Bull. Mater. Sci., Vol. 10, Nos 1 & 2, March 1988, pp. 105–115. © Printed in India.

Study of crystal defects using ion channelling and channelling radiation

ANAND P PATHAK
School of Physics, University of Hyderabad, Central University P.O., Hyderabad 500 134, India.

Abstract. The channelling technique to study crystal defects is described and its applications to various kind of defects to study their atomistic nature have been reviewed. Special emphasis has been placed on the applications to extended defects like dislocations. Finally a related new technique being developed for the last few years, namely the channelling radiation technique has been discussed along with its applications to study the dislocations.

Keywords. Defects; dislocations; channelling; channelling radiation.

1. Introduction

Unless special care is taken in the fabrication and growth of material crystals, defects of one kind or the other are always present in these crystals. These defects can be classified as point defects (like vacancies and interstitials), line defects (dislocations), planar defects (for example stacking faults, grain boundaries etc.) and volume defects (like voids, gas bubbles, precipitates, amorphous regions etc.). From the viewpoint of fundamentals of defects physics in solids as well as from the application point of view, it is very important to know the nature and concentration of the defects present in solids. For such investigations, apart from the well-established method of electron microscopy, several new techniques have recently been developed. These include channelling, Mossbauer effect, perturbed angular correlation, positron annihilation, infrared absorption, electron paramagnetic resonance etc. The main advantage of these new techniques is their capability to select a given type of defect and provide information on the atomistic nature of the chosen defect. We shall discuss here the channelling technique and its use to probe the crystal defects.

2. The channelling technique

When single crystals are bombarded with charged particles along one of their major crystallographic directions or planes, they penetrate anomalously long distances along these directions. The particles are steered along these directions or planes, moving in their collective potential field (called *continuum potential*) and are said to be channelled. The presence of defects poses as perturbation to this continuum potential and particles are dechannelled if the deflecting force (due to perturbation) is larger than the restoring force (due to continuum potential). The mechanism by which the different types of defects cause dechannelling depends upon the nature of these defects.

In principle, all defects give rise to some amount of distortion in the crystals. However, from the channelling point of view, it is possible to classify them between those which cause very small amount of distortion and that too, only in the immediate neighbourhood of defects and those that cause large distortions in larger regions surrounding the defects. The defects like point defects, stacking faults etc.

would fall in the first category, and will cause dechannelling only when the channelled particle directly hits them i.e. they obstruct the particle leading to *obstruction* dechannelling. Defects like dislocations fall in the second category and most of the dechannelling occurs due to large distortions even in the regions away from the defect core, leading to *distortion* dechannelling.

2.1 *Theory of channelling*

As mentioned above, the charged particles see continuum potential due to string or plane when they move along or at very small angles with respect to these strings or planes. The criteria, first proposed by Lindhard (1965), is that the time of flight of the projectile between successive atoms along the string or plane should be small compared to the collision time between the projectile and one of the atoms along the trajectory. This means that during its motion, before the particle can realize, that it is in the potential field of one atom, it has already moved to the next atom of the string or plane. Lindhard chose the interatomic potential of power law form

$$V(R)=\frac{z_1 z_2 e^2}{R}\left(1-\frac{R}{\sqrt{R^2+C^2a^2}}\right), \tag{1}$$

where z_1 and z_2 are atomic numbers of projectile and target atoms respectively, R the distance between them, C is a constant ($\cong\sqrt{3}$) and a the Thomas-Fermi screening radius. The above mentioned condition for channelling then leads to critical angles for channelling (Lindhard 1965; Gemmell 1974)

$$\psi_a=\sqrt{2z_1z_2e^2/dE}, \qquad \text{(axial case)} \tag{2}$$

$$\psi_p=\sqrt{2\pi\, Nd_p z_1z_2e^2\, a/E}, \qquad \text{(planar case)} \tag{3}$$

where E is the projectile energy, d the interatomic distance along the string (for axial case), d_p the interplanar spacing (for planar case) and N the bulk density of atoms in the target.

Apart from the Lindhard standard potential (1), several other forms of Thomas-Fermi type of statistical potentials (Torrens 1972) have been used in channelling theory. Some of these are mathematical modifications of equation (1) (Mory and Quere 1972; Pathak 1975a, 1976a, 1979, 1982) while others are altogether different in functional dependence like for example Moliere potential which is a 3-term exponential fit to the Thomas-Fermi potential. Because of the simplicity of (1) or its mathematical approximations, we shall use these power law potentials.

2.2 *Dechannelling*

As mentioned above, the defects present in the solids cause dechannelling of projectiles either through direct obstruction effects or through distortions produced in the solid. Before discussing these effects in detail, we present some generalities. Let a flux I of particles be channelled along the z-direction. The rate of dechannelling due to the defects and due to thermal motion of atoms is governed by the equation (Quere 1970, 1974)

$$\mathrm{d}I/\mathrm{d}z=-I\,(\xi_{\mathrm{th}}+\Sigma\,\sigma_i C_i), \tag{4}$$

where ξ_{th} describes the thermal dechannelling and σ_i is the dechannelling cross-section of the defects of type i which has a concentration C_i. From (4) we get

$$I(t)=I(0)\exp[-(t\xi_{th}+\textstyle\int_0^t \sigma_i C_i \, dz)], \tag{5}$$

where $I(0)$ is the channelled flux just beyond the entry surface and can be written as $I(0)=I(1-\chi_{min})$ where I_0 is the total incident intensity and χ_{min} is the minimum yield due to surface dechannelling which can be written as

$$\chi_{min}=N\,d\pi(\rho_{\perp}^2+a^2) \tag{6}$$

with $\rho_{\perp}$ as the root mean square displacement of atoms normal to strings or planes. The opacity of the sample can be defined as

$$O(t)=1-\exp[-(t\xi_{th}+\textstyle\int_0^t \sum_i \sigma_i C_i \, dz)]. \tag{7}$$

The thermal effects can be eliminated by comparing the opacities with and without defects, so that the relative opacity is given by

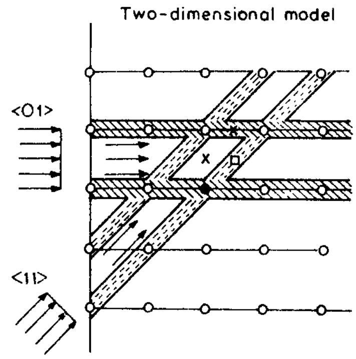
$$O=[I_0(t)-I_c(t)]/I_0(t)=1-\exp[-\textstyle\int_0^t \sum_i \sigma_i C_i \, dz], \tag{8}$$

where $I_0(t)$ and $I_c(t)$ are fluxes of channellons emerging from a given sample, at a given temperature, without and with defects respectively. If the dependence of the dechannelling cross-section σ on the energy is known in an analytical form, the above expression can be calculated in different stopping power regions.

2.2a *Obstruction dechannelling*: As discussed above, defects such as point defects and stacking faults do not produce any significant distortion, and effects are almost entirely of the obstruction type. For the case of point defects, this fact is used to find the lattice locations of implanted species in the crystals with the help of channelling technique. When the impurity is situated on a regular lattice site (i.e. substitutional) it will have no effect on channelling. However, when it is located at an interstitial position, it may obstruct the path of channelled particles along certain directions and may be shadowed by atomic strings along certain other directions. This situation is illustrated for a two-dimensional lattice in figure 1. Thus by measuring the minimum yield, one can precisely know the interstitial position of the impurity. A great deal of work has been done on lattice location of implanted ions (Eriksson *et al* 1969; Davies 1970, 1972; Andersen *et al* 1971; Bernas 1974; Miller *et al* 1975; Matsunami and Itoh 1976). Here, we give some details of the underlying processes.

(i) *Interstitial atoms*

Several authors (Quere 1970, 1974; Jousset *et al* 1974; Quillico and Jousset 1975; Morita and Sizmann 1975; Dunlop *et al* 1978) have studied dechannelling by interstitial atoms. Jousset *et al* (1974) studied the dechannelling of α-particles by hydrogen and carbon interstitials in Pd crystals for planar case. The theoretical description is based on the assumption that dechannelling is caused essentially by the Rutherford scattering of α-particles by the impurities. If the scattering angle causes the transverse energy to increase beyond the critical transverse energy i.e. the



	Directional effect ?		
	•	x	□
<01>	Yes	50%	No
<11>	Yes	No	Yes

Figure 1. A two-dimensional model illustrating how the channelling effect may be used to locate foreign atoms in a crystal. As shown by the table, three possible sites for a foreign atom (○, □ and ×) can be readily distinguished by comparing the channelling behaviour along the ⟨01⟩ and ⟨11⟩ directions (Davies 1972).

potential barrier, the particle is dechannelled. Jousset *et al* (1974) used simplified power law planar potential of the form

$$V(x)=\frac{4V_0La}{L^2-x^2}\equiv\frac{4\pi z_1z_2e^2Nd_p}{L^2-x^2}, \tag{9}$$

where $L=l+a$, l being the half-width $(=d_p/2)$ of the channel and x the distance measured from the midpoint between two planes. The dechannelling cross-section for planar dechannelling is found to be

$$\sigma=\frac{z_1z_2e^2L\pi}{2\sqrt{EV(x_c)}}, \tag{10}$$

where x_c is the maximum allowed value of x. The $E^{-1/2}$ dependence of σ was confirmed in the experiments of the same authors. The above theoretical estimates assumed the stopping power dependence on the energy to be of the form $KE^{-3/4}$ and the energy loss due to additional electrons contributed by the introduced impurity (e.g. H in Pd in α-phase) was neglected, which is reasonable as shown later (Pathak 1976a).

A similar calculation for axial dechannelling due to interstitials has been carried out by Morita and Sizmann (1975) who find that for axial case the dechannelling cross-section is much smaller than for the planar case. This is understandable because the potential barrier of an axial channel is much higher than for a planar channel. These authors divide the process into *instantaneous* and *delayed* dechannelling, the former referring to dechannelling due to a single large angle scattering event while the latter refers to successive small angle deflection resulting in loss of alignment of the projectile leading to dechannelling. These authors find that the delayed dechannelling is much more effective (1·7 to 2·5 times, depending on the actual position of the interstitial) than the instantaneous dechannelling. This happens because the fraction of particles which can directly hit the interstitials to be deflected by large angles is small compared to the majority of the remaining particles which undergo small deflections successively and hence contribute to delayed dechannelling.

In both cases, therefore, by studying dechannelling along various directions, the actual position of interstitial atom can be found. This was one of the first applications of channelling phenomena.

(ii) *Stacking faults*

Another example of obstruction without distortion is encountered in stacking faults (SF). The situation is shown in figure 2. Depending upon the initial transverse energy and phase, the particle channelled prior to meeting the stacking fault can travel further after meeting the fault with the possibilities of channelling being made less efficient (case 1), more efficient (case 2) or the particle becoming dechannelled altogether either on the SF (case 3) or at some point further on (case 4). The situation is described in terms of the dechannelling probability p such that the dechannelling cross-section is $\sigma = pS$ where S is the projected surface of the SF. Mory and Quere (1972) used a simple model to calculate the dechannelling probability where the potential curves of the two regions are shifted by the fault parameter. The change in transverse energy is then used to find the dechannelling probability which turns out to be independent of particle energy, in agreement with experimental results.

2.2b *Distortion dechannelling*: The dislocations present the most important example of distortion dechannelling. The atomic rows and planes around a dislocation exhibit curvature so that the trajectory of the channelled particle is modified, the magnitude modification depending on the magnitude of the curvature (i.e. distortion). As is well known from the dislocation theory, the distortion is maximum near the dislocation core and decreases as one moves away from the core as shown in figure 3. Thus one can think of a cylindrical region around the dislocation axis, the so-called "dechannelling cylinder" (Quere 1968) where the distortion is large enough to greatly modify the trajectory resulting in complete dechannelling. In the region outside this dechannelling cylinder, the distortion is not enough for dechannelling to occur, although even here the amplitude of the channelled particles will change with a corresponding change in the rate of energy loss of these particles. Quere and coworkers (Quere 1968; Mory and Quere 1972; Pathak 1976c, 1977) have studied this problem in detail and we shall briefly discuss their analysis and give some important

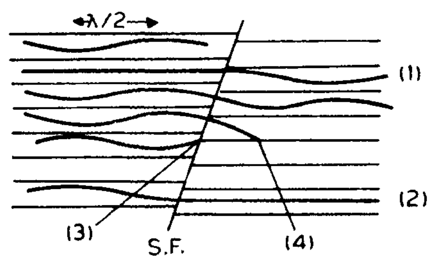


Figure 2. The channellons can pass through SF with possibilities of channelling made worse (case 1) or better (case 2) or they can be dechannelled either on SF (case 3) or further on (case 4).

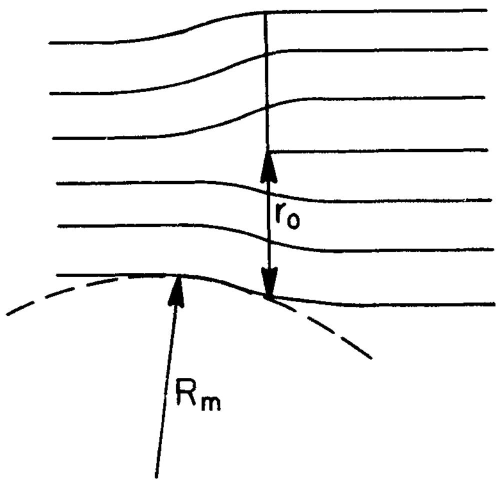


Figure 3. Example of minimal radius of curvature R_m of a channel at a distance r_0 from an edge dislocation.

results. The basic idea is to use the continuum model potentials to calculate the effects of curvature introduced in planar and axial channels due to dislocations. The curvature itself is calculated using the standard displacement equations of dislocation theory. The effect of this curvature is to introduce a transverse centrifugal force on the propagating particles; this force should therefore be combined with the force due to the continuum potential in writing the equations of motion of these particles. When this centrifugal force causes the transverse energy $E_\perp (=E\psi^2)$ to exceed the critical transverse energy $E_\perp^c (=E\psi_c^2$ where $\psi_c=\psi_a$ or ψ_p for axial or planar case), the particle is dechannelled.

(i) *Axial case*

Using Lindhard's standard potential (1), the continuum potential for a string is obtained as

$$U(r)=\frac{2z_1z_2e^2}{d}\ln\frac{Ca}{r}, \tag{11}$$

so that the repulsive restoring force is $-\mathrm{d}U/\mathrm{d}r=2z_1z_2e^2/dr$ which acts to keep the particle channelled. This restoring force is countered by the centrifugal force $2E/R$ whose maximum value is $2E/R_m$ (corresponding to the minimum radius of curvature R_m). Thus, we have

$$2E/R_m=2z_1z_2e^2/\mathrm{d}r. \tag{12}$$

The critical distance of approach r_c for dechannelling to take place corresponds to the dechannelling energy $E\psi_c^2=2z_1z_2e^2/d$ and is obtained, using the above equation

$$\ln(Ca/r_c)=1 \quad \text{or} \quad r_c=Ca/2{\cdot}7.$$

Therefore the critical value of minimum radius of curvature is given by

$$R_{mc}=\frac{E\,\mathrm{d}r_c}{z_1z_2e^2}\cong\frac{0{\cdot}64\,E\,\mathrm{d}a}{z_1z_2e^2}. \tag{13}$$

All the channels situated at a distance r_0 from the dislocation axis and having a radius of curvature $R_m(r_0)$ smaller than R_{mc} will dechannel the particles so that the radius of dechannelling cylinder r_0 around the dislocation axis is obtained by solving the equation

$$R_m(r_0) = R_{mc}.$$

Using the standard dislocation theory in conjunction with the above equations Quere (1968) found the mean diameter of dechannelling cylinder as

$$\bar{A}_x(E) = (bdaE/\alpha z_1 z_2 e^2)^{\frac{1}{2}}, \tag{14}$$

where b is the Burgers vector and α equals 12·5 for a straight screw dislocation, 4·5 for a straight edge dislocation and 7·2 for a mixture of both types in equal concentration.

(ii) *Planar case*

Using equation (9) for planar potential due to two planes surrounding the particle trajectory, and following similar analysis as done in the axial case, the average diameter of dechannelling cylinder for screw dislocations is obtained to be

$$\bar{A}_p(E) = \left(\frac{Eb}{8{\cdot}6\, z_1 z_2 e^2 N d_p}\right)^{1/2} \tag{15}$$

A corresponding formula for edge dislocations in the planar channelling case has not yet been derived because the analysis becomes considerably more complicated.

From (14) and (15) we note that the dependences of the dechannelling diameter (and hence of the dechannelling cross-section) on the particle energy E, the Burgers vector b and on the projectile and target atomic numbers are identical in both the cases i.e. axial and planar channelling. However, the absolute values are much larger for planar case than for axial case. The qualitative behaviour and the quantitative magnitudes are in reasonable agreement with experimental results (Mory and Quere 1972; Pronko and Merkle 1975; Rimini 1977; Picraux *et al* 1978) for carefully performed experiments i.e. for special cases where nucleation of dislocation loops is avoided and where appropriate types of dislocations (screw or edge) are introduced in moderate concentrations. It is worth pointing out the differences in dechannelling cross-section due to dislocations, point defects and stacking faults as regards their dependence on energy namely $E^{1/2}$, $E^{-1/2}$ and E^0 (independent) respectively.

The above model has also been used to calculate the effects of dislocations on channelling stopping power. This is done by first finding the change in oscillation amplitude due to dislocations and then using the position (in the channel) dependence of stopping power (Pathak 1975b, 1976c, 1977). The well-channelled particles before encountering dislocations, start oscillating so that a shift in the edge of energy spectrum was predicted. As regards the full energy spectrum, a numerical calculation was performed (Steenstrup and Pathak 1981) and the resulting energy spectra compared for the cases, with and without dislocations and with the experimental data available.

3. Channelling radiation technique

Another technique based on channelling of relativistic particles is being developed for the last few years. This is based on the observation of e.m. radiation from these channelled particles. This channelling radiation spectrum is severely modified when defects are present in the crystal. Emission of electromagnetic radiation from charged particles moving in condensed matter is quite well known as bremsstrahlung but when the particle is channelled, a new type of radiation is emitted due entirely to its transverse motion, which is oscillatory. Quantum-mechanically, the charged particle can be considered to be bound by the transverse electrostatic potential of the crystal axis or plane and channelling radiation occurs as spontaneous transitions between eigenstates of this potential. Normally, these transverse energy levels are spaced only by few electron volts and observation of radiation would be difficult because of other background radiation. But for relativistic electrons and positrons, a combined effect of Lorentz transformation and Doppler shift results in pushing the photon energies to be observed into the keV region for MeV electrons and positrons or into the MeV region for GeV electrons and positrons.

If ω is the characteristic frequency of transverse motion, then because of time dilation, this becomes $\gamma\omega_0$ in the rest frame of the particle where $\gamma \simeq \gamma_z = (1-\beta^2)^{-1/2}$ with $\beta = v/c$. Here, the longitudinal velocity has been assumed to be almost equal to total particle velocity. Thus the frequency of radiation emitted in the longitudinal rest frame is $\omega_R = \gamma\omega_0$. In the lab frame, Doppler shift occurs and the observed frequency is given by $\omega = \omega_R/\gamma(1-\beta\cos\theta) \simeq 2\gamma^2\omega_0/(1+\gamma^2\theta^2)$ where θ is the angle of emission with respect to forward direction. Thus for $\theta = 0$, the forward direction frequency is given by $2\gamma^2\omega_0$. Now considering the positron channelling and using potential (9) we can expand $V(x)$ for small x as

$$V(x) = V_0' + \frac{1}{2}k_1x^2 + \frac{1}{4}k_2x^4 + \ldots . \tag{16}$$

where

$$V_0' = 4\pi z_1 z_2 e^2 N d_p C a^2/L,\ k_1 = 2V_0'/L^2 \text{ and } k_2 = 4V_0'/L^4.$$

The solution of Schrodinger equation for transverse motion with first two terms of (16) is just the harmonic oscillator energies $E_n = (n+\frac{1}{2})\hbar\omega_0$ with $\omega_0 = (k_1/m)^{\frac{1}{2}}$ where $m = \gamma m_0$, m_0 being the rest mass. The observed channelling radiation frequency is therefore given by

$$\omega = 2\gamma^2\omega_0 = 2\gamma^{3/2}(k_1/m_0)^{\frac{1}{2}}. \tag{17}$$

The effects of quartic anharmonic terms having fourth power in x, are included by the first order perturbation theory. The nth energy level is then given by

$$E_n = \hbar\omega_0[(n+\tfrac{1}{2}) + \tfrac{1}{4}\varepsilon(2n^2+2n+1)], \tag{18}$$

where

$$\varepsilon = \frac{3\hbar}{4\sqrt{m_0\gamma}}\frac{k_2}{k_1^{3/2}}, \tag{19}$$

so that the emitted radiation frequency for $n \to n-1$ transition is given by

$$\omega_{n\to n-1} = \omega(1+n\varepsilon). \tag{20}$$

For successive values of n, $\omega_{n\to n-1}$ differ by $\omega\varepsilon$ which turns out to be small so that in an actual experiment where a convoluted spectrum is measured, this contributes to the linewidth. The effects of dislocations and strained layer superlattices on channelling radiation properties are discussed below.

3.1 *Dislocations*

Using a simplified constant curvature model for dislocation-affected channel it has been shown (Pathak 1976c, 1982) that for planar case a well-channelled particle (i.e. not emitting any radiation) after passing through a dislocation affected channel, gains an average amplitude

$$x_{amp} = 0{\cdot}49\, L^3 Eb/4 V_0 a\pi^2 r_0^2 \tag{21}$$

and hence oscillates with period

$$T = \left(\frac{2m_0 L(L^2 - x_{amp}^2)}{V_0 a}\right)^{1/2} F\left(\frac{x_{amp}}{L}\right), \tag{22}$$

where F is the complete elliptic integral of the second kind. This means that an additional channelling radiation frequency $\omega = 4\pi\gamma^2/T$ is to be expected. Similarly for axial case (Pathak and Balagari 1986a) the average amplitude gained by an otherwise well-channelled particle is

$$r_{amp} = 4R_0^2\, Eb/3\pi^3 r_0^2 U_0, \tag{23}$$

with $U_0 = 6z_1 z_2 e^2 C^2 a^2/dR_0^2$ and R_0 is channel radius. Therefore in the first approximation the period is given by

$$T = 2\left(\frac{2m_0 R_0^4}{U_0(R_0^2 + 2r_{amp}^2)}\right)^{\frac{1}{2}} E\left(\frac{r_{amp}}{(2r_{amp}^2 + R_0^2)^{\frac{1}{2}}}\right). \tag{24}$$

The fractional increase in frequency is given by

$$f = \frac{\omega^{(d)} - \omega}{\omega} = \left(1 + \frac{2r_{amp}}{R_0^2}\right)^{\frac{1}{2}} \frac{\pi}{2E\left(r_{amp}/(2r_{amp}^2 + R_0^2)^{\frac{1}{2}}\right)} - 1, \tag{25}$$

where E is the complete elliptic integral of the first kind.

It should be mentioned here that the above theoretical results in an analytical form are obtained in a very simplified model of constant curvature and first order approximation for potential expansion. Similarly the only experimental results available on the effects of defects on channelling radiation (Park *et al* 1984, 1985) correspond to the case where the defect structure is very complicated. Thus a direct quantitative comparison is not possible at present. However, qualitatively, the above results are comparable with the experimental findings. The technique needs to be developed further.

3.2 *Strained layer superlattices* (SLS)

Another possible application of channelling radiation technique explored recently (Pathak and Balagari 1986b) is to study the strained layer superlattices. In the absence of any experimental results, a qualitative investigation, using a very simplified model, was made. In the SLS samples where misfit defects are not generated and lattice mismatch is accommodated by uniform layer strains for thin layers, a small tilt angle is introduced at each interface. the channelled particle then effectively sees a weakened potential and hence a reduction in the channelling radiation frequency is predicted. Of course the technique has to be developed both experimentally as well as theoretically for SLS investigation. One thing, however, seems to be clear and well-founded from even the simplified calculations and that is the qualitative difference expected in the channelling radiation spectrum when misfit dislocations are generated and when they are not. For, in the presence of dislocations, we expect an increase in frequency while in SLS (without misfit defects) a decrease is expected and this decrease is much smaller in magnitude. Thus, one can hope to study SLS in detail, as the technique develops further.

4. Conclusions

Because of space limitations, this review has been rather restrictive, giving only the final results. However, it is clear from what has been presented and the underlying approximations that a lot more work is to be done to improve upon these results. The qualitative predictions are very well founded and most of these are experimentally confirmed.

Because of its capability to probe the atomistic nature of defects, the channelling technique provides a powerful tool for defect studies. Since the channelled ions are scattered by atoms displaced from lattice sites, the technique can be used to study any type of lattice defect, and above all, differentiate among various types of defects. This technique is particularly powerful for measuring the lattice position of solute atoms and those on the surfaces of crystals. The energy dependence of dechannelling cross-section provides unique information about the nature of defects and the magnitude of dechannelling cross-section can be used to find the concentration of defects. One important advantage is that the channelling analysis is non-destructive and the data accumulation is rapid so that a complete irradiation, lattice location analysis and annealing experiment can be completed in a few hours. For some elements like ^2H, the channelling/Rutherford back-scattering is the only method for studying surface coverage, concentration profiles and lattice locations. In general, the channelling results are in agreement with results from other conventional methods (optical methods, electrical resistivity and chemical analysis) and also with results from more modern selective techniques like Mössbauer effect, LEED, diffuse X-ray scattering, positron annihilation and perturbed angular correlation. In many cases channelling is a complimentary method to other techniques like electron microscopy which measures other regimes of defect size and distribution.

The channelling radiation technique is a relatively new technique and needs to be developed experimentally as well as theoretically. Because of great sensitivity of channelling radiation frequencies and linewidths to the finer details of interaction potentials, this technique holds great promise for defect studies as well as the fundamental quantity like crystal potential. For the same reason, the application to strained layer superlattices studies is also of great importance and holds great promise for these applied researches. Already from the preliminary studies made so far, it seems possible to investigate the strains in the layers, the relative tilt of channels in successive layers (and hence the magnitude of potential weakening) and any misfit defects generated. Further investigations will give more detailed information about these and other aspects of stained layer superlattices as well as normal semiconductor superlattices.

References

Andersen J U, Andreasen O, Davies J A Uggerhoj E 1971 *Radiat. Eff.* **7** 25

Andersen J U, Laegsgaard E and Feldman L C 1972 *Radiat. Eff.* **12** 219

Bernas H 1974 *J. Appl. Phys.* **9** 575

Dunlop A, Lorenzalli N and Jousset J C 1978 *Phys. Status Solidi* **49** 643

Davies J A 1970 in *Physics of ionized gases*; (ed.) B Navinsek (Yugoslavia: Herceg Novi) p. 270

Davies J A 1972 in *Channelling, theory, observation and applications*; (ed.) D V Morgan (New York: John Wiley)

Eriksson L, Davies J A, Johnson N G E and Mayer J W 1969 *J. Appl. Phys.* **40** 842

Friedel J 1964 *Dislocations* (New York: Pergamon)

Gemmell D S 1974 *Rev. Mod. Phys.* **46** 129

Jousset J C, Mory J and Quillico J J 1974 *J. Phys. Lett.* **35** L229

Lindhard J 1965 *K. Dan. Vid. Selsk. Mat. Fys. Medd.* **34** No. 14

Matsunami N and Itoh N 1976 *Radiat. Eff.* **31** 47

Miller J W *et al* 1975 *Phys. Rev.* **B11** 990

Morita K and Sizmann R 1975 *Radiat. Eff.* **24** 281

Mory J 1971 *J. Phys.* **32** 41

Mory J 1976 CEA Report R4745

Mory J and Quere Y 1972 *Radiat. Eff.* **13** 57

Park H, Kephart J O, Klein R K, Pantell R H, Berman B L, Datz S and Swent R L 1984 *J. Appl. Phys.* **57** 1661

Pathak A P 1975a *J. Phys.* **C8** L439

Pathak A P 1975b *Phys. Lett.* **155** 104

Pathak A P 1976a *Radiat. Eff.* **30** 193

Pathak A P 1976b *Phys. Rev.* **B13** 461

Pathak A P 1976c *Phys. Rev.* **B13** 4688

Pathak A P 1977 *Phys. Rev.* **B15** 3309

Pathak A P 1979 *Radiat. Eff. Lett.* **43** 55

Pathak A P 1982 *Radiat. Eff.* **61** 1

Pathak A P and Balagari P K J 1986a *J. Appl. Phys.* **60** 955

Pathak A P and Balagari P K J 1986b *Appl. Phys. Lett.* **48** 1075

Picraux S T, Rimini E, Foti G and Compisano S U 1978 *Phys. Rev.* **B18** 2078

Pronko P P and Merkle K L 1975 in *Application of ion beams to metals* (New York: Plenum)

Quere Y 1968 *Phys. Status Solidi* **30** 713

Quere Y 1970 *Ann. Phys.* **5** 105

Quere Y 1974 *J. Nucl. Mater.* **53** 262

Quillico J J and Jousset J C 1975 *Phys. Rev.* **B11** 1971

Rimini E 1977 *Proc. 7th Int Conf. At. Coll. in Solids*, (Moscow)

Steenstrup S and Pathak A P 1981 *Radiat. Eff.* **55** 17

Torrens I M 1972 *Interatomic potentials* (New York: Academic Press)