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DEFORMATION OF $In_xGa_{1-x}As$ SUPERLATTICES UNDER BENDING AND NANOINDENTATION

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Coherently strained $In_xGa_{1-x}As$ superlattices have shown enhanced stability to strain relaxation at temperatures up to nine-tenths of their melting point.[1] In addition, the hardness of these superlattices varies in inverse proportion to their strain modulation.[2] Here we examine directly the deformation induced by compressive bending (at elevated temperature) and indentation (at room temperature) in the transmission electron microscope (TEM). The superlattices were grown by molecular beam epitaxy on InP substrates[1] and details of the two structures are given in table 1. Three-point bending was performed at 500 ºC and carried out such that the superlattice was under a compressive stress with a radius of curvature of about 2 mm. Nanoindentation was performed using a UMIS 2000 system, with a spherical diamond indenter (3 μm nominal radius) at loads of 15 and 40 mN. A load of 15 mN was just at the threshold of pop-in on the load-depth plot. Loads below this showed no plastic deformation. Thin foils suitable for examination in the TEM were prepared using a FEI focused ion beam (FIB) workstation as described elsewhere.[3]

Surface steps could be seen on the bent sample viewed in the optical microscope. The steps are also evident on the TEM cross-section shown in fig.1(a). The layered structure is particularly useful here as it is an internal marker to chart the plastic flow within the material. Examining fig.1(b) it can be seen that a ruck in the layering has developed in the third multilayer repeat from the surface that propagates along the {111} planes through the whole structure to create a step at the free surface and a step (of opposite sign) in the substrate. Lines of defects are seen most predominantly localized on {111} planes which are the usual slip planes for this crystal and they extend into the substrate. Given that the original structure has a very low dislocation density it is likely that the steps in the layers arise from the passage of many dislocations originating from a source nucleated in the third compressive layer. Since the substrate is 300 μm thick, the stress varies little through the 2.5 μm thickness of the superlattice hence it appears that the source has nucleated randomly at this point. The height of the step created on the surface is around 40 nm, which corresponds to the passage of around 100 dislocations. Misfit dislocations have also been generated in the thinner tensile layers. The diffraction pattern from the multilayer indicates that the deformation maintains the original lattice orientation with no rotations evident.

The localized loading induced by the indenter at room temperature showed contrasting behaviour. Fig.2(a) is a bright field image of the indent produced at a load of 40 mN in which several twins are evident parallel to the {111} planes. (Additional diffraction spots arising from the twins can be seen in the diffraction pattern inset). The shear associated with each twin is 35.3º, and for 5 twins approximately 30 nm in width this produces a total vertical displacement of around 100 nm, which is about two-thirds of the indent depth. Regions of high dislocation density are also present around the twins and this presumably accounts for the lattice rotations evident in the diffraction pattern. For the 15 mN indent (fig.2(b)) the deformation was similar although fewer twins were present and the volume of plastically deformed region was smaller as expected. These observations are similar to those previously obtained in monolithic GaAs in which twinning was also found to be the dominant deformation process under loading of a pointed Berkovich indenter.[3]

References

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3. S.J. Lloyd et al., *J. Mater. Res.* 16 (2001) 3347.
4. The authors are grateful to the Royal Society and the EPSRC for financial support.

TABLE 1. Details of the $In_xGa_{1-x}As$ superlattices. t is the layer thickness and ε is the strain measured by X-ray diffraction in the compressive (-) and tensile (+) layers.

Specimen	x	t (nm)	ε (%)
bent	0.576	100	-0.25
	0.356	25	+1.25
indented	0.633	50	-0.50
	0.489	50	+0.63

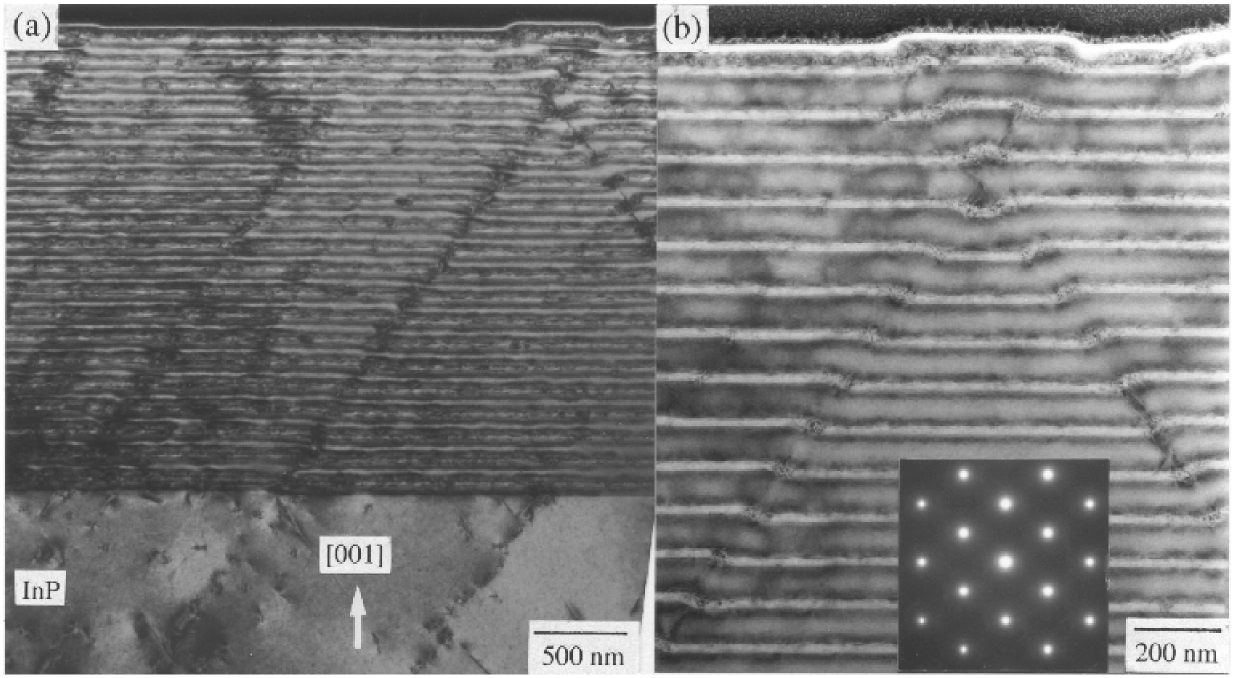

FIG. 1. Superlattice after compressive bending. (a) bright field image showing whole superlattice. (b) higher magnification bright field image of the region where shearing of the layers has been initiated. Diffraction pattern inset.

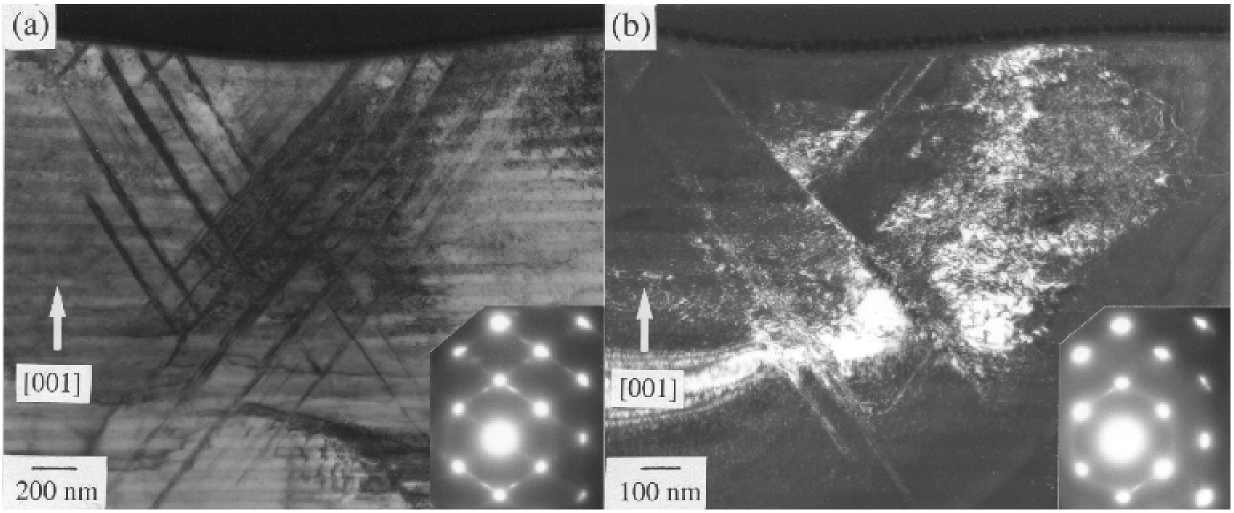

FIG. 2. Indented superlattice. (a) bright field image of the 40 mN indent. (b) 220 dark field image of the 15 mN indent. Diffraction patterns from the indented regions are inset.