Incident-Angle Dependence of Catastrophic Dechanneling for Strained-Layer Superlattices

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A strong *asymmetry* has been observed in the angular dependence of the catastrophic dechanneling depth in strained-layer superlattices. This new effect occurs under resonance conditions, where the wavelength of the planar-channeled particles equals the period of the superlattice, and is demonstrated for {110} planar channeling in $GaP/GaAs_xP_{1-x}$. A theoretical, phase-plane analysis shows that the angular tilt required for shifting of the catastrophic depth by one layer is a direct measure of the strain in the first few layers.

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In a recent Letter we reported the discovery of a resonance upon matching between the wavelength of planar-channeled particles and the period of a strained-layer superlattice (SLS).[1] By varying the incident energy (and thereby the particle wavelength) we showed that catastrophic dechanneling occurs on resonance and argued that the depth of the dechanneling can be correlated with the amount of strain in the superlattice. The distinct nature of this channeling effect suggests that it may exhibit interesting new features for the study of layered structures.

In this Letter we report for the first time the existence of a strong and *asymmetric angular dependence* of the depth where catastrophic dechanneling occurs. We discuss the origin of this new phenomenon and demonstrate its use to probe the structure of superlattices. The catastrophic depth can be moved to shallower or greater depths by tilting with or against the angular shift at the first interface. A theoretical, phase-plane analysis reveals that the asymmetric dechanneling behavior can be directly described in terms of the strain between layers in the superlattice.

To study the resonance effect, a $GaP/GaAs_xP_{1-x}$ SLS containing thirty layers of equal thicknesses (325/325 Å) was grown[2] on a GaAsP buffer layer on a GaP substrate by metal organic chemical vapor deposition with $x \approx 0.12$, corresponding to a lattice mismatch between layers of about 0.5%. By comparing the {110} planar-channeled–particle backscattering oscillations in single-crystal GaP with the As composition oscillations in the random backscattering spectrum from the superlattice, the resonance condition (characteristic particle wavelength equal to the superlattice period) was found at 1.2 MeV for ^4He.

In Fig. 1 catastrophic dechanneling in the SLS is shown by the rapid rise to the random level for three incident angles, ψ_0, relative to the {110} planes of the top layer [$+\psi_0$ ($-\psi_0$) is defined as towards (away) from the second layer direction]. The most striking

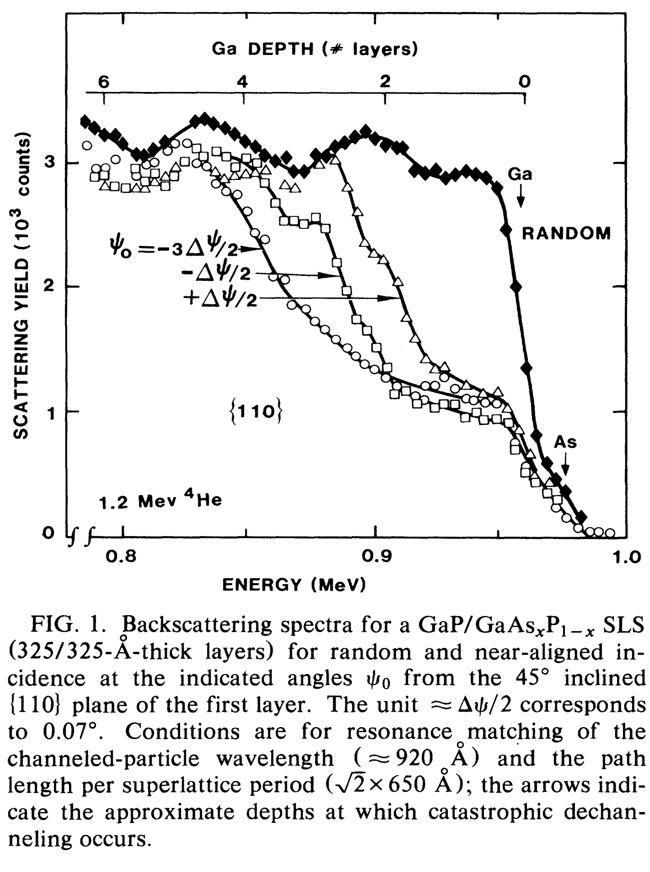

FIG. 1. Backscattering spectra for a $GaP/GaAs_xP_{1-x}$ SLS (325/325-Å-thick layers) for random and near-aligned incidence at the indicated angles ψ_0 from the 45° inclined {110} plane of the first layer. The unit $\approx \Delta\psi/2$ corresponds to 0.07°. Conditions are for resonance matching of the channeled-particle wavelength (≈ 920 Å) and the path length per superlattice period ($\sqrt{2} \times 650$ Å); the arrows indicate the approximate depths at which catastrophic dechanneling occurs.

feature is that the depth at which the catastrophic dechanneling occurs is shifted by a large amount for a small change in the incident angle. Here, ψ_0 values of 0.07°, −0.07°, and −0.21° are given approximately in units of $\Delta\psi$ (determined later), which is the tilt angle at each interface for the {110} crystal planes (see Fig. 2). This tilt is a result of the elastic accommodation of the strain, which gives rise to a single in-plane lattice constant in the SLS and, as a result of the Poisson effect, alternating tetragonal distortions in the growth direction.[2] In SLS $\Delta\psi$ is a direct measurement of the strain.

The depth of catastrophic dechanneling is seen in Fig. 1 to be asymmetric in tilt angle with better channeling for negative ψ_0. This result is surprising, since from Fig. 2(a) one might have anticipated the best channeling along the average {110} direction, corresponding to $+\Delta\psi/2$. Thus in SLS crystal alignment under resonance conditions, a single-channel analyzer set to a width of several layers for alignment by an angular scan will be influenced by the shifting of the catastrophic depth, so that the best aligned position will be shifted towards negative angles.

The above angular asymmetry for the depth of catastrophic dechanneling can be understood by a phase-plane analysis. The basic physics of catastrophic dechanneling is that a large fraction of the planar-channeled particles are simultaneously focused into the channel wall for resonance conditions. The existence of the resonance relies on the fact that all of the channeled particles have similar wavelengths and thus maintain their relative phase for small depths. Figure 2 shows calculated channeled-particle trajectories at resonance assuming a harmonic continuum potential. In (a) the incident angle $\psi_0 = +\Delta\psi/2$ corresponds to the average direction of the {110} planes in the SLS. With each layer, the focal point is seen to shift further from the center of the channel until the particles collide into the channel wall.

We note that ψ_0 is a small tilt angle within the critical angle for {110} planar channeling ($< 0.4°$ here) and $\Delta\psi$ is orthogonal to the {110} plane. If, instead, the tilt is within the plane, only the path length per SLS period is changed.

The phase-plane evolution of the channeled-particle position and angle relative to the channel direction is described theoretically in Fig. 2 by a modified harmonic model.[1] Normalized position and angle are shown

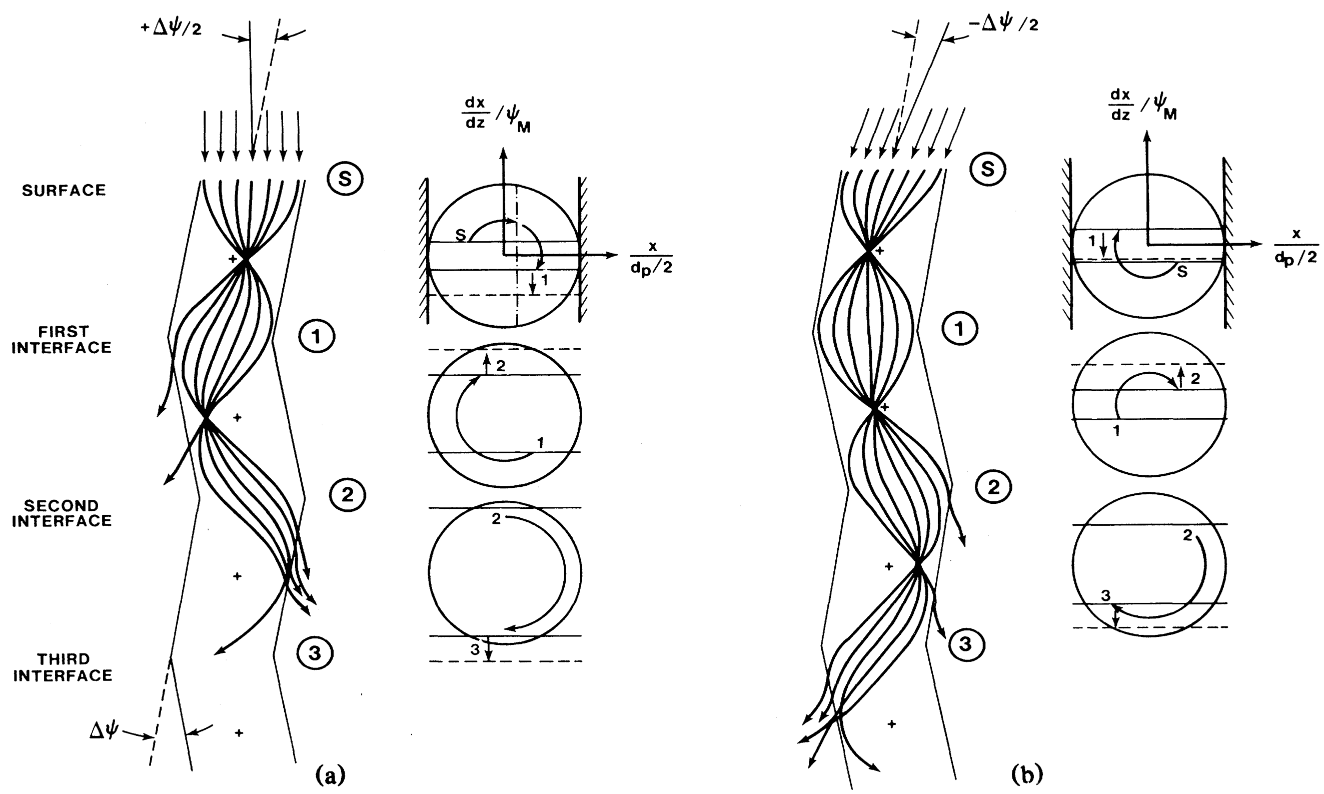

FIG. 2. The calculated trajectories for 1.2-MeV He in an SLS are shown for two different incident angles, (a) $+\Delta\psi/2$ and (b) $-\Delta\psi/2$, where $\Delta\psi$ is the tilt between layers. Catastrophic dechanneling due to focusing of the particles into the planer wall is delayed by one layer thickness by tilting to $-\Delta\psi/2$. Phase-plane results are shown to the right of the trajectories.

where ψ_m is the maximum angle for channeling, d_p is the planar spacing, and the unit circle corresponds to the critical transverse energy for particles to remain channeled. A uniform incident beam of particles is represented in (a) by a horizontal line (S) shifted up from the origin by a distance $\Delta\psi/2\psi_m$. The dot-dashed line at 90° rotation corresponds to the quarter wavelength point at which all the particles are focused at a single position. Motion through the first layer corresponds to a 180° clockwise rotation of the line. Upon crossing the interface, the particles change their direction with respect to the channel walls by an angle $-\Delta\psi$; this corresponds to the line of particles being shifted down to the dashed line at 1 in the upper phase plane of Fig. 2(a). Segments of the line outside the unit circle after the kick correspond to particles that will be rotated into the planar walls and be dechanneled upon further evolution on the phase plane. Under the resonance condition (180° rotation per layer) the line is alternately kicked up or down at each interface, until at 3 in Fig. 2(a) the line moves outside the circle and all particles become dechanneled. This phase-plane evolution describes the rapid increase in dechanneling of particles shown experimentally in Fig. 1 for $\psi_0 = +\Delta\psi/2$.

In Fig. 2(b) the phase-plane analysis for $\psi_0 = -\Delta\psi/2$ shows that the starting line of particles is below the origin, and as a result, its evolution out of the circle at each interface trails that of Fig. 2(a) by exactly one layer. In fact, the particle trajectories immediately after the interface in Fig. 2(b) are the mirror image of the case at the surface in Fig. 2(a). Thus one predicts a delay in depth for catastrophic dechanneling of one layer, consistent with both the sign and approximate magnitude of the catastrophic-dechanneling shift down experimentally in Fig. 1.

The source of angular asymmetry in the catastrophic dechanneling is now clearly seen from the phase-plane analysis. Moving the incident angle to increasingly larger negative values shifts the line S lower on the unit circle and thereby delays the focusing of the channeled particle into the planar wall.

Using the phase-plane description, we can calculate the catastrophic dechanneling depth as a function of incident angle. Immediately after passing the jth interface, the phase line, which corresponds to the channeled beam of particles, is horizontal with ordinant position $h_j = (-1)^j(2jh + h_0)$, where $h_0 = \psi_0/\psi_m$ is the normalized incident angle, $E\psi_m^2 = U(d_p/2)$ defines a critical transverse energy, and $h = \Delta\psi/2\psi_m$ is the normalized SLS half tilt at each interface. Since the part of the phase line which enters and remains inside the circle is the channeled fraction, the dechanneled fraction, $\chi(j)$, as a result of passing the jth interface, is given by the Pythagorean theorem to be

$$1-\chi(j) = \begin{cases} (1-h_0^2)^{1/2}, & j < -h_0/h,\ |h_0| \leq 1, \\ (1-h_j^2)^{1/2}, & j \geq -h_0/h,\ |h_j| \leq 1, \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

If we consider j as a continuous variable and let χ_c denote a critical dechanneled fraction corresponding to the catastrophic-dechanneling depth j_c, then

$$j_c = \begin{cases} \{[1-(1-\chi_c)^2]^{1/2}\psi_m - \psi_0\}/\Delta\psi, & |\psi_0| \leq \psi_m[1-(1-\chi_c)^2]^{1/2}, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

The catastrophic dechanneling depth is seen to be described in terms of the incident angle, the SLS strain-induced tilt angle, and the maximum angle for channeling (ψ_m), which can be determined independently by theory or by experiment in bulk crystals. Thus one can directly relate the depth of catastrophic dechanneling to the strain in the superlattice and predict its angular dependence.

To compare the theoretically predicted angular dependence to observations, we have measured spectra at a large number of incident beam angles near {110}. The results are shown in Fig. 3 for 85% and 50% χ_c levels by the filled and open circles, respectively. The dechanneled level due to the resonance effect was determined by taking the initial channeled level ($\approx 1\times10^3$ at about 0.95 MeV in Fig. 1), constructing a background level for intrinsic dechanneling parallel to that measured for bulk GaP crystal dechanneling, and then determining the depth at which an increase of 0.85 or 0.50 relative to the random level was obtained. The experimental data exhibit a triangular shape, indicating the strongly *asymmetric angular dependence* about the direction of alignment with the first layer, in contrast to most observations in channeling, where nearly symmetric distributions along the channeling directions (e.g., channeled yield at a given depth or depth for a certain dechanneled level) are observed. This key aspect distinguishes this new channeling phenomenon that occurs during resonance.

Two distinct features of the angular dependence at resonance can be directly related to fundamental parameters of the channeling and the superlattice. From Eq. (2) it can be seen that the base of the triangle in Fig. 3 determines the maximum angle for channeling, ψ_m, and that in the limit of $\chi_c = 1$, the width of

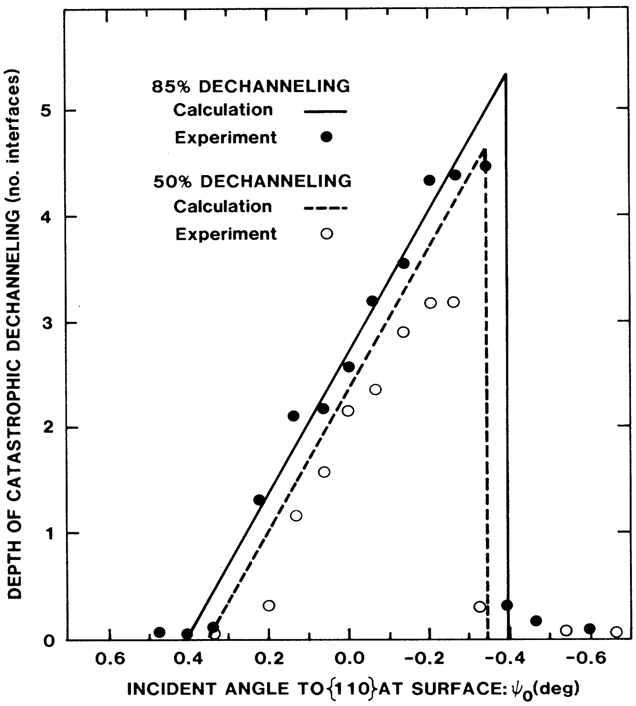

FIG. 3. Experimental results for the catastrophic-dechanneling depth vs incident angle ψ_0 for an 85% and 50% dechanneling criteria. The solid and dashed lines are the theoretical calculations based on the phase-plane analysis [Eq. (2)] for the above dechanneling conditions. The only free input parameter is the lattice strain ($\Delta\psi = 0.15°$), which is obtained from the reciprocal of the slope.

the base equals $2\psi_m$. For the present case we obtain $\psi_m = 0.40°$, which is identical with that given theoretically using a thermally averaged Moliere continuum potential.

The second interesting feature of Fig. 3 is the well-defined slope of the triangular shape of the data points. From Eq. (2),

$$dj_c / d\psi_0 = -1/\Delta\psi. \tag{3}$$

Thus the catastrophic-dechanneling depth increases in Fig. 3 with a slope that is theoretically predicted to be the reciprocal of the tilt angle, thus providing a direct measure of the strain in the superlattice. For this SLS we obtain from the data of Fig. 3 $\Delta\psi = 0.15°$ ($\pm 20\%$). Using this value for $\Delta\psi$ and 0.4° for ψ_m, we obtain from Eq. (2) the solid and dashed lines in Fig. 3 for the 85% and 50% dechanneling levels, respectively. The agreement between experiment and theory is quite good, considering the approximations of the modified harmonic model. The value $\Delta\psi = 0.15°$ is somewhat lower than the strain value $\Delta\psi = 0.24°$ for $x = 0.12$ calculated using linear combinations of the GaP and GaAs elastic constants and assuming 100% accommodation of the lattice mismatch by strain. This resonance angular method of determining strain in SLS is more sensitive at low strains that the axial-channeling angular-scan techniques.[3,4]

In conclusion we have observed at resonance a shift in the characteristic dechanneling depth with an incident angle that exhibits a strongly symmetric and catastrophic character. We have described this new type of channeling behavior with a theoretical, phase-plane analysis and find good agreement with the experiment. In this analysis we obtain directly from the data both $\Delta\psi$ and ψ_m, which are the key parameters describing the strain in the strained-layer superlattices and the strength of the steering potential of the crystal planes.

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