Ion dechanneling due to lattice strains in semiconductor superlattices

John H. Barrett
Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 10 February 1983)

A new source has been considered for the unusual ion dechanneling found in InAs-GaSb superlattices. This new source stems from the strains that occur in the layers because of the slight mismatch between the lattice constants of the two materials. The strains cause the rows and planes of atoms in the crystal that are inclined to the surface normal to have small directional misalignments at the interfaces between the layers. The effects of these misalignments have been incorporated into computer simulations of ion trajectories in the crystal and have been shown by means of the simulations to account in a reasonable manner for the observed dechanneling behavior. Two ways of measuring the amount of misalignment are suggested as a result of the simulations. Calculations have also been done as a function of the amount of misalignment to give some indication of how much dechanneling might be expected for superlattices composed of other pairs of materials with different degrees of mismatch.

INTRODUCTION

Ion dechanneling of an unusual nature has been reported by Saris, Chu, Chang, Ludeke, and Esaki[1,2] for (1—2)-MeV He ions in InAs-GaSb superlattices. With the use of specimens grown by molecular-beam epitaxy on GaSb substrates with (100) surfaces, they observed that ions remained channeled to considerable depths for incidence along the surface normal but were dechanneled near the surface for incidence along directions such as [110] that are inclined to the normal. They suggested a model in which the dechanneling was caused by small offsets in the rows at each interface of about 0.02 nm produced by differences in bond lengths at the interfaces.

In order to provide a better understanding of the dechanneling behavior in these materials, the author has done a series of computer simulations. In one set of calculations[3] the effectiveness of row offsets at the interfaces in producing dechanneling was explored, and it was found that offsets could produce the observed dechanneling, but only if they were 0.08 nm or larger. Because of the very large size of the required offsets and of the indirect method of inferring them, a second method of observing the offsets was sought which would confirm their presence and allow a more accurate determination of their size. The method proposed[4] involved using planar channeling under conditions in which the path length through the first superlattice layer would be about a quarter wavelength of the oscillation of the ions in the channel. Application of this procedure[5] indicated that offsets as large as 0.08 nm were not present although ones of 0.02 nm might be.

As a result of the contradictions for the row-offset model, the author was led to consider a source of dechanneling that had been overlooked in the earlier considerations. This source is the presence of strains in the superlattice layers due to the slight mismatch of their lattice constants, which results in slight changes at the interfaces in the directions of non-normal axes such as [110]. Simulations incorporating this feature of the lattice produce a satisfactory account of all observations. The purpose of the present paper is to present these new calculations. In doing so, a discussion will first be given of the strain due to the lattice-constant mismatch and the resulting production of changes in axial directions at the interfaces. Then the incorporation of these changes into the simulations will be described and the simulation results will be presented and discussed.

LATTICE STRAINS

The perfection in an overlayer of one material grown epitaxially on another depends on the degree of mismatch of their lattice parameters. If the mismatch is small, layers of considerable thickness can be grown with the mismatch being absorbed by lattice strain without defects. For larger mismatches, misfit dislocations will be created to avoid large stresses. For very large mismatches, epitaxial growth may not even be possible.

Consider the situation in which two cubic materials are used to grow a superlattice on a (100) substrate of one of them with the substrate being much thicker than the superlattice. If the lattice mismatch is small enough that there are no dislocations, the strains may be readily computed. In the layers which are not the same material as the substrate, the y and z components of the strain will be equal and will be determined by conformity to the substrate dimensions. The other component of the strain in the second material will be given by

$$e_{xx} = -(2C_{12}/C_{11})e_{yy} \ . \tag{1}$$

The superlattice layers of the same material as the substrate will be unstrained. An example of such a pair of materials with a small mismatch (0.14%) is GaAs-AlAs on a GaAs substrate, which has been studied by Segmüller, Krishna, and Esaki[6] using x-ray diffraction. Their measurements were in excellent agreement with strains computed in the manner just described, and there was no evidence for the presence of any appreciable num-

ber of dislocations.

For InAs and GaSb the lattice constants are 0.605 84 and 0.609 54 nm, respectively.[7] This mismatch of 0.61% is still small enough that dislocations should not occur for sufficiently thin layers, although they may occur for thicker ones. Under the assumptions in the preceding paragraph, the y and z dimensions of the unit cell of InAs must increase by 0.003 70 nm so as to conform to those of GaSb. When the elastic constants of InAs (Ref. 8) are used in Eq. (1), the x dimension of the unit cell in InAs is found to decrease by 0.004 02 nm. The resulting deformation of InAs in the superlattice is shown in Fig. 1. In this situation, the InAs is tetragonal and the [110] axis makes an angle of 45.36° with the surface normal. A GaSb layer of the superlattice will be undistorted and its [110] axis will remain at 45.00°. This change in direction at each interface of an off-normal axis such as [110] will be referred to subsequently as axis tilt. A similar calculation can be done assuming that the stresses in the two types of layers of a superlattice are equal in magnitude but of opposite sign; this will involve the elastic constants of GaSb as well as of InAs. The difference in direction of [110] in this second case is 0.35° so that the axis tilt is virtually independent of how the strain might be shared between the layers of the superlattice.

Before proceeding to the computer simulations, however, something should be said about the possible effects of misfit dislocations. For larger amounts of misfit, there will be a limit to how thick an overlayer can be before dislocations begin to occur in it to relieve some of the strain.[9] When layer thickness and other conditions are favorable to the existence of misfit dislocations, the maximum relief of strain occurs when the dislocations are located at the interfaces. However, the conditions in superlattices composed of semiconductors may not be favorable to the motion of dislocations from potential sources into the layers. Dislocations already present in the substrate are one possible source, a source which is most likely to be effective in the layers closest to the substrate.[10] A reduction in the tendency to introduce misfit dislocations can be achieved by having the lattice constant of the substrate matched to the average lattice constant of the overlayers.[10] Since the first overlayers form part of the substrate for the later ones, more misfit dislocations may occur in the earlier layers until the desired average lattice constant is reached. All in all, the density of dislocations in the InAs-GaSb superlattices of interest here is very difficult to predict, and definitive knowledge of the extent to which they are present and act to relieve some of the misfit strain is probably obtainable only by electron microscopy.

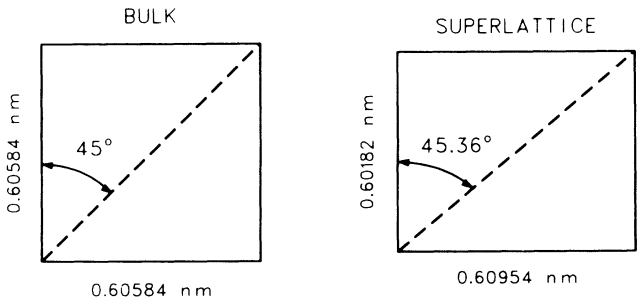

FIG. 1. Distortion of InAs in an InAs-GaSb superlattice grown on a GaSb(100) substrate when there are no misfit dislocations. This information is given in the text.

COMPUTER SIMULATIONS

Computer simulation of channeling is a calculational technique in which a large number of trajectories are followed collision by collision through a lattice. It has been described previously[11] so that only the special features involved in the present calculations will be mentioned here. Electron multiple scattering has been incorporated as in the earlier superlattice calculations.[3] For the thermal vibration amplitude, Kyutt's measured value[12] of $u_1=\langle x^2\rangle^{1/2}=0.0108$ nm in GaSb has been used. At each interface, the positions of the high-charge (In or Sb) and low-charge (Ga or As) rows were interchanged as is appropriate for the [110] direction, and for convenience in doing the calculations the high-charge rows always had $Z=50$ and the low-charge rows $Z=32$. The rows were offset at each interface by 0.02 nm in accord with the 7% difference in bond lengths expected there. Finally, the direction of the [110] rows was changed at each interface by 0.36° as calculated above or by other amounts as desired. It was assumed that no dislocations were present to relieve any of the strain.

The quantity generally calculated for comparison with experiment was the distance into the lattice required to dechannel half the beam or, more specifically, to bring the backscattered yield up to 0.5 of the value for a random direction in the solid. The calculated dependence of this quantity on layer thickness is shown in Fig. 2 together with measured values. The error estimates for the calculated values in the figure as well as similar estimates elsewhere in this article are statistical ones associated with the finite number of trajectories and do not incorporate any

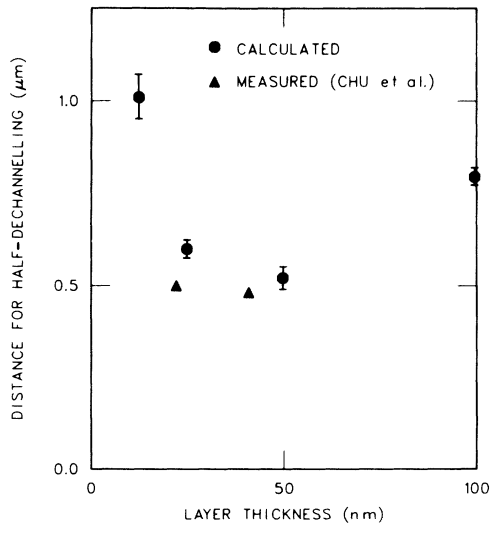

FIG. 2. Dependence on layer thickness of the dechanneling distance for 2.225-MeV He incident along [110] in an InAs-GaSb superlattice with an axis tilt of 0.36°. (The measured values were obtained from Figs. 9 and 10 of Ref. 2.)

allowance for possible inaccuracies in the treatment of thermal vibrations, electron multiple scattering, or other factors. In earlier results[3] it was found that the calculated minimum yield and dechanneling rate for the GaSb substrate were underestimated when using the simulation conditions outlined in the preceding paragraph and that an increase of u_1 to 0.0156 nm gave very nearly the measured minimum yield and dechanneling rate for GaSb. The use of a larger vibration amplitude in the earlier calculations was regarded only as a convenient way of introducing more multiple scattering, and it was felt that any additional scattering would more likely be from some other unkown or inadequately treated source. Results for a larger vibration amplitude have been obtained for only one of the layer thicknesses in Fig. 2. For the 50-nm layer a distance for half-dechanneling was calculated for $u_1=0.0156$ nm; the value of 0.32 ± 0.04 μm. It is to be expected that lower results would also be obtained for the other thicknesses if a larger value of u_1 were used. However, the agreement betwen calculated and measured valaues in Fig. 2 is satisfactory in view of the uncertainties in both the calculated and measured values so that calculations for other layer thicknesses with $u_1=0.0156$ nm were not done. The calculated values are higher toward either the left or the right of Fig. 2, and the two separate reasons for this can be seen. For a small layer thickness, as on the left, the ion beam does not travel far enough in a layer to encounter the rows and get adjusted to the direction in that layer before the direction switches to that for the other layer. Consequently, for thin layers the full effect of the axis tilt is not felt. For larger thickness the ion beam does travel far enough to feel and accomodate to the direction in a layer, and dechanneling takes place primarily during the readjustment period. For the thicker layers, the tendency is to require about the same number of layers for a given amount of dechanneling so that the distance to dechannel the ions is then somewhat in proportion to the layer thickness.

A second calculation done for comparison with experiment was the dependence on energy. The calculated and measured dependences on this parameter are shown in Table I. As the ion energy increases, the acceptance angle for channeling decreases as $E^{-1/2}$, which would produce a variation in the same sense as, but stronger than, that shown in the table. As the energy increases, however, the multiple scattering decreases, producing a variation in the opposite sense to that shown in the table. It appears that the two tendencies nearly balance with only a slight energy dependence remaining. The trend in the calculated values agrees very well with the trend in the experimental ones, and the magnitudes again agree within the uncertainties in calculation and experiment.

TABLE I. Variation with energy of the dechanneling distance for He ions incident along [110] in an InAs-GaSb superlattice with an axis tilt of 0.36°.

Energy (MeV)	Distance for half-dechanneling (μm) Expt.[a]	Calc.[b]
1.01	0.53	0.61 ± 0.04
1.50	0.52	0.53 ± 0.04
2.23	0.48	0.54 ± 0.04

[a]From Figs. 9, 11, and 12 of Ref. 2 for a specimen with 41-nm-thick layers.
[b]For 50-nm-thick layers.

Enhanced dechanneling should be expected in a strained superlattice for planes inclined to the surface normal, just as it is for inclined axes, since the planes will have small misalignments at the interfaces just as the axes do. An interesting comparison to make would be between two sets of planes having the same spacing with one set normal and one set inclined to the surface. Measurements have been made recently[5] for two such sets, (022) and $(2\bar{2}0)$, in an InAs-GaSb specimen having 19- and 14-nm-thick layers, respectively. When a pair of thicknesses for a superlattice is given in this way, the first is for the InAs layers and the second is for the GaSb layers; when a single thickness is given, it is for all layers. Because the backscattering yield for the planes starts with a value of 0.3—0.4 near the surface, the quantity selected for comparison between experiment and calculation was the depth at which 0.7 of the beam was dechanneled, which will be called $D_{0.7}$. The observed values for this depth were 0.71 μm for (022) and 0.33 μm for $(2\bar{2}0)$. The simulations for (022) were done with zero row offset and zero axis tilt, and $D_{0.7}$ was calculated to be 2.1 ± 0.2 μm. The simulations for $(2\bar{2}0)$ were done with a row offset of 0.02 nm and an axis tilt or misalignment of the [110] axis of 0.36°. When the beam was aligned with the center of $(2\bar{2}0)$ in the surface layer, over 0.7 of the trajectories were dechannled after passing through the first interface. However, at small tilts further away from the surface normal, channeling conditions are improved. The optimum angle is about 0.22°, and this orientation would have the appearance of being the channel center. For this optimum direction $D_{0.7}$ was calculated to be 0.32 ± 0.04 μm. The variation of channeling behavior with angle will be discussed more fully in the following paragraph. Because the calculated value for (022) is so much higher than the measured one, a calculation was done with the larger value of u_1, 0.0156 nm, just as done earlier[3] for axial channeling; the resulting $D_{0.7}$ was 1.2 ± 0.1 μm. Although there is poor agreement between the calculations and experiments for planar channeling with regard to the intrinsic dechanneling mechanisms of the crystal, the simulations do show that the expected axis tilt provides a satisfactory prediction for the difference between the dechanneling observed in (022) and $(2\bar{2}0)$.

For InAs-GaSb there is no strong reason to consider other values for the axis tilt than the one calculated above. However, pairs of materials with other degrees of mismatch would have other values of axis tilt. For this reason it is of interest to consider how the distance for half dechanneling varies with this parameter, and such results are shown in Fig. 3. The results shown in the figure together with a value of 3.1 ± 0.3 μm calculated for zero axis tilt are all fit very well by the empirical expression

$$D_{0.5}=(0.32+7.6\alpha^{1.5})^{-1}\,, \tag{2}$$

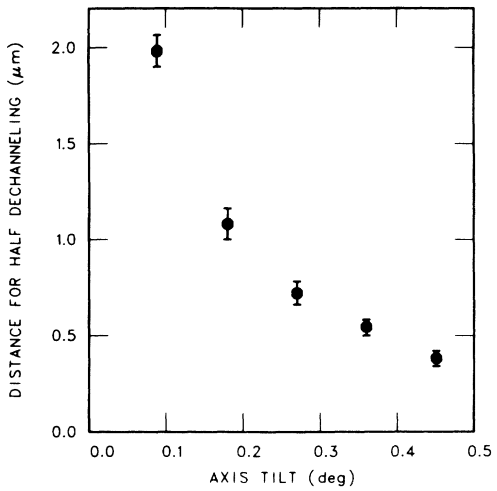

FIG. 3. Dependence on axis tilt of the dechanneling distance for 2.225-MeV He incident along [110] in an InAs-GaSb superlattice with layer thicknesses of 50 nm.

where $D_{0.5}$ is the distance for half-dechanneling in μm and α is the axis tilt in degrees. If the value for zero axis tilt is not included, the points in the figure are fit with a lesser but still acceptable accuracy by $D_{0.5}=0.186/\alpha$. Although there is no obvious reason why either of these relationships should hold, one of them, together with the results in Fig. 2 and some form of scaling according to the critical angle for channeling, might provide a useful guide for predicting behavior in other cases.

As pointed out above, the row-offset model had a serious defect in that the offset required to account for the observed dechanneling was at least 4 times larger than the offset expected on reasonable physical grounds. The axis-tilt model has no such defect since the expected amount of axis tilt accounts for the observed dechanneling behavior very satisfactorily. Nevertheless, it would be desirable to demonstrate the axis tilt and measure its magnitude in a more direct way. Although such a measurement might be made by x-ray diffraction, as it was for GaAs-AlAs,[6] InAs-GaSb presents some difficulty because of the nearly identical x-ray scattering power of these two materials. Channeling and backscattering might offer a useful alternative, and one specific method would be to use planar channeling under conditions for which the path length through the first superlattice layer is a near match to a quarter wavelength of the oscillations of the ions in the channel, just as proposed earlier[4] to look for large offsets. Accordingly, a series of simulations were done at various angles to the $(2\bar{2}0)$ planes. The results are shown in Fig. 4 as contours over the angle-depth plane of backscattering yield relative to that from a random direction in the solid. The contours were constructed by means of a standard computer algorithm, and the simulations used the estimated axis tilt, a row offset of 0.02 nm, the kinematic factor for each element, and a Gaussian depth resolution with 20 nm full width at half maximum (FWHM). The layer thicknesses used correspond to those of the most suitable specimen available for use in a possible experiment, the top layer of which was GaSb. In Fig. 4, the minimum yield occurs for an angle of 0° from the plane in the surface layer but is shifted to angles between 0.2 and 0.35° in the deeper layers. The shift puts the minimum further from the surface normal in the deeper layers than in the surface layer, just as would be expected from the strains estimated above. Since the shifts in most regions appear to have no definite relationship to the axis tilt of 0.36° incorporated into the simulations, it is to be expected that values of axis tilt that may be inferred from experiment will be somewhat imprecise. The measurements made to look for large row offsets[5] are of the general nature needed to look for these angular shifts. Consequently, they were anlayzed by finding the angular dependence for the average yield in several depth ranges. At the time the experiment was done, the specimen was estimated to have the layer thicknesses shown in the figure caption, and an energy of 1.9 MeV was judged to give the best match of the quarter wavelength to the path length through the top layer on the crystal. From the analysis of the experiment, it was observed that the minimum yield was shifted by about 0.1° in all of the deeper layers relative to the surface layer. The conditions of the experiment were such as to allow these relative measurements between layers, but not measurements with sufficient accuracy relative to the surface normal, to be meaningful. Measurements at 1.0 MeV were also made, and their analysis in the same way showed the angle giving the minimum yield in all of the deeper layers to be shifted by about 0.2° relative to the surface layer. It seems puzzling to see a shift twice as large at 1.0 MeV energy as at 1.9 MeV, which was the energy that was expected to give the best match of quarter wavelength to path length in the top layer. However, there was later evidence that the layers were thinner than originally thought, so that 1.0 MeV might have been a good energy for matching the quarter wavelength to the path length in the top layer. The experiments just discussed were not

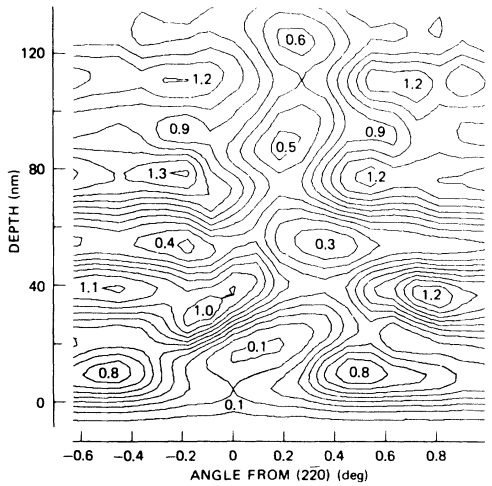

FIG. 4. Backscattering contours for 1.9-MeV He ions in InAs-GaSb with 19- and 14-nm-thick layers, respectively. The beam direction was 7° from [110], and the axis tilt was 0.36°. The levels of local maxima and minima are shown, and the interval between contours is 0.1.

made with the present analysis in mind and were not made under the best conditions for measuring the shift between layers of the angle of the minimum; it would be desirable to have a better set of measurements. Nevertheless, within their limited accuracy they do appear to be in agreement with the results in Fig. 4.

The 7% difference in bond length and the resulting 0.02-nm row offset suggested by Saris and co-workers[1,2] seem to be very reasonable expectations, and it is of interest to look for their consequences. In doing the simulations reported above for the distance for half-dechanneling, an effort was made to assess the role in the presence of axis tilt of the proposed row offsets at each interface due to the differences in bond lengths. With the use of an axis tilt of 0.36°, simulations with no offset and with a 0.02-nm offset showed no difference in dechanneling distance. However, the contours in Fig. 4 differ from ones done with zero row offset; the differences are illustrated in Fig. 5 by showing a comparison of the two cases. The two sets of contours were calculated for exactly the same conditions except for the magnitude of the row offset. Only two contour levels are shown to avoid clutter in the figure. The contours are very similar except in the depth range between 20 and 50 nm, which encompasses the encounter of the beam with the first interface.[13] Within this depth range there are two differences. The first is a general shift in angle of the dip containing the yield minimum. Since the position of this dip also depends on the axis tilt in a somewhat uncertain way, its position might be an unreliable test for row offset. The second difference is in the 1.0 contour level in the vicinity of $-0.02°$ in angle and 35 nm in depth. This difference is of a qualitative nature and should be a more definitive manifestation of the expected row offset of about 0.02 nm. An average of the yield over depths between 35 and 40 nm should show a shallow local minimum at about $-0.2°$ for the expected row offset but no such minimum for zero offset. An experimental demonstration of such a secondary minimum would provide evidence for the existence of a change in bond length at the interfaces, perhaps the only way such evidence could be obtained.

The dependence of channeling behavior on the angle

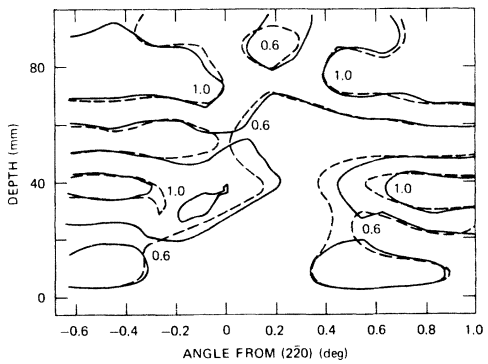

FIG. 5. Backscattering contours for 1.9-MeV He in InAs-GaSb with 19- and 14-nm-thick layers, respectively. The beam direction was 7° from [110] and the axis tilt was 0.36°. The solid lines are contours for a row shift of 0.02 nm, and the dashed lines are contours for no row shift.

discussed in the preceding two paragraphs is very complex. It is appealing to search for any limiting cases that might have simpler behavior. Two possibilities would seem to be when the path length through a layer is either very large or very small compared to the wavelength of the ions in the channel. As an approach to the thick-layer limit, simulations were done for [110] and (2$\bar{2}$0) channeling of 1-MeV He ions in a superlattice with 50-nm layers. For (2$\bar{2}$0) the path through one layer constituted between 1 and 1.5 wavelengths. For axial channeling the oscillations are more complex in character but the ratio of the path through a layer to wavelength would be comparable for [110] to what it is for (2$\bar{2}$0). The angular dependence was quite strong and assymetrical for (2$\bar{2}$0), and was different for different depth ranges. For [110] the behavior was less striking but exhibited considerable complexity. It did not appear that any limiting behavior had been reached at this thickness. This limiting case was not pursued to greater thicknesses because it was felt that the necessary thickness would be so great that a large amount of dechanneling would occur within just one or a few layers, due mostly to intrinsic dechanneling processes and only slightly to superlattice structure. As an approach to the thin-layer limit, simulations were done for [110] and (2$\bar{2}$0) channeling of 2.5-MeV He ions in a superlattice with 5-nm layers. For these conditions, the path through a layer was about one-tenth of a wavelength. For both [110] and (2$\bar{2}$0), the backscattered yield for layers deeper than the first was centered at 0.18°, which is just the average of the axial direction for the two layers. The thin-layer limit does appear to be achievable and gives just the result one would expect. There was one observation[14] in the original set of experiments which was not reported but which might be relevant to the simulations discussed just above. This observation, made for 2.225-MeV He on the specimen with 41-nm layers, was that the angle between [110] and [1$\bar{1}$0] was $90.0°\pm0.1°$. The measurements in this case were made by averaging the yield over several superlattice layers deeper into the crystal than in the simulations just described. The experimental conditions provide a wavelength-to-thickness ratio slightly smaller than for the simulation done above as a probe for the "thick-layer" limit. Because of the different depth ranges averaged over, it is not clear what correspondence is to be expected between this experiment and the "thick-layer" simulation or how any disagreement between them might be compared to the computational and experimental uncertainties involved.

One dechanneling mechanism which was not of importance for InAs-GaSb, and which was not included in the simulations, but which might be important for certain other pairs of superlattice materials is the variation of atomic number between layers. One example of such a pair is GaAs-AlAs, wherein Al has an atomic number less than half that for the other elements involved. Although this dechanneling mechanism might be observable, it is probably not large since the interchange of high-charge and low-charge rows that occurs at each interface in the present set of simulations, although less extreme than switching between Ga and Al, produced only a barely noticeable amount of dechanneling. Other superlattices

would not have to be composed of semiconductors but could be made of pairs of metals or alloys or of any other pair of materials that would grow epitaxially.

CONCLUSION

The new source of dechanneling introduced into the computer simulations described above provides satisfactory agreement of the calculated results with the various channeling measurements.[1,2,5,14] on InAs-GaSb superlattices. This new source is the axis tilt or small misalignment of off-normal directions in different layers of the superlattice caused by strains due to the slight mismatch of lattice constants between the layers. For axial channeling the calculated and measured values are in good agreement, including the dependence on layer thickness and energy of the ion beam. The measured distances for half dechanneling are all slightly below the calculated distances, which is probably due to the fact that the simulations do not provide enough intrinsic dechanneling to agree with measurements for the GaSb substrate crystal; this is undoubtedly the largest systematic source of uncertainty in the calculations. For planar channeling the agreement between the calculations and the limited experimental results is not as good as for axial channeling but is acceptable. In the simulations it was assumed that there were no misfit dislocations present to relieve the strain, and the axis tilt was calculated from the lattice-constant mismatch. The good agreement between theory and published experiments suggests several conclusions. The first is that there are probably too few dislocations in the specimens used to affect the dechanneling in a significant way. In this regard it is to be noted that when misfit dislocations are known to exist, as in PbSe-PbS bicrystals, their dechanneling effect can be observed, even for channeling along the growth direction.[15] For a small number of dislocations, the reduction of dechanneling by relieving misfit strain and thereby reducing axis tilt might be more important than the increased atomic scattering produced by distortions of the lattice around the dislocation itself. A second conclusion is that row offsets at the interfaces due to different bond lengths there produce only a very minor amount of dechanneling. The change in bond length required to produce significant dechanneling is too large to appear reasonable and is ruled out by the planar channeling measurements.[5] A third conclusion from the simulations is that the interchange of high- and low-charge rows at each interface also produces only a minor contribution to the dechanneling. Clearly, the principal source of the unusual dechanneling observed in InAs-GaSb superlattices is the strain and resulting axis tilt produced by the lattice-constant mismatch between the two materials.

Another topic explored was whether the axis tilt for superlattice materials could be observed directly by ion backscattering and channeling. Planar channeling measurements of the kind shown in Fig. 4 offer the best possibility for such an observation. The most desirable type of measurement would be to measure for any given layer the angle between a direction such as [110] and the surface normal or a symmetrically located direction such as [1$\bar{1}$0]. Such a measurement requires a goniometer that can measure large angular differences with very high accuracy. An easier type of measurement, as made in Ref. 5, is to make relative measurements between different layers. Either type of measurement will be most accurate for layers nearest the surface but can be made for deeper layers as well. A limiting case of some simplcity is provided when the path length through a layer is very small compared to the wavelength of the ions in the channel; in this situation averaging over some depth into the crystal allows a direct measurement of the average axis tilt for either axial or planar channeling. X-ray measurements, as in Ref. 6, provide what is probably a generally more accurate alternative for measuring the strain averaged over all layers of the same composition in the superlattice. However, the x-ray technique cannot single out one layer of a superlattice at or near the surface as ion scattering can do; so the two techniques tend to be complimentary. An additional ability of the ion scattering technique would be to make measurements on a top layer which had a thickness as small as only a few atomic planes. A related use of ion scattering to measure strains in a single epitaxial overlayer has been demonstrated by Larson, White, and Appleton[16] for B-doped Si on Si and more recently by Tromp, van Loenen, Iwami, and Saris[17] for Pd_2Si on Si.

One further measurement that should be possible is to demonstrate the existence of bond lengths at the interfaces shorter or longer than the average value, which would manifest themselves by producing row offsets at the interfaces. The demonstration again would involve setting up experimental conditions such that a quarter wavelength for the ions in a planar channel would approximately equal the path length through the first layer of the superlattice. As discussed in connection with Fig. 5, the expected amount of offset should produce a small secondary minimum in an angular scan at the depth of the first interface. This method would have limited accuracy but offers what is probably the only way to demonstrate the existence of a different bond length. Clearly, planar channeling with a quarter wavelength for the ions approximately equal to the path length through the first layer has multiple uses and is an important measuring technique when using ion beams to study superlattices.

Any pairs of semiconductor or other superlattice materials to which the ion backscattering and channeling method might be applied will have other amounts of axis tilt than that of InAs-GaSb. For those materials, the dependence of dechanneling distance on axis tilt shown in Fig. 3 might provide helpful guidance. With other materials, it is possible that large variations of atomic number between alterate layers could make a significant contribution to the dechanneling. It should also be remembered that materials with a large lattice-constant mismatch are more likely to have misfit dislocations which could relieve the strain leading to the axis tilt and could become a direct source of dechanneling themselves. Another measuring technique that might be useful for superlattices that are suspected or known to have misfit dislocations is to use channeling measurements to find the spatial distribution

of misfit dislocations.[15,18] For superlattices the best channeling direction for this purpose might be along the surface normal so as to suppress axis tilt as a source of dechanneling.

ACKNOWLEDGMENTS

This research was sponsored by the Division of Materials Sciences, U. S. Department of Energy under Contract No. W-7405-eng-26 with the Union Carbide Corporation.

[1]F. W. Saris, W. K. Chu, C. A. Chang, R. Ludeke, and L. Esaki, Appl. Phys. Lett. 37, 931 (1980).

[2]W. K. Chu, F. W. Saris, C. A. Chang, R. Ludeke, and L. Esaki, Phys. Rev. B 26, 1999 (1982).

[3]John H. Barrett, Appl. Phys. Lett. 40, 482 (1982).

[4]John H. Barrett, J. Vac. Sci. Technol. 21, 384 (1982).

[5]B. R. Appleton and W. K. Chu (unpublished).

[6]A. Segmüller, P. Krishna, and L. Esaki, J. Appl. Cryst. 10, 1 (1977).

[7]*CRC Handbook of Chemistry and Physics,* 58th ed., edited by Robert C. Weast (Chemical Rubber Co., Cleveland, 1977), p. E-101.

[8]*American Institute of Physics Handbook,* 3rd ed., edited by Dwight E. Gray (McGraw-Hill, New York, 1972), p. 9-73.

[9]J. W. Matthews, in *Dislocations in Solids,* edited by F. R. N. Nabarro (North-Holland, Amsterdam, 1979), Vol. 2, pp. 461–545.

[10]J. W. Matthews and A. E. Blakeslee, J. Vac. Sci. Technol. 14, 989 (1977).

[11]John H. Barrett, Phys. Rev. B 3, 1527 (1971).

[12]R. N. Kyutt, Fiz. Tverd. Tela (Leningrad) 20, 395 (1978) [Sov. Phys.—Solid State 20, 227 (1978)].

[13]The depth scales in Figs. 4 and 5 are meant to correspond to ones obtained by converting an experimental energy-loss scale to a depth scale by use of the average stopping power for the superlattice. Zero depth has been taken to correspond to scattering from Sb at the surface; each of the other elements is shifted uniformly to greater apparent depths by an amount determined by the difference of its kinematic factor from that of Sb and by the average stopping power.

[14]W. K. Chu and F. W. Saris (private communication).

[15]A. Kyoshima, J. Phys. Soc. Jpn. 50, 2395 (1981).

[16]B. C. Larson, C. W. White, and B. R. Appleton, Appl. Phys. Lett. 32, 801 (1978).

[17]R. Tromp, E. J. van Loenen, M. Iwami, R. Smeenk, and F. Saris, Thin Solid Films 93, 151 (1982).

[18]R. S. Williams, B. M. Paine, W. J. Schaffer, and S. P. Kowalczyk, J. Vac. Sci. Technol. 21, 386 (1982).