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Superlattice interface and lattice strain measurement by ion channeling

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The ion-beam channeling technique has been used to characterize the interface and the first few layers of [100] GaSb/AlSb superlattice structures. Strain caused by alternating tensile and compressive stress has been detected by measuring the oscillation of the [110]-aligned direction with depth. From the angular displacement and its oscillation, the amount of strain in the superlattice has been determined directly.

Recently there has been very intense interest in the study of superlattices. Man-made superlattices consisting of alternating layered structures are of fundamental interest as well as being potentially interesting for electronic and optical applications. Ion beam channeling has proven to be very effective in the study of modulated layers. On the other hand, samples of modulated layers provide unusual opportunity for testing the capability of channeling analysis.

Channeling measurements on superlattices were first studied on a set of GaSb/InAs samples using high-energy helium backscattering.[1,2] The measurements reveal higher dechanneling along ⟨110⟩ directions than along the [100] growth direction. A row offset model based on bond-length changes at and only at the interface was proposed.[1,2] However, Monte Carlo simulations indicate that a row offset at the interface is insufficient to produce the observed high dechanneling along the [110] direction of these superlattices.[3] The high dechanneling along the [110] direction has been considered due to the lattice strain that occurs in the layers because of the slight mismatch between the lattice constants of the two materials.[4] Recent channeling measurements on strained-layer superlattices[5-7] are consistent with the lattice strain model that strain causes very high dechanneling. So far, however, no channeling experiment has unambiguously verified that alternate tensile and compressive strain exists in the modulated epitaxy system.

The shadowing underlying atoms by surface atoms has been used for studying surface relaxation phenomena as well as the registry of adatoms.[8] Recently there has been reported an investigation where the motivation was similar to the present. That investigation[9] was motivated by the interest in strained-metal layers. The investigations measured the registry of atoms that were added during the growth process as it developed up to a few monolayers.

In this Rapid Communication, we demonstrate for the first time that channeling experiments can be used to measure the minute amount of strain ($\leq 1\%$) caused by alternating tensile and compressive stress on AlSb/GaSb superlattice layers. The selection of GaSb/AlSb system has the advantage of sharing the same anion, Sb, which enables us to separate the row offset model from the strain study. GaSb/AlSb (30 nm/30 nm) periodic structures with 10 periods were grown epitaxially on [100] GaSb substrates by molecular-beam epitaxy. Growth detail of the GaSb/AlSb system has been described elsewhere.[10] Channeling measurements and analysis were made using a 2-MeV Van de Graaff accelerator at Phillips Hall, University of North Carolina, Chapel Hill. Figure 1 shows a series of energy spectra of 1.76-MeV $^4He^+$ ions backscattered from a superlattice sample at various experimental conditions. The best channeled spectrum, i.e., the lowest curve in Fig. 1, is obtained with the ion beam aligned to the [100] growth direction (0° with respect to the surface normal) of the GaSb/AlSb superlattice. The next lowest spectrum, plotted as solid dots, is an aligned spectrum for [110] axial channeling (45° tilted from normal). A very broad energy window is set for the alignment to ensure that the alignment is based on a sampling of scattering from several layers inside the superlattice. The higher dechanneling along the [110] direction compared with that along the [100] growth direction for this superlattice sample is consistent with all the earlier measurements[1,2,5-7] on superlattices. The random spectrum was obtained by tilting the surface normal of the sample to 43° away from the beam direction with a 10° rotation away from the {110} plane. Between the best [110] aligned spectrum (solid dots on Fig. 1) and the random spectrum (solid curve on Fig. 1), more than fifty spectra were taken at various tilt angles between 43° to 47° at 0.05° or 0.1° intervals. In order not to clutter the figure, only two more spectra (dashed curves) are given in Fig. 1 corresponding to tilt angle of 44.25° and 44.50°. All measurements around and near the [110] axis are taken outside the (110) planes. With a two-axis goneometer, this is done by a small gradual change in the rotational angle in combination with a change in the tilt angle.

It is interesting to learn that the precise angular position for the best alignment along the ⟨110⟩ direction (defined later) is a function of where we set the energy window. In Fig. 1 an energy window of about 15 keV (3 channels) is shown. In the present example this corresponds to a depth in the superlattice between the second and third layers. Since the energy scale of Fig. 1 can be translated to a depth scale, a change in the energy window corresponds to probing different depths of the sample. In Fig. 1 the energy positions are indicated which correspond to the individual GaSb and AlSb layers in both the Sb part of the spectrum (1.4–1.6 MeV) and to those of the overlapping counts from Ga and Sb (below 1.4 MeV). Each layer corresponds to an alternating GaSb (1,3,5, . . .) and AlSb (2,4,6, . . .) layer, with a layer thickness of 30 nm.

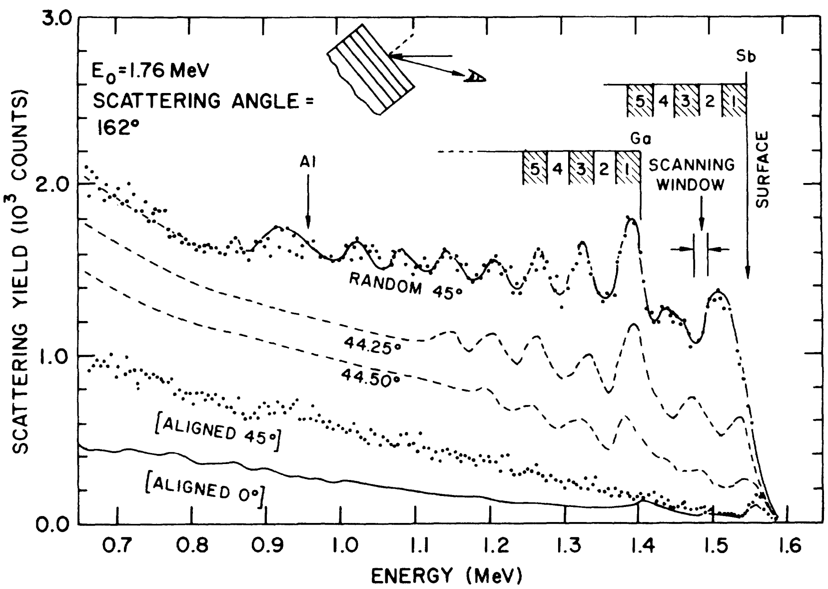

FIG. 1. Energy spectra of 1.76-MeV $^4He^+$ ions backscattered from [100] GaSb/AlSb superlattices. Depth scale based on Sb signals and Ga signals are marked in the unit of number of layers (30 nm/per layer), [100] aligned, [110] aligned, random, and two more spectra are given.

Figure 2 shows the backscattering yield normalized to the random level (around 45° tilt) plotted as a function of tilt angle. Two window settings are given, the first one is set between 1.535 to 1.550 MeV corresponding to the Sb signal of the surface layer of GaSb (plotted as solid circles). The second window is set between 1.490 to 1.505 MeV which corresponds to the Sb signal of the second layer of the superlattice. The center of an angular yield curve (Fig. 2) is defined by the average of the two angular positions corresponding to the midheight on either side of the angular scan. We believe that the center corresponds to an angle of incidence giving the least dechanneling-"best" channeling for a given layer.

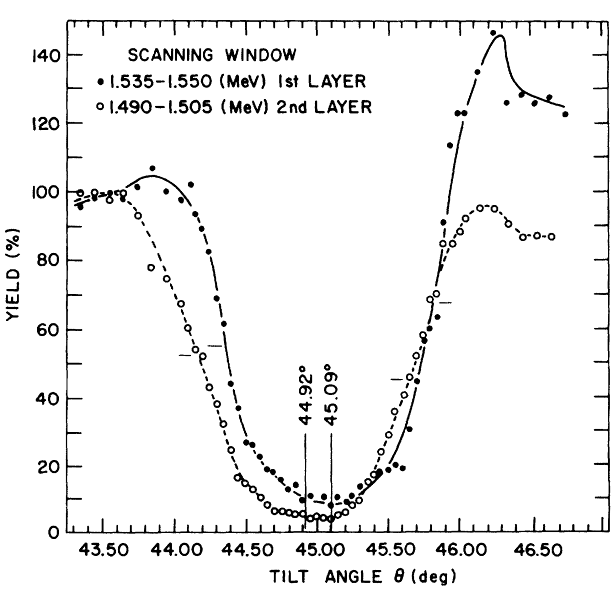

FIG. 2. Angular scan by setting an energy (depth) window at the first layer (solid circles) and second layer (open circles) for 54 spectra run at 54 different angles. The center position of the angular scan changes from layer to layer indicating the [110] direction varies.

One can see from Fig. 2 that the two angular yield curves for two different depths do not have a common center. The first layer is centered at 45.09°, and that of the second layer at 44.92°. This is a direct evidence that the [110] axis for the second layer is not in line with that of the first layer. A small angular difference of 0.17° is observed. This difference is presumably due to the lattice strain caused by intrinsic lattice mismatch between GaSb and AlSb in the superlattice.

We will elaborate our observation of the strain in Fig. 3. The top part of Fig. 3 illustrates a model of a strained superlattice (Poisson effect), and its effect on the channeling along the $[1\bar{1}0]$ or [110] direction. It has been shown that lattice mismatched heteroepitaxy can be grown with essentially no misfit defect if the layers are sufficiently thin and the mismatch is accommodated totally by uniform lattice strain.[11,12] The resulting strains in the superlattices consist of both hydrostatic and [100] uniaxial components which alters the lattice constants. For our superlattice sample, we have

$$a(\mathrm{AlSb})_\perp > a(\mathrm{AlSb}) > a_\parallel > a(\mathrm{GaSb}) > a(\mathrm{GaSb})_\perp ,$$

where $a(\mathrm{AlSb})$ and $a(\mathrm{GaSb})$ are bulk lattice constants, $a_\parallel$ is the lattice constant in the planes parallel to the interfaces, and $a_\perp$ are lattice constants for GaSb or AlSb perpendicular to the interfaces. Lattice strain causes the $[1\bar{1}0]$ and [110] channeling direction to oscillate between an angle greater than 45° and an angle less than 45° degrees as predicted earlier.[4] This is what we observe experimentally and present in the lower portion of Fig. 3.

In Fig. 3, the angular position of the minimum yield, as defined in Fig. 2, is plotted as a function of depth of the superlattice. The window width is three channels wide equivalent to a 15-keV energy interval and is the same as our energy resolution of the backscattering system. From

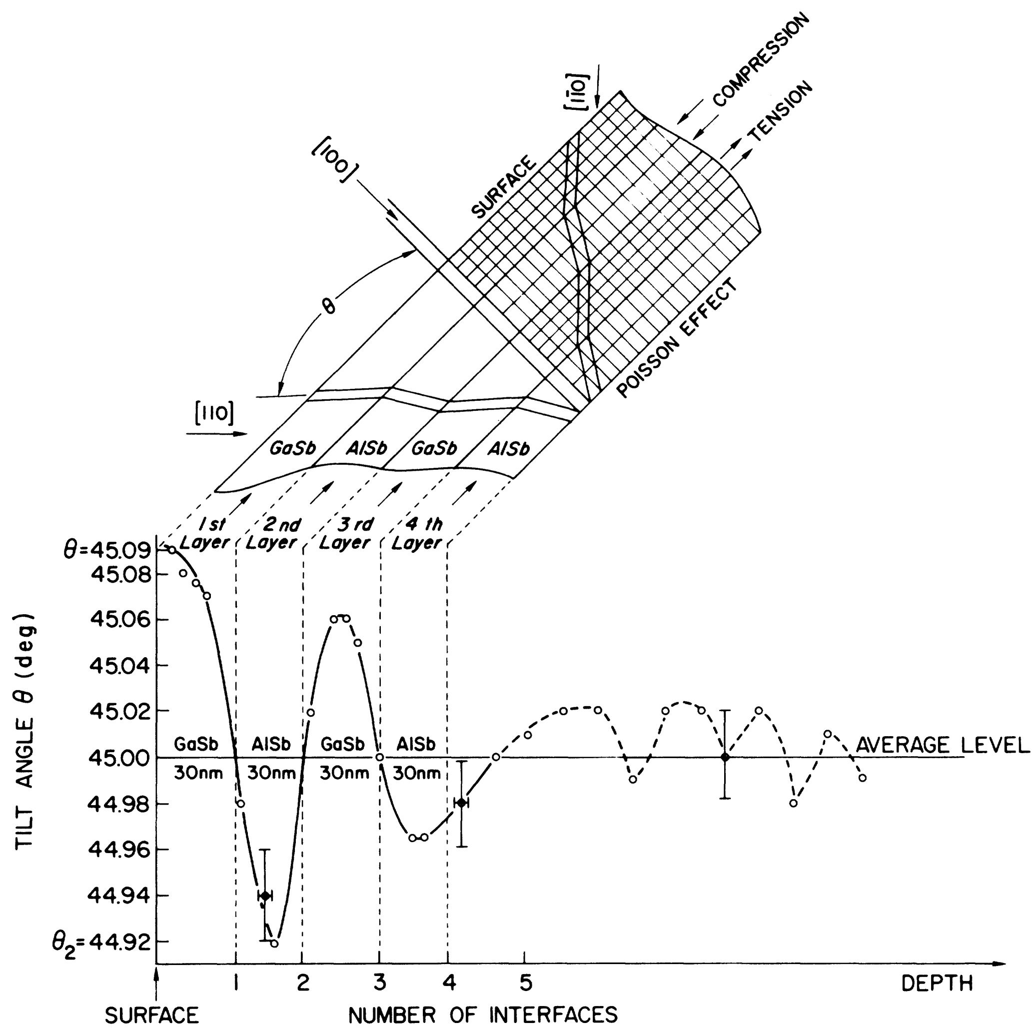

FIG. 3. Top portion shows a schematic drawing of a strained superlattice and its influence on the channeling (see text). The bottom part shows the angular position of the minimum yield defined by Fig. 2 as a function of depth. The oscillations are evidence of a kinked [110] channel.

energy-loss calculation, 30-nm GaSb produces a 34-keV energy shift, while 30-nm AlSb produces a 29-keV energy shift at our experimental conditions. The oscillation of the angular position of the minimum yield is a direct evidence of the alternating tensile and compressive nature of the strain. The damping of the oscillations is due to the fact that an ion channeling at a given layer is always influenced by the previous history of the ion trajectory. We may assume that the change in angular direction of the [110] axis at each interface is the same. For all layers, the lower limit of this "kink" angle is given by the difference of the angular positions between the first and second layers, and from Fig. 3 this is found to be 0.17° ±0.03°.

When the analysis reaches layer 5, i.e., the layer between interfaces 4 and 5, the backscattering yield information is complicated by crowding of the Sb signal from layer 5 and a portion of the Ga signal from layer 1. This can be seen from the overlapping of the depth scales of Sb and Ga given in Fig. 1. This restricts our depth analysis to the top four layers.

Our channeling measurements of Fig. 2 and Fig. 3 indicate a (0.17° ±0.03°) "kink" between the layers of GaSb/AlSb. The results of our strain calculations are summarized in Table I based on the elastic constants of the materials. Because two different lattice parameters have been quoted in the literature for GaSb, the strain calculations are made for both values in separate columns of Table I. $a_{\parallel}$ is related[12] to the moduli[13,14] and lattice constants[15,16] of GaSb and AlSb. The value of $a_{\perp}$ is calculated from the Poisson effect $\Delta x = -\Delta y C_{12}/C_{11}$ where C_{11} and C_{12} are moduli of elasticity. The kink angle

$$\Delta\theta = \tan^{-1}[a(\mathrm{GaSb})\perp/a_{\parallel}] - \tan^{-1}[a(\mathrm{AlSb})\perp/a_{\parallel}] \quad ,$$

TABLE I. Strain analysis.

a(GaSb)	6.095 Å (Ref. 15)	6.118 Å (Ref. 16)
a(AlSb)	6.135 Å (Ref. 15)	6.135 Å
$a_{\parallel}$	6.115 Å	6.126 Å
$a(\mathrm{GaSb})_{\perp}$	6.077 Å	6.111 Å
$a(\mathrm{AlSb})_{\perp}$	6.155 Å	6.144 Å
$\Delta\theta$ (calculated)	0.37°	0.15°
$\Delta\theta$ (This expt.)	0.17° ±0.03°	

and is evaluated to be 0.37° or 0.15° depending on which lattice parameter is used for GaSb. The experimental value gives 0.17° ±0.03°.

In conclusion, we have demonstrated for the first time that channeling can be used to measure the minute amount of *alternating* tensile and compressive strain in a strained superlattice. The experimental result is in good agreement with that calculated from the elasticity of the materials. Oscillation of the [110] direction versus depth and the amount of angular deviation are consistent with the "strained-layer superlattice model" and with recent optical measurement of the GaSb/AlSb superlattice.[17]

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