The Use of Colour Film in the Study of Proton Channelling

R. S. NELSON, B. W. FARMERY
Metallurgy Division, Atomic Energy Research Establishment, Harwell, Berks, UK

G. DEARNALEY, I. V. MITCHELL
Nuclear Physics Division, Atomic Energy Research Establishment, Harwell, Berks, UK

Received 23 December 1966

This note describes a technique which uses colour film to provide semi-quantitative energy analysis as well as information on the spatial distribution of protons emerging from thin single-crystal foils. Characteristic "star patterns", which are produced when a well-collimated proton beam is incident parallel to a major crystal direction, appear red on a yellow background, and show clearly the two distinct energy groups corresponding to the channelled and random components.

1. Introduction

The phenomenon of channelling – the steering of fast ions along the open channels and planes of a crystal lattice – is now well established for both light and heavy particles for energies ranging from tens to tens of millions of electron volts. A detailed understanding of the phenomenon is of importance in connexion with sputtering and ion implantation of impurities in semiconductor crystals. The most sophisticated channelling experiments have been concerned with the passage of protons through thin single-crystal foils [1-4]. Experiments have been of two basic types: those which examine both the energy spectrum and spatial distribution of transmitted protons using solid-state particle detectors; and those which record the spatial distribution alone by interrupting the transmitted proton paths with X-ray film. In general, the protons emerging from the far side of a single-crystal foil, orientated so that the incident beam is close to a major crystal axis, can be separated into two groups called the *random* and *channelled* components respectively. The random component results from a series of statistically independent small-angle collisions with lattice atoms, whereas the channelled component consists of protons which have undergone correlated glancing collisions with rows or planes of atoms and travel along channels of low atomic density. However, a two-dimensional small-angle scattering of the channelled protons can occur between adjacent atomic planes, and this results in the scattering of channelled protons from axial channels into the planar channels in which they lie. Under these conditions, characteristic "star patterns" can be seen on a photographic plate, as illustrated in fig. 1. In general, energy is lost from a fast particle by both electronic and atomic collisions; however, in the case of protons in the MeV range, electronic stopping dominates and the energy lost in atomic collisions can be neglected. Electronic stopping can be divided into two distinct parts: that which occurs as a consequence of direct collision with electrons; and that which is a consequence of long-range resonant encounters. According to Lindhard [5], the contribution to the energy loss due to these two processes should be about equal, but it is only the random component which traverses regions of high electron density and suffers direct collisions with electrons. This component will therefore emerge with approximately twice the mean energy loss of the channelled component. These two components therefore fall into two distinct energy groups and, as they also have greatly differing distributions in the "star pattern", a photographic technique which gives energy analysis as well as positional information would be extremely valuable.

2. Colour Film Technique

We shall now describe a photographic technique using colour film which can be used to give semi-quantitative information on the relative energies of the normal and channelled components as well as their spatial distribution. Colour film is usually made from the superposition of three or more colour-sensitive emulsion layers, each of which, when sensitised by ionising radiation such as protons, will produce a characteristic colour. A proton beam can therefore sensitise either one, two, or more layers depending on its energy and on the stopping power of the emulsion. Energy discrimination can therefore be achieved and recorded by the combination of those characteristic colours which are sensitised by the protons before they come to rest. Thus, as the random and channelled components are each associated with a distinct energy group, the incident proton energy can be adjusted relative to the foil thickness so that each group comes to rest in a separate emulsion layer. In this way, a particular colour will correspond to a particular energy band, and, in principle, star patterns recorded this way will provide visual information on energy as well as the spatial distribution of the two components.

To evaluate the feasibility of this technique, a 30 μm-thick single crystal of Si was bombarded with a beam of 1.5 MeV protons collimated to ~0.01° from the 5 MeV van der Graaff accelerator at Harwell. The star patterns produced by protons transmitted through the crystal were recorded on colour films held at a distance of 20 cm behind the crystal. The film chosen was "Agfa-CN17" colour negative which has the specification listed in table I. Then, using existing data on the rate of energy loss from protons in emulsion and in Si [6], the incident proton energy was adjusted so that the normal proton component emerging from the crystal would be just stopped by the first emulsion layer of the film.

Fig. 2 is a photograph of a typical <110> star pattern produced directly in the colour negative film and clearly shows a most remarkable effect. The random component which emerges in a broad gaussian distribution about the incident proton direction has only penetrated the yellow emulsion layer, as expected, whereas

TABLE I The composition of "Agfa-CN17" colour negative film, together with the colours observed when successive emulsion layers are penetrated.

Emulsion	Emulsion colour	Observed colour			
Top	Yellow	Yellow	Red	Black	Total thickness 20 to 22 μm
Filter layer	Colloidal silver		Red	Black	
Centre	Magenta		Red	Black	
Bottom	Cyan blue			Black	

the channelled component has penetrated well into the magenta layer and appears as a red star. The black spot in the centre suggests that the protons channelled exactly along the <110> directions have suffered the least energy loss, and some penetration into the third, cyan-blue layer has occurred. The protons in the extreme wings of the star have undergone small-angle scattering in the planes and have consequently suffered a greater energy loss than those nearer the centre, this results in a lower penetration and a change from red to yellow in the film.

Coloured star patterns are clearly much more informative than simple black and white patterns produced in X-ray film and have provided useful information which is otherwise only obtainable by tediously scanning with an energy-sensitive detector.

Acknowledgement

We should like to thank Mr P. N. Coldwell for his advice on colour films and for arranging their processing.

References

1. R. S. NELSON and M. W. THOMPSON, *Phil. Mag.* **8** (1963) 1677.
2. G. DEARNALEY, *IEEE Trans. Nucl. Sci.* **11** (1964) 249.
3. W. GIBSON, C. ERGINSCY, H. E. WAGNER, and B. R. APPLETON, *Phys. Rev. Letts.* **15** (8) (1965) 357.
4. G. DEARNALEY, B. W. FARMERY, I. V. MITCHELL, R. S. NELSON, and M. W. THOMPSON, *Phil. Mag.* (1967) to be published.
5. J. LINDHARD, *Mat. Fys. Medd. Dam. Vid. Selsk.* **34** (1965) 14.
6. E. SEGRE, *Experimental Nucl. Phys.* **1** (1953) 166.

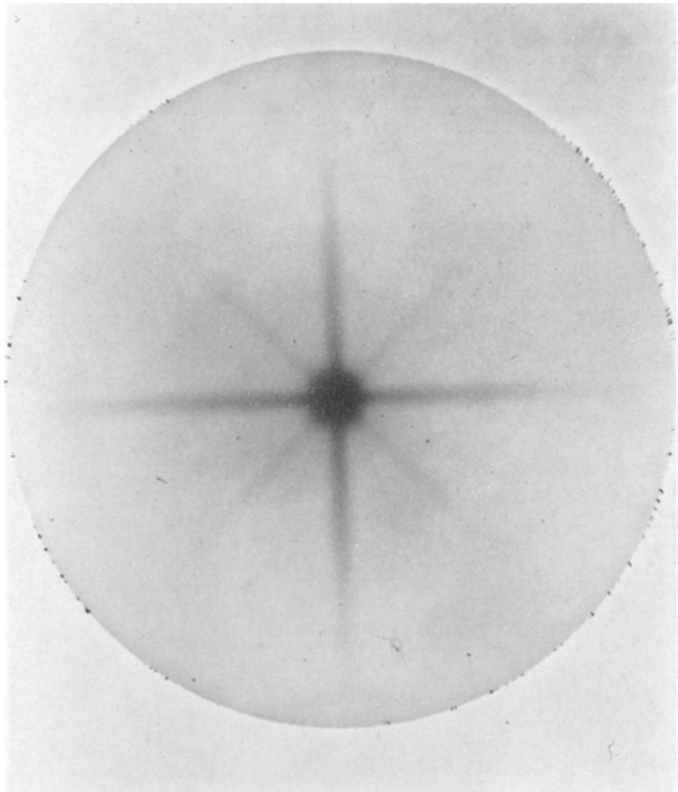

Figure 1 <100> star pattern produced on X-ray film by passing 3 MeV protons through a 50 μm MgO single crystal. The distance to the film was 20 cm.

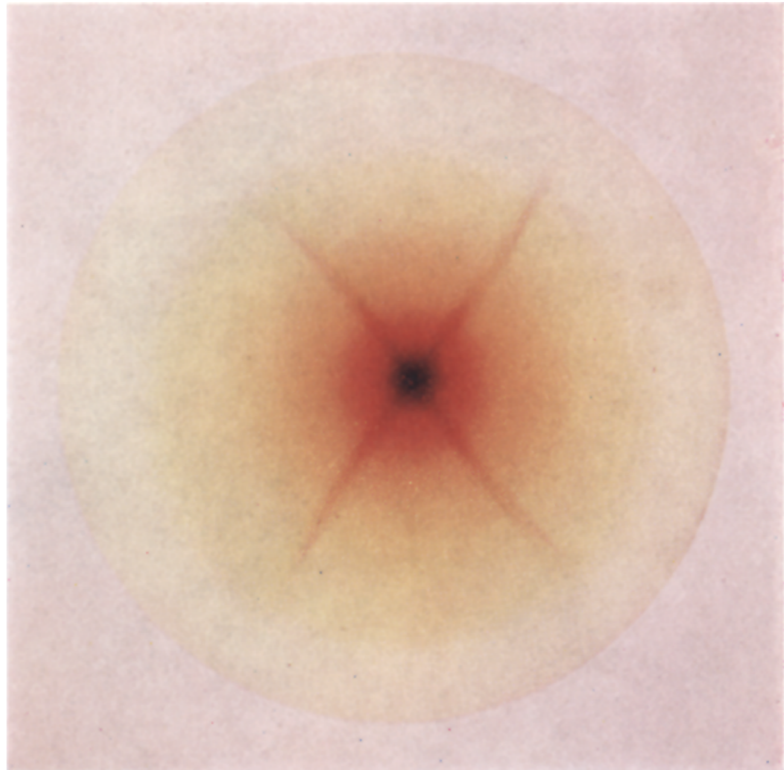

Figure 2 <100> star pattern produced on "Agfa-CN17" colour negative film by passing 1.5 MeV protons through a 30 μm Si single crystal. The distance to the film was 20 cm.