THE DEPTH DISTRIBUTION OF DISORDER PRODUCED BY ROOM TEMPERATURE 30 keV Ar^+ AND Cl^+ ION IRRADIATION OF SILICON

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The depth distribution of disorder produced by room temperature 30 keV Ar^+ and Cl^+ ion irradiation of silicon was monitored by high depth resolution Rutherford backscattering–channelling techniques. A bimodal depth distribution of disorder was observed and under certain implantation conditions a clear dependence of the magnitude of disorder upon incident ion flux noted.

It has recently been reported that for light ions, a bimodal depth distribution of disorder resulted under certain implantation conditions of ion flux and fluence [1–3]. In particular it was demonstrated that light ions including N, B, He, generate a bimodal depth distribution, while this was apparently absent in the case of medium and heavy mass implants such as Cl, P, Ar, Xe [2,3]. Studies of the depth distribution of disorder created by medium mass ions should provide more valuable information on the mechanism of defect formation, processes of defect accumulation, and self interaction of defects and impurities. Therefore, the prime aim of the present study was to identify whether medium mass ions (such as Ar^+ and Cl^+), which have earlier been reported to have no bimodal [2,3] depth distribution, do exhibit such a depth distribution by using a recently developed and more accurate technique of combining channelling and low angle exit geometry Rutherford backscattering.

A series of ⟨111⟩ silicon single crystals were implanted at 12° off the surface normal, at room temperature, with 30 keV Ar^+ and Cl^+ ions in the University of Salford isotope separator. Ion fluences between 3×10^{13} cm^{-2} and 1×10^{14} cm^{-2} were used and great care was taken to ascertain that the Ar and Cl beams were free from impurities and that the ion flux (beam current) was maintained constant (to within ± 10%). The samples were implanted either with a dc beam or a swept beam of 100 Hz. The dc ion beam was operated in a broad line beam mode by using a defining aperture which selected the central $\frac{1}{2}$ cm core of the beam. Measurements of the beam profile revealed a slight non-uniformity (~ 10%), and therefore a small 50 Hz sinusoidal perturbation was applied to the beam so that improved uniformity of implantation resulted. This perturbation did not constitute a full beam "sweep" however since the modulation only extended the implanted width by 10% relative to the unperturbed beam width. Implantation at selected fluences were repeated by varying the beam current thus leading to different flux conditions in the range 1–10 μA/cm^2. RBS analysis employed 2 MeV $^4He^+$ ions, taken with aligned ⟨111⟩ and random spectra, with the ingoing beam at normal incidence and the outgoing beam making a low angle (~ 10°) with the target surface. This geometry provides an improvement in depth resolution by a factor of ~ 5, to the order of ~ 40 Å.

Investigation of the disordered structure of the surface region as a function of depth after Ar^+ and Cl^+ bombardment with a dc beam showed that in a definite range of ion fluences and a fixed ion flux a bimodal depth distribution of disorder is observed. Fig. 1 shows the result of a series of aligned low-angle exit analyses following 30 keV Ar^+ bombardment with a dc beam for ion fluence over the range $3 \times 10^{13} - 1 \times 10^{14}$ ions cm^{-2} and for an ion flux of 10 μA cm^{-2}. The major feature of fig. 1 is that the deeper peak of the bimodal depth distribution of disorder increases rapidly with ion

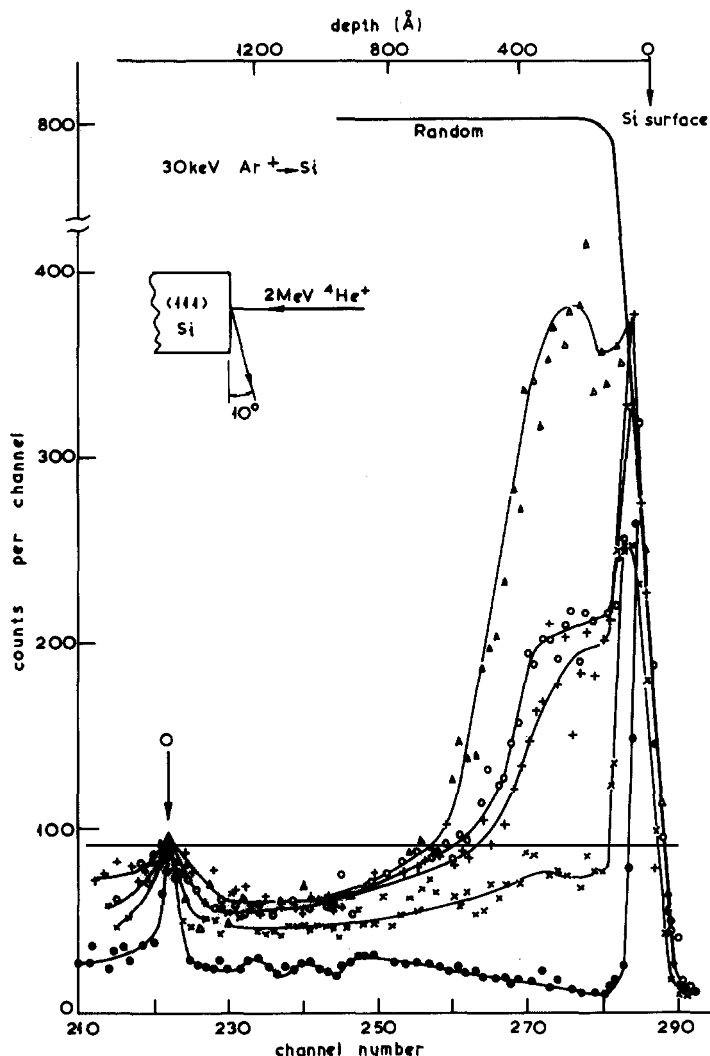

Fig. 1. Low angle exit (10°) aligned ⟨111⟩ RBS spectra from (111) silicon samples, implanted with 30 keV $^{40}Ar^+$ using a dc beam at a flux of 10 μA cm^{-2} and fluences of (•) virgin, × –3 × 10^{13} ions cm^{-2}, + 5 × 10^{13} ions cm^{-2}, ○ 7 × 10^{13} ions cm^{-2}, △ 1 × 10^{14} ions cm^{-2}. Analyses by 2 MeV $^4He^+$.

fluence and the surface peak increases slowly until at high ion fluence (~1 × 10^{14} ion cm^{-2}) the peaks merge and the disorder approaches that of a continuously amorphous layer. This behaviour was, however, found to be ion flux dependent at a given ion fluence. Thus fig. 2 shows that following 30 keV Cl^+ bombardment with a dc beam, and an ion fluence of 5 × 10^{13} ion cm^{-2}, the deeper peak of the depth distribution of disorder increases in magnitude with increasing ion flux. Such a behaviour was found to be much weaker or absent following 30 keV Ar^+ and Cl^+ bombardment with swept beams of 100 Hz with similar average fluxes to the dc case but with much higher instantaneous fluxes and under similar experimental conditions, as shown in fig. 3 for a range of ion fluxes (1–10 μA cm^{-2}). It should be noted that the flux effect for Ar^+ and Cl^+ ions, although real, is much weaker than the corresponding effect for N^+ ions where it was observed that the disorder generated continued to increase rapidly with increasing flux at a given fluence whereas from

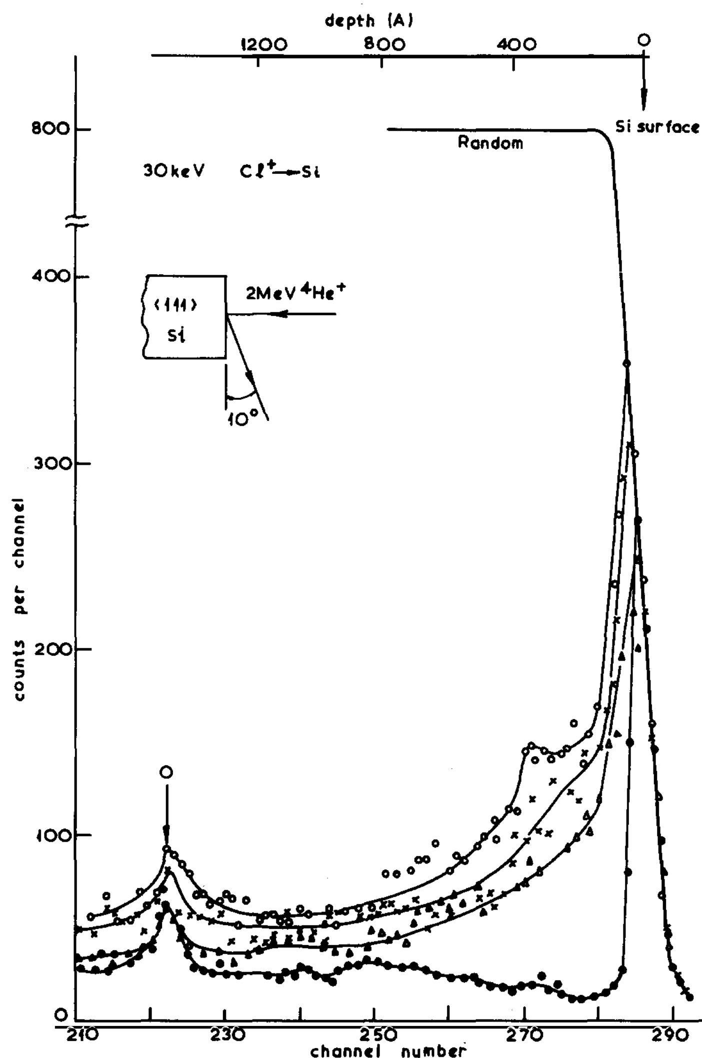

Fig. 2. Low angle exit (10°) aligned ⟨111⟩ RBS spectra from (111) silicon samples, implanted with 30 keV Cl^+ using dc beam at a fluence of 5×10^{13} ion cm^{-2} and flux of • virgin, △ 1μA cm^{-2}, × 2μA cm^{-2}, ○ 10μA cm^{-2}. Analyses by 2 MeV $^4He^+$.

figs. 2 and 3 it is evident that the dose rate dependence is a non-linear function of current and probably approaches a maximum level at a dose rate $\geqslant 10$ μA cm^{-2}, while the swept beam implantation data indicate that disorder may even decrease at higher instantaneous dose rate. The explanation of these effects is not fully evident at present, but it seems probable that during implantation, both simple point defects and amorphized zones are produced by the radiation. At low ion fluence these point defects which are mobile at room temperature diffuse to and may annihilate or be trapped below the surface oxide. Some of these defects may contribute to the near surface peak, although since the magnitude of the surface peak is less flux dependent than the deeper peak it seems probable that the majority of the surface peak results directly from enhanced disordering effects in the region of the strained silicon–oxide interface. Such disorder enhancement effects have been reported previously by Kool et al. [4] and Ahmed et al. [5]. As ion fluence is increased and disordered zone creation is enhanced it would be expected that point defects could be trapped before migration to

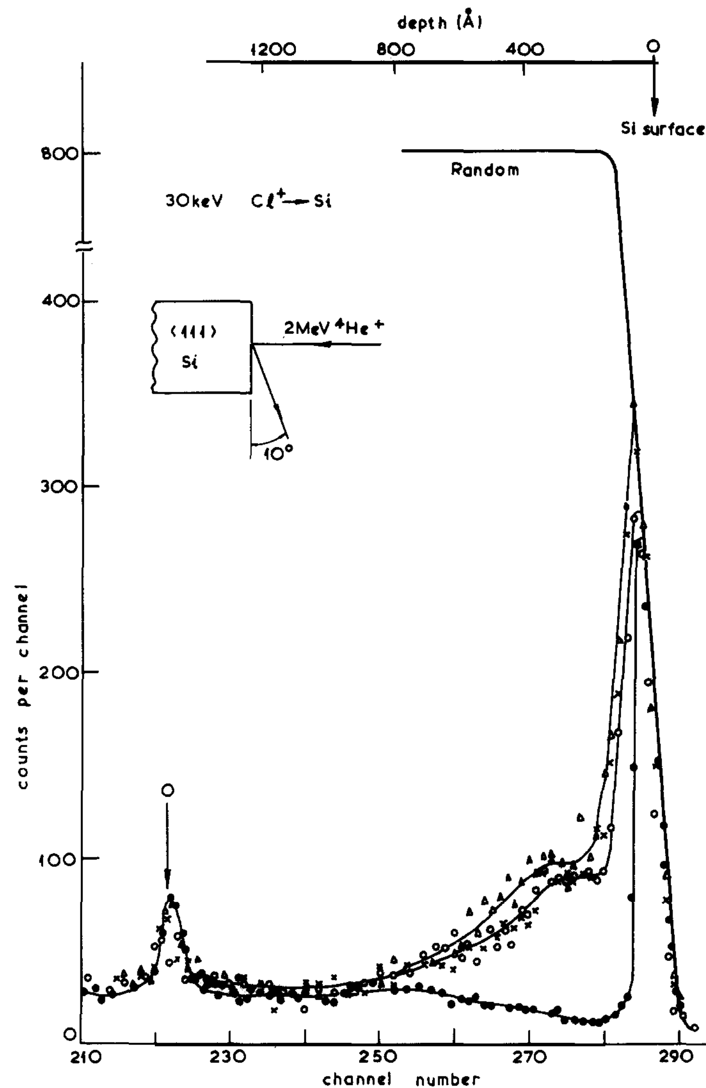

Fig. 3. Low angle exit (10°) aligned ⟨111⟩ RBS spectra from (111) silicon samples, implanted with 30 keV Cl^+ using swept beam at a fluence of 5×10^{13} ion cm^{-2} and flux of • virgin, × 1 $\mu A\ cm^{-2}$, △ 5 $\mu A\ cm^{-2}$, ○ 10 $\mu A\ cm^{-2}$. Analyses by 2 MeV $^4He^+$.

the surface, whilst increasing the ion flux at a given fluence would enhance the probability of point defect clustering, thus leading to an increase in stable observable disorder production. For medium mass projectiles such as Ar^+ and Cl^+ however, it would be anticipated that the major form of damage production would be via disorder zone production and only a minor component of the disorder would be produced in simple defect form whereas with lighter ions such as N^+ the major component of disorder would be in point defects. Thus the influence of defect migration and clustering would be expected to show a stronger ion flux effect with the lighter projectile, than with the medium mass projectile studied here, as is evident by comparison of the present data with previously reported studies with N^+. Because of the dual nature of disorder production with the medium mass projectiles and the competition between point defect generation, migration to the disorder zones and capture or annihilation and point defect agglomeration into stable clusters, the flux dependence would be expected to be

more complex for the medium mass ions than for the lighter ions, as observed. Clearly, however, the dose rate effect is not negligible with medium mass ions and this result should be contrasted with earlier studied by Dennis and Hale [6] who concluded, from dose rate variation measurements of both light (N^+) and heavy (Kr^+) ion bombardment of Si, that disorder zone production is the totally dominant mechanism in both light and heavy ion induced radiation damage in Si. The present data indicate that such a model is not completely tenable, even for medium mass projectiles at 300 K, whilst the earlier N^+ data [1] obtained in our laboratories are totally incompatible with such a model. A more reasonable explanation would appear to lie in terms of both disorder zone and point defect creation and their interaction as was suggested by Nelson [7]. Indeed earlier experiments with Kr^+ bombarded GaAs [8] (which is an approximately equal mass projectile : target atom case) and In^+ implanted GaAs [9] also revealed a flux dependence of the disorder generation suggesting that the results discussed above may be rather generally applicable to light and medium mass irradiation of groups IV and III–V semiconductors at temperatures where single defects are mobile.

The effects reported here would be expected to diminish with decreasing substrate temperature since defect migration and agglomeration would be inhibited and for heavy ion bombardment where direct amorphous zone creation, via for example, spike processes [10] would be expected to be completely dominant. It may be noted that other recent studies [11] of ion bombarded Si have suggested that the character of disorder generation is substantially different for light and heavy ions and that Baranova et al. [12] also indicated their belief that light ion irradiation largely creates point defects which increase in density with increasing fluence until a critical concentration is reached [13] and a local relaxation to an amorphous-like zone occurs whereas heavy ions create such zones directly. Although the present data cannot distinguish between these modes of amorphization, a comparison with the earlier N^+ results [1] does indicate that there are probably two modes of disorder production with simpler defect generation dominating for lighter ion irradiation and more complex disorder becoming increasingly important as the projectile mass is increased.

In summary, the results suggest that point defect production processes in Si may be assuming rather more importance even with intermediate mass ions than has been previously assumed and that, at an irradiation temperature of 300 K a fraction of the point defects may migrate to and be trapped at the silicon–oxide interface, contributing to the near surface peak, and may agglomerate to form stable clusters or may interact with the amorphous zones also generated by the irradiation.

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