The Influence of Channelling on Radiation Damage Produced in Silicon during Ion Bombardment

R. S. NELSON, D. J. MAZEY
Metallurgy Division, Atomic Energy Research Establishment, Harwell, Berks, UK

Received 27 February 1967

The ion bombardment of silicon results in the formation of an amorphous phase in the vicinity of the bombarded regions. This gives rise to a milky appearance which is easily distinguishable from an adjacent unbombarded region. An experiment is described which was specifically designed to study the influence of channelling of incident 80 keV Ne^+ ions on the formation of this amorphous phase. It is found that channelling significantly reduces the rate at which this phase is produced, and in the particular case of the <110> axial channel this corresponds to a reduction in radiation damage by a factor of about 8. The results are compared with the current theories of channelling and are found to be in reasonable quantitative agreement.

1. Introduction

With the growing interest in the use of ion beams to implant semiconducting materials with electrically active doping elements, it is essential to have a clear understanding of the interaction of ion beams with these materials. The basic physics associated with various atomic collision phenomena, such as channelling, which influences the ion's range, and radiation damage, which can influence the electrical properties, must therefore be studied in some detail if we are to employ these techniques successfully.

As a bombarding ion slows down in a crystalline solid, it suffers atomic collisions with the lattice atoms; these atoms subsequently recoil and initiate cascades of atomic collisions which are ultimately responsible for the creation of radiation damage. However, if the bombarding ion is incident along a *channelling* direction, such that its trajectory is constrained to travel in the open planes and channels between the atoms, the probability of large-angle atomic collisions is reduced. Consequently, radiation damage will occur at a slower rate than that observed for a non-channelled or random trajectory. The actual reduction in damage under conditions typical of implantation is an important parameter, for it has a direct bearing on the question of whether or not doping should be carried out with crystals oriented so as to permit channelling.

This paper describes an experiment specifically designed to examine the influence of channelling on the formation of radiation damage in silicon during bombardment with 80 keV Ne^+ ions. Neon is a "non-active" impurity, and as such is useful from the point of view that damage and impurity doping effects can be distinguished.

2. Characterisation of Ion Bombardment Damage in Silicon

Recent studies of ion-bombarded silicon [1, 2] and germanium [3] have indicated that the radiation damage is manifest in the creation of an "amorphous" phase in the vicinity of the bombarded regions. The detailed formation of this phase will not be discussed in the present paper as this discussion will appear separately; however, we will describe some of the characteristic features which permit its formation to be observed visually with the naked eye.

Electron microscopy and diffraction studies have shown that during bombardment with 80 keV Ne^+ ions, under conditions where the incident ions are not channelled, the surface layers of a silicon crystal turn amorphous to a depth of ~1800 Å after a total dose of more than ~10^{14} Ne^+ ions/cm^2 at 20° C. This effect is independent of the resistivity or the type of silicon used, and it results from the destruction of the crystalline lattice. On annealing at 630° C for 10 min, this amorphous layer recrystallises epitaxially onto the underlying crystalline substrate and appears crystallographically identical to the original unbombarded material, except for an array of dislocation loops and dipoles [2], which persist to a temperature of just over 1000° C.

If the bombarded surface is viewed with the naked eye, it exhibits a characteristic "milky" appearance which is easily discernible from an adjacent unirradiated area. Fig. 1 shows a photograph of a silicon slice bombarded through an electron microscope specimen support grid so as to provide a series of demarcation lines; the milky appearance is readily apparent. It is thought that the amorphous phase is composed of a random aggregate of minute crystallites ($\lesssim$10 Å) which give rise to a diffuse scattering of the light reflected from its surface layers, and that this in turn gives rise to the milky appearance which is so readily observed. If a bombarded silicon slice is kept under observation whilst it is heated in a high vacuum, the milkyness disappears at exactly the same temperature as the amorphous phase recrystallises (as determined by electron diffraction). This observation therefore provides further evidence that the amorphous phase and the milky appearance go together.

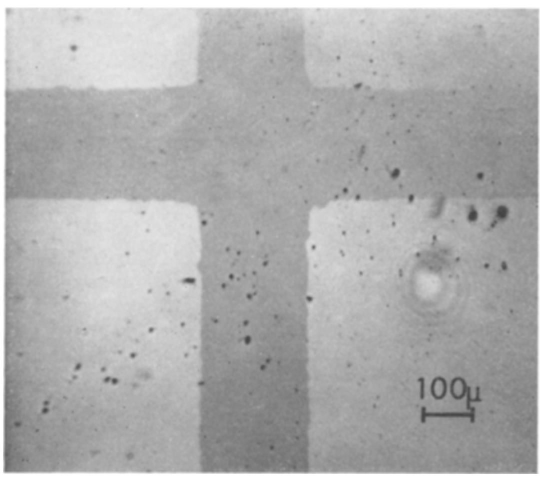


Figure 1 Photograph of a silicon slice, bombarded with 80 keV Ne^+ ions to a dose of 10^{15} ions/cm^2, showing the milky appearance. The cross corresponds to that part of the slice which was shielded from the ion beam by a grid.

If then the crystal is bombarded under conditions of channelling, where the probability of large-angle elastic collisions with lattice atoms is reduced, the milkyness should appear after a dose greater than that corresponding to random trajectories of the incident ions. This therefore suggests a simple experimental technique for studying the influence of channelling on the creation of radiation damage in silicon during ion bombardment.

3. The Experiment

3.1. The Bombardment Conditions

A single crystal of silicon 2.5 cm in diameter and 0.3 mm thick, having either its {111}, {100}, or {110} planes parallel to its flat, chemically polished surface, was mounted on a rotatable target holder which allowed simultaneous rotation about two orthogonal axes (see fig. 2).

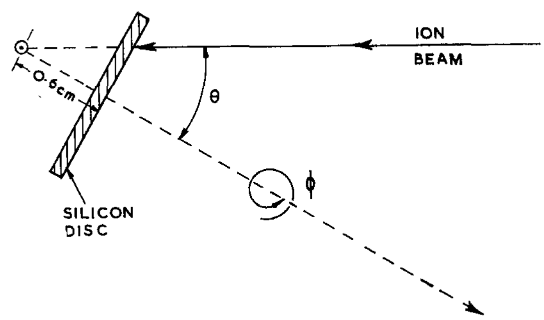
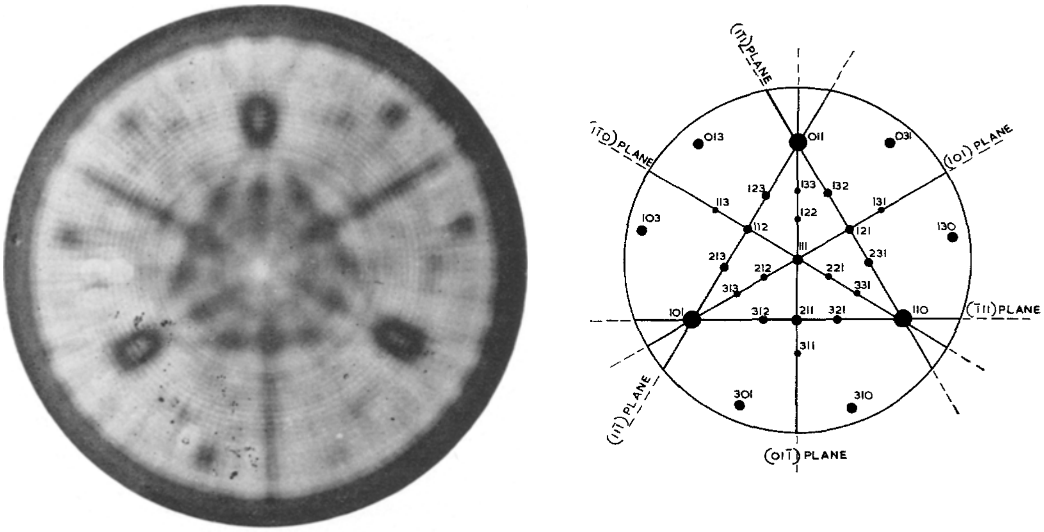


Figure 2 Schematic experimental arrangement indicating the sense of the two orthogonal rotations (θ, ϕ) of the crystal relative to the ion beam.

The vertical axis provided changes in inclination between the crystal and the ion-beam direction (θ), and the horizontal axis provided continuous rotation about the normal to the crystal surface (ϕ). The face of the crystal was held at a distance of 6 mm from the vertical axis so that, as θ was increased by 1° intervals, the beam would describe a series of concentric circles on its surface. The crystal was set into rotation at a rate of 2 rev/min at an inclination of 50° to the beam direction, and was bombarded with 80 keV Ne^+ ions collimated to 0.08 cm diameter with a divergence of $\sim$0.01°, in a vacuum bettei than 10^{-6} torr. After a dose just sufficient to form the amorphous layer under non-channelling conditions, as determined by the onset of the milky appearance viewed through the vacuum window, the angle of inclination was reduced by a succession of 1° intervals until the whole sample had been scanned with the ion beam. The irradiation time was carefully adjusted at each angular setting so as to produce a uniform dose over the bombarded surface.

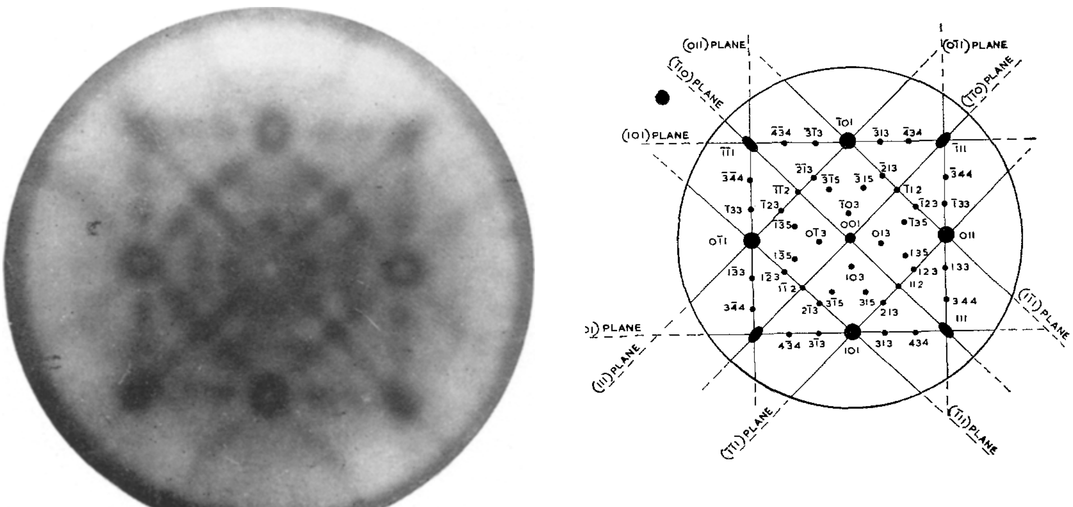
3.2. Results

Figs. 3, 4, and 5 are direct photographic reproductions of the crystal surfaces after bombardment, together with simple radial projections of



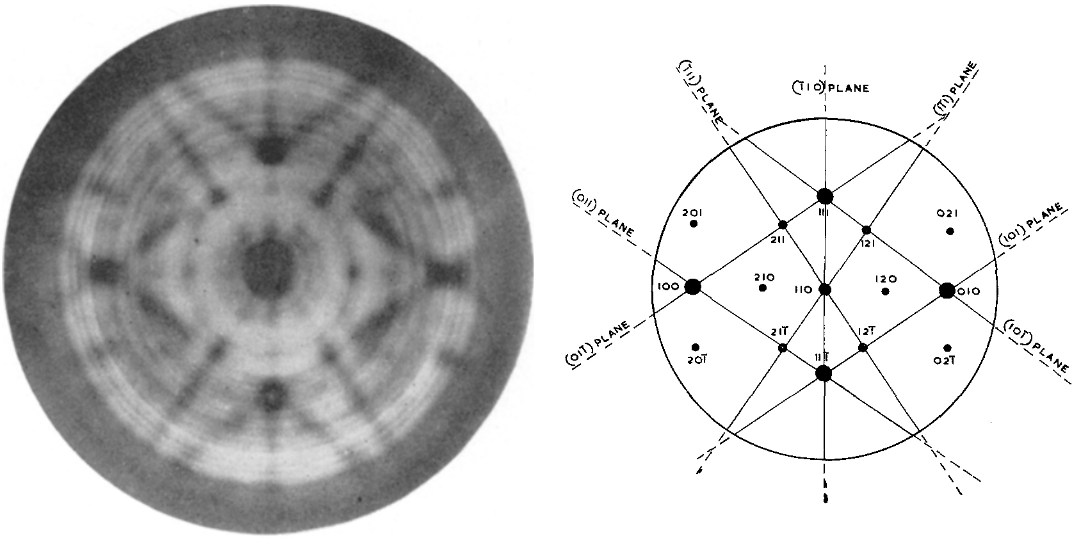
(a) (b)

Figure 3 (a) A photographic reproduction of a <111> crystal surface, after programmed bombardment with 80 keV Ne^+ ions, showing the regular crystallographic patterns corresponding to a reduction in radiation damage whenever the ion beam is channelled. (b) A simple radial projection of the {111} face of a fcc crystal showing the low index planes and poles for comparison.



(a) (b)

Figure 4 Same as fig. 3 but for a {100} crystal.



(a) (b)

Figure 5 Same as fig. 3 but for a {110} crystal.

the corresponding crystal faces for comparison. Unfortunately, although great care was taken in recording this effect, such as photographing through a liquid of high refractive index, illuminated with sodium light, the photographs do injustice to the actual result; however, they serve as a guide to the reader. It is evident, from the regular patterns mapped out on the crystal surfaces, that those regions which do not exhibit a milky appearance correspond to angles of incidence close to the major axial and planar channelling directions. It should be noted that the apparent milkyness at the centre of some of the larger spots is an optical effect, believed to be a consequence of the photographic reproduction only. The results are consistent with a reduction in radiation damage and, hence, the rate of amorphous phase formation, whenever the incident ion is channelled.

As the bombardment was continued, the milkyness steadily spread into those parts of the patterns which corresponded to channelling, until eventually the whole silicon surface had been turned amorphous. To provide a measure of the reduction in radiation damage under conditions of channelling, the dose required to obliterate the patterns was then compared to the dose just necessary to turn the surface milky under conditions when the incident ions were not channelled. For the major channelling direction, the <110>, this occurred after a dose increment of about 8×, and therefore implies a reduction in radiation damage by a factor 8 when the crystal is oriented so as to present its <110> channels to the incident ion beam.

4. Discussion

The phenomenon of channelling has been discussed theoretically for both protons and heavy ions [4-6]. It is a useful approximation to smear out the interatomic potential from the individual atoms of a channel into a continuum, so that a particle entering a crystalline solid sees regular rows and sheets of high potential. Then, basing the interaction on the familiar, exponentially screened, Coulomb potential suggested by Thomas-Fermi, i.e.

$$V(r) = (Z_1 Z_2 e^2/r)\,\Phi\,(r/a)$$

where $\Phi\,(r/a)$ is the Fermi function with screening length a:

$$a = a_0\,0.8853(Z_1^{\frac{2}{3}} + Z_2^{\frac{2}{3}})^{-\frac{1}{2}}$$

and Z_1 and Z_2 are the atomic numbers of the incident particle and the lattice atoms respectively, the critical channelling angle corresponding to a simple axial channel is given by:

$$\psi_{\mathrm{hkl}} = \left(\frac{2Z_1Z_2e^2}{Ed_{\mathrm{hkl}}}\right)^{\frac{1}{2}}$$

for $$\psi_{\mathrm{hkl}} < a/d_{\mathrm{hkl}}$$

where d_{hkl} is the effective interatomic spacing of atoms in those rows which define the walls of an axial channel and E is the particle energy. At large Z, or when the energy is low, this expression for the critical channelling angle smoothly changes to:

$$\psi_{hkl} = [(a/d_{hkl})(2Z_1Z_2e^2/Ed_{hkl})^{\frac{1}{2}}]^{\frac{1}{2}}$$

for $\psi_{hkl} < a/d_{hkl}$

and so ψ_{hkl} is proportional to $(d_{hkl})^{-\frac{3}{4}}$.

The channelling patterns produced on the silicon slices shown in section 3 can, in general, only be used to provide an indication of the absolute critical channelling angle, for the following reason. If the dose required to turn the surface amorphous is recorded as a function of angle about a <110> direction, we obtain a curve as illustrated in fig. 6. The relevant parameter which must be compared with the critical channelling angle is the half-width at half-maximum of this distribution. However, in most cases, channelling patterns correspond to a dose which is just greater than that necessary to turn the non-channelled part milky, and so a measurement of the effective channel widths will give an angle somewhat greater than ψ_{hkl} (see table I for a comparison). On the other hand, the ratio of the angular widths of the major axial channels measured from the silicon surface should be proportional to $(d_{hkl})^{-3/4}$ to a first approximation. A logarithmic plot of these measured angular widths as a function of d_{hkl} is shown in fig. 7, together with a line having a slope of (−3/4) drawn for comparison.

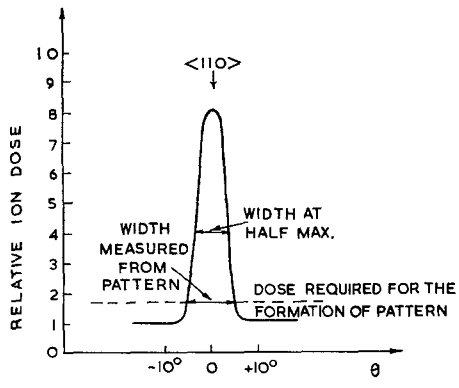


Figure 6 Schematic representation of the ion dose required to create an amorphous surface plotted as a function of angle of incidence about the <110> channel.

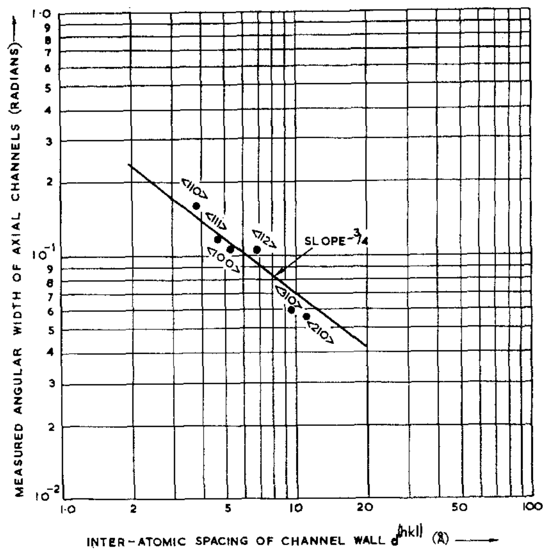


Figure 7 Logarithmic plot of the angular channel widths measured from the patterns as a function of d_{hkl}.

TABLE I Values of the half-widths measured from the patterns together with the calculated values of ψ_{hkl} for different axial channels.

Axis of channel	Interatomic spacing d_{hkl} (Å)	Measured half-width of channel	Theoretical half-width of channel
<110>	3.83	4° 45′	3° 42′
<111>	4.78	3 46	3 12
<100>	5.42	3 13	3 0
<112>	6.63	3 21	2 27
<310>	9.75	1 43	1 51
<210>	12.15	1 33	1 27

In the case of the <111> direction, the interatomic spacing between those atoms which constitute the channel walls is not constant; it alternates between two values, d_1 and d_2; the value for d_{hkl} has therefore been approximated to $(d_1 + d_2)/2$ in this case. The fit to a slope of (−3/4) is quite good and, together with table I, provides reasonable agreement between the current theory of channelling and experiment.

5. Conclusions

(*a*) Channelling of the incident ions during the ion bombardment of silicon results in a reduction of radiation damage. In the particular case of the <110> axial channel, this reduction is of the order of 8 when bombarded with 80 keV Ne^+ ions.

(*b*) The measured angular widths of axial channels agree reasonably well with current theories of channelling.

Acknowledgements

We should like to thank D. F. Holloway for his capable assistance with the experiments, and E. M. Wittam for his skill and patience in obtaining a photographic reproduction of the channelling patterns.

References

1. U. F. GIANOLA, *J. Appl. Phys.* **28** (1957) 868.
2. D. J. MAZEY, R. S. BARNES, and R. S. NELSON, *Proc. 6th Int. Congr. for Electron Micr.*, Kyoto, Japan **1** (1966) 363.
3. J. R. PARSONS, *Phil. Mag.* **12** (1965) 1159.
4. R. S. NELSON and M. W. THOMPSON, *ibid* **8** (1963) 1677.
5. M. T. ROBINSON and O. S. OEN, *Appl. Phys. Lett.* **2** (1963) 30.
6. J. LINDHARD, *Mat. Fys. Medd. Dan. Vid. Selsk.* **34** No. 14 (1965).