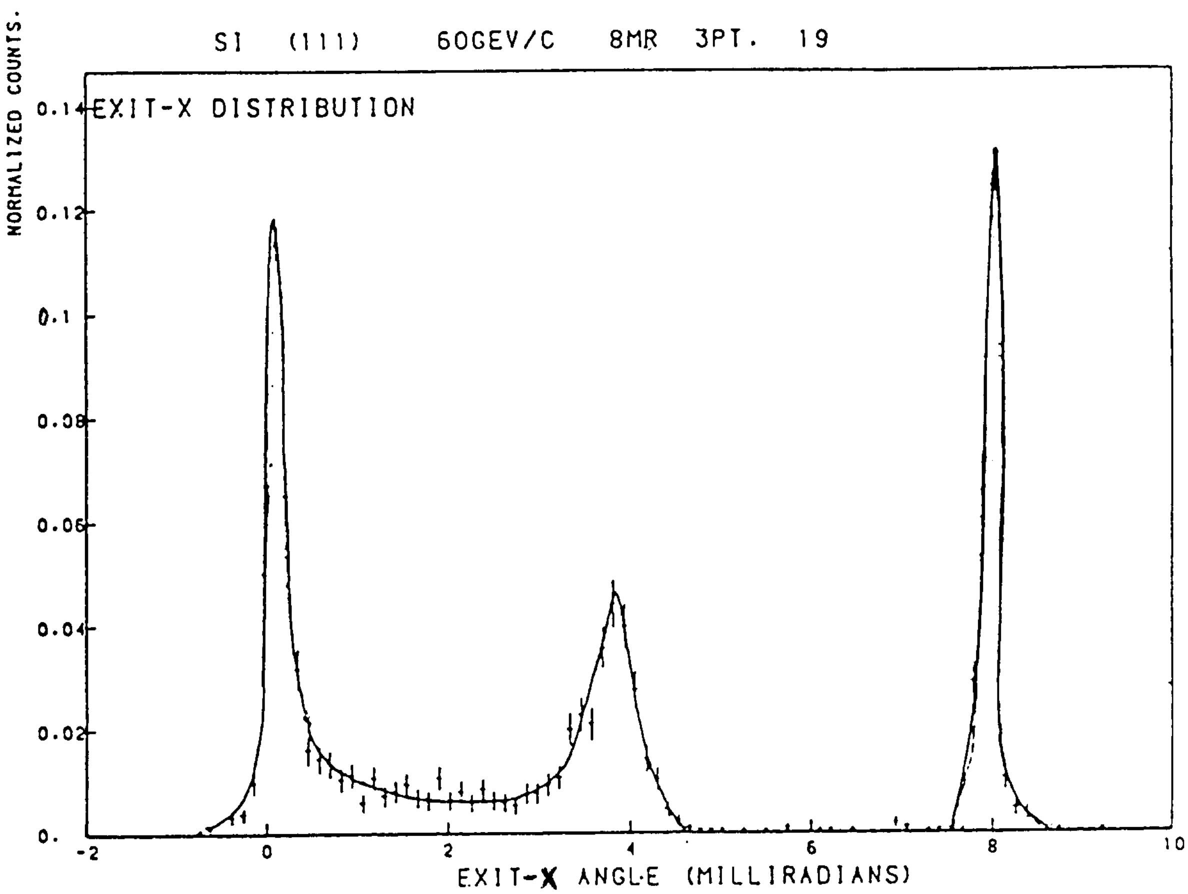

Fig. 1. Typical exit angular distribution of channeled particles through the bent crystal (3-point benders).

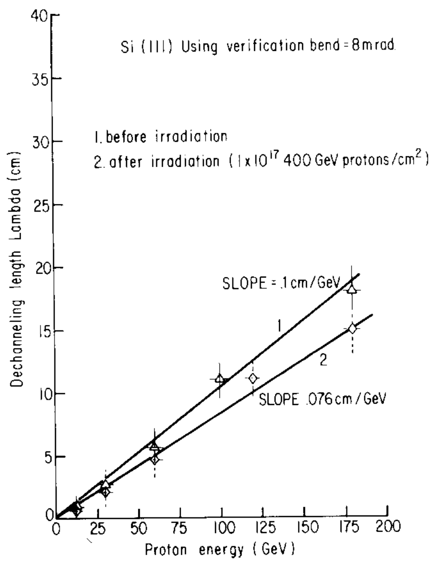

Fig. 2. Dechanneling length versus proton energy.

From this comparison it is concluded that particle fluence of $10^{17}/cm^2$ can be tolerated for many potential particle deflection applications [3].

3. Low energy ^{4}He ion channeling study

The crystals used in this part of the program were prepared to optimize study with helium ion channeling of disorder produced by high energy protons. The three samples used were taken from adjacent slices cut from a high resistivity (100 Ω cm) zone refined silicon crystal. The samples were 0.7×1.25 cm in area and 1.0 mm thick before the final cleaning and chemical etching preparation. They were oriented with a (110) plane perpendicular to the surface and parallel to the short sides of the rectangle. The surface normal was midway between a ⟨110⟩ axis and a ⟨111⟩ axis each of which could be reached by tilting the sample about its long axis through 17.7°. One of the samples was used as a control. It was cleaned with organic solvents and etched in 20:1 HNO_3:HF solution to a final thickness of

~ ½ mm. The second sample was cleaned and etched in the same way and then irradiated with 400 GeV/c protons in an unbent condition. The irradiation was perpendicular to and centered on the flat surface of the sample. The irradiation dose, determined by high purity aluminum foil activation, was 6×10^{16} protons/cm^2 at the center decreasing to 3×10^{15}/cm^2 at the edge. The third sample was cleaned and etched and bent in a simple Torlon (TM) plastic apparatus (which was necessary to reduce multiple scattering which would adversely affect other experiments being carried out with the same proton beam) which put pressure across each end of the sample on one side and across the middle on the other side by means of a Torlon bar of 2 mm radius. The 0.61 mm thick sample was bent through an average radius of 120 cm. For a three point bending arrangement the curvature is parabolic and the radius of curvature at the center is ½ the average, or 60 cm in this case. The strain is highest at the center pin and is complicated because of local distortion caused by the pin [4]. This sample was irradiated with the 400 GeV/c proton beam incident on the center of the convex side of the sample. The irradiation fluence was 1.6×10^{17}/cm^2 at the center (which also corresponds to the point of highest stress). The sample temperature did not exceed 50°C during the irradiation.

Defect production by the high energy proton beam was measured by channeling of 1.5 to 3.0 MeV He^+ ions along ⟨110⟩ and ⟨111⟩ axes inclined at 17.7° to the surface normal. The observed channeling spectra were of the form shown in fig. 3. These spectra show a peak due to ions scattered from silicon atoms in the amorphous surface oxide and in disordered surface films. The yield of particles scattered with energy lower than the surface peak is a measure at different depths in the crystal of the number of ions not undergoing channeling. Extrapolation of this distribution to the surface (center of the surface peak) divided by the yield of scattered particles at the same energy for random incidence is known as the minimum yield $\chi(0)$ and $1 - \chi(0)$ is a measure of the channeling probability in the crystal. The comparable yield ratio, $\chi(d)$ at any given depth d,

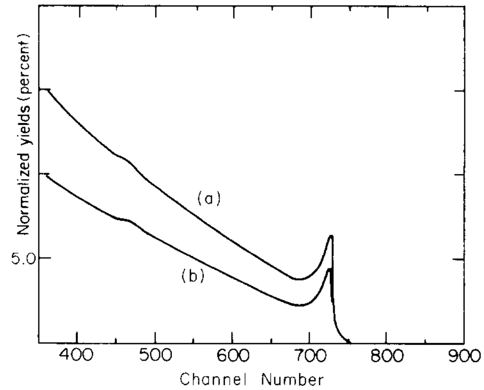

Fig. 3. Pulse height spectrum for 2.0 MeV ^{4}He ions scattered from an irradiated silicon crystal for ion incidence on (a) the side of the crystal that was *convex* during the "irradiation" and (b) the side of the crystal that was *concave*.

in the crystal is a measure of the non-channeled fraction at that depth.

A convenient indicator of crystal disorder produced by ion irradiation is [5,6]:

$$\frac{N_d(0)}{N} = \frac{\chi(0) - \chi_v(0)}{1 - \chi_v(0)},$$

where N is the atomic density in the crystal and $\chi_v(0)$ is the minimum yield for an unirradiated (virgin) crystal *. A summary of $N_d(0)/N$ for the crystals irradiated in both unbent and bent condition is shown in table 1.

Irradiation of a bent crystal in the conditions of the present experiment does not appear to increase the residual disorder, therefore recombination of initially produced interstitials and vacancies is not suppressed by the strain field in the bent crystal. Indeed, considering that the bent crystal experienced nearly three times as much 400 GeV proton fluence, the effect might even be in the opposite direction. A more detailed study

* The observed $\chi_v(0)$ was 2.05% for 2.0 MeV ^{4}He ions for the 110 and 111 directions, respectively.

Table 1
Disorder parameter $N_d(0)/N = [\chi(0) - \chi_v(0)]/[1 - \chi_v(0)]$ measured with 3.0 MeV ^{4}He ions (in percent) [$\chi_v(0) = (2.65 \pm 0.14)\%$ for ⟨111⟩ = $(2.05 \pm 0.13)\%$ for ⟨110⟩]

Radiation dose (400 GeV protons)	Unbent			Bent	
	6×10^{16}/cm^2		3×10^{15}/cm^2	1.6×10^{17}/cm^2	
	front	back	front	front [a]	back [b]
⟨110⟩	0.87 ± 0.10	0.64 ± 0.20	0.32 ± 0.16	1.23 ± 0.14	0.21 ± 0.20
⟨111⟩	1.34 ± 0.12	1.08 ± 0.14		1.59 ± 0.14	0.19 ± 0.20

[a] Convex.
[b] Concave.

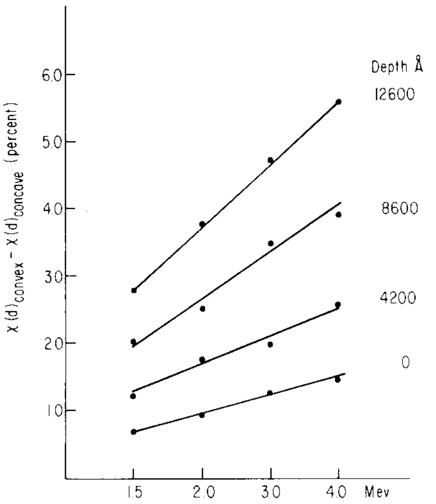

Fig. 4. The difference in dechanneled fractions $\chi(d)_{convex} - \chi(d)_{concave}$ at 4 different depths as a function of the analyzing beam energy (⟨111⟩).

would be necessary to determine the effect of bending on the total residual defect yield.

A striking difference is apparent, however, between the apparent defect concentration observed at the convex surface of the bent crystal compared to that observed at the concave surface. This difference is even more evident when the yields at depths removed from the surface are considered. This is evident from the spectra of fig. 3 and is summarized in fig. 4 for different analyzing particle energies. This change with depth should not be interpreted as a non-uniform defect concentration over the depths probed by the incident beam but arises from the increased dechanneling produced by a higher effective defect concentration as the channeled particles penetrate the crystal.

Differences in the defects observed at the convex and concave sides of the bent crystal are also apparent from the energy dependence of the measured defect parameter as shown in fig. 5. Qualitatively it has been observed that dislocations should exhibit an $E^{1/2}$ dependence [7]; stacking faults, cavities, bubbles, etc. should exhibit an E^0 dependence [8] and randomly distributed defect clusters or isolated defects should exhibit an $E^{-1/2}$ dependence [9]. It is not possible from the present results to identify the dominant defect types involved but it appears that those contributing to dechanneling at the surface of a crystal that was under tensile strain (convex) during the high energy proton bombardment are different in type (and probably concentration) from those at the surface that was under compressive strain.

The macroscopic segregation of residual defects by the strain field in a bent crystal has a number of important implications. (1) It offers the possibility to separate interstitial type defects from vacancy type defects. (2) The large strain fields produced at the edges and interior boundaries of ion implanted, alloyed or heavily diffused layers may cause segregation of defects and therefore influence the final defect distribution. (3) Strain fields at surfaces and interfaces may enhance or retard defect motion to or from the surface or interface.

Further studies are planned to investigate defect production, aggregation and segregation in elastically deformed single crystals.

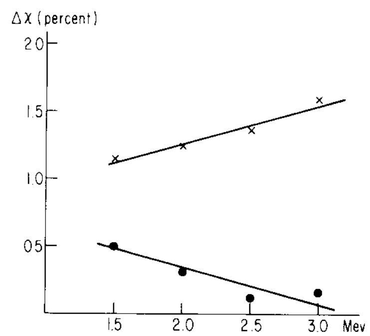

Fig. 5. ⟨111⟩ dechanneling yields $\Delta\chi$ from the convex side (a) and the concave side (b) of a bent crystal after irradiation with 1.6×10^{17} protons/cm^2 as a function of ^{4}He analyzing beam energy.

References

[1] A.F. Elishev et al., Phys. Lett. 88B (1979) 387.
[2] J. Bak et al., Phys. Lett. 93B (1980) 505.
[3] R.A. Carrigan, Jr, W.M. Gibson, C.R. Sun and E.N. Tsyganov, Nucl. Instr. and Meth. 194 (1982) 205.
[4] S. Salman, State Univ. of New York at Albany, PhD Thesis (1982). Available from University Microfilms International, Ann Arbor, Michigan; S.I. Baker et al., Phys. Rev., to be published.
[5] E. Bøgh, Can. J. Phys. 46 (1968) 653.
[6] W.K. Chu, J.W. Mayer and M.A. Nicolet, Backscattering spectroscopy (Academic Press, New York, 1978) p. 257.
[7] Y. Quéré, Ann. Phys. 5 (1970) 105.
[8] D. Ronikier-Polonsky, G. Desarmot, N. Housseau and Y. Quéré, Rad. Eff. 27 (1975) 81.
[9] J.C. Jousset et al., J. de Phys. Lett. 35 (1974) 229.