Anisotropy and growth-sequence dependence of atomic-scale interface structure in InAs/$Ga_{1-x}In_xSb$ superlattices

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We have used cross-sectional scanning tunneling microscopy to study the atomic-scale interface structure of InAs/$Ga_{1-x}In_xSb$ superlattices grown by molecular beam epitaxy. Detailed, quantitative analysis of interface profiles obtained from constant-current images of both (110) and (110) cross-sectional planes of the superlattice indicate that interfaces in the (110) plane exhibit a higher degree of interface roughness than those in the (110) plane, and that the $Ga_{1-x}In_xSb$-on-InAs interfaces are rougher than the InAs-on-$Ga_{1-x}In_xSb$ interfaces. The roughness data are consistent with anisotropy in interface structure arising from anisotropic island formation during growth, and in addition a growth-sequence-dependent interface asymmetry resulting from differences in interfacial bond structure between the superlattice layers. *© 1997 American Institute of Physics.* [S0003-6951(97)02401-7]

InAs/$Ga_{1-x}In_xSb$ strained-layer superlattices have shown great promise for application in mid-to-long wavelength infrared imaging applications.[1,2] However, the atomic-scale interfacial properties of the superlattice structure have been found to be of crucial importance in determining material and device properties. Because both groups III and V constituents change from one superlattice layer to the next, two distinct bond configurations—InSb-like and $Ga_{1-x}In_xAs$-like—can be present at each interface. $Ga_{1-x}In_xSb$/InAs superlattices grown with InSb-like interfacial bonds have been demonstrated to possess superior device characteristics compared to those grown with $Ga_{1-x}In_xAs$-like bonds.[3,4] A detailed understanding of the atomic-scale structural and compositional properties of these interface is therefore essential to the optimization of electrical and optical properties of device structures based on InAs/$Ga_{1-x}In_xSb$ and related materials systems.

In this letter, we describe a detailed, quantitative analysis of interface structure in InAs/$Ga_{1-x}In_xSb$ superlattices using cross-sectional scanning tunneling microscopy (STM). Previous studies provided evidence of atomic-scale interface roughness and asymmetry in InAs/GaSb[5–8] and InAs/$Ga_{1-x}In_xSb$[9] superlattices. In the present work, high-resolution cross-sectional STM images of InAs/$Ga_{1-x}In_xSb$ superlattices are used to investigate directly and quantitatively the degree of directional anisotropy and growth-sequence dependence in interface structure. To quantify the interface structure observed by STM, individual interface profiles are extracted from the images and their roughness spectra calculated. The roughness spectra show that interfaces in the (110) plane of the superlattice exhibit larger roughness amplitudes and correlation lengths than interfaces in the (110) plane, and that interfaces in which $Ga_{1-x}In_xSb$ has been grown on InAs exhibit larger roughness amplitudes and correlation lengths than interfaces in which InAs has been grown on $Ga_{1-x}In_xSb$.

The InAs/$Ga_{1-x}In_xSb$ superlattice structure was grown by solid-source molecular-beam epitaxy (MBE) in a VG V80 MKII MBE system on an *n*-type GaSb (001) substrate. The growth system and substrate preparation techniques have been described elsewhere.[5] The superlattice consisted of 50 Å $Ga_{0.75}In_{0.25}Sb$ alternating with 17 Å InAs for 150 periods, capped with 500 Å GaSb. The epitaxial layers were grown at 380 °C on a 1000 Å GaSb buffer layer. At each interface in the superlattice layers, a 5 s Sb soak was used to induce the formation of InSb-like bonds. The average composition and overall structural quality of the sample were confirmed by high-resolution x-ray diffraction.

STM experiments were conducted in an ultrahigh-vacuum system at a base pressure of approximately $1-2 \times 10^{-10}$ Torr. Superlattice samples were cleaved *in situ* to expose either a (110) or a (110) cross-sectional face on which STM imaging was performed. While atomically flat cross-sectional surfaces were obtained for both the (110) and (110) planes, we found that cleaving to expose the (110) surface was generally more successful. Both Pt–Ir and W tips cleaned *in situ* by electron bombardment were used for these studies.

Figure 1 shows a high-resolution constant-current cross-sectional image of the superlattice structure, obtained at a sample bias voltage of -1.5 V and a tunneling current of 0.1 nA. Clearly visible in the image are electronically induced contrast between the bright $Ga_{1-x}In_xSb$ layers and the darker InAs layers, as well as corrugations in both the $Ga_{1-x}In_xSb$ and InAs layers corresponding to atomic bilayers on the surface. Monolayer-level roughness can be seen at the interfaces between the InAs and the $Ga_{1-x}In_xSb$ layers. A large number of images of similar quality were obtained over regions up to 1000 Å×1000 Å in size from both (110) and (110) cross sections of the sample.

Individual interface profiles are extracted from the images by enhancing the contrast between the InAs and

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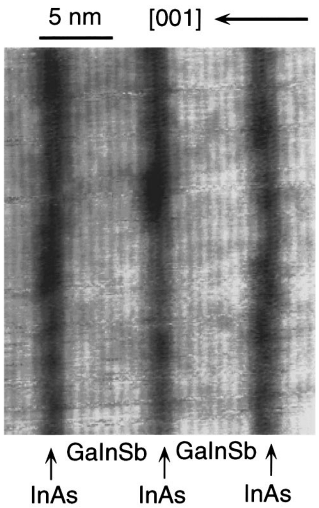

FIG. 1. High-resolution constant-current STM image of the $Ga_{0.75}In_{0.25}Sb/InAs$ superlattice, obtained at a sample bias of -1.5 V and a tunneling current of 0.1 nA. The gray-scale range of the image is 2.5 Å. Monolayer roughness is visible at the interfaces between the InAs layers and the $Ga_{1-x}In_xSb$ layers.

$Ga_{1-x}In_xSb$ layers, and then using an edge-detection algorithm. Quantitative profiles $a(x)$ are obtained by measuring the distance between the interfaces and a baseline corresponding to the profile of the atomic bilayers in the image from which the interfaces have been extracted. Figure 2 shows representative interface profiles extracted from images similar in quality to that of Fig. 1. In total, several dozen interface profiles, each 500 Å in length, were extracted from multiple STM images of both (110) and (110) cross-sectional surfaces.

The roughness spectra of the interfaces are calculated by taking discrete Fourier transforms of the extracted profiles. The roughness frequency components A_q are given by

$$A_q=\frac{2}{N}\sum_{n=0}^{N-1} a(\mathrm{nd})e^{-iqd}, \qquad (1)$$

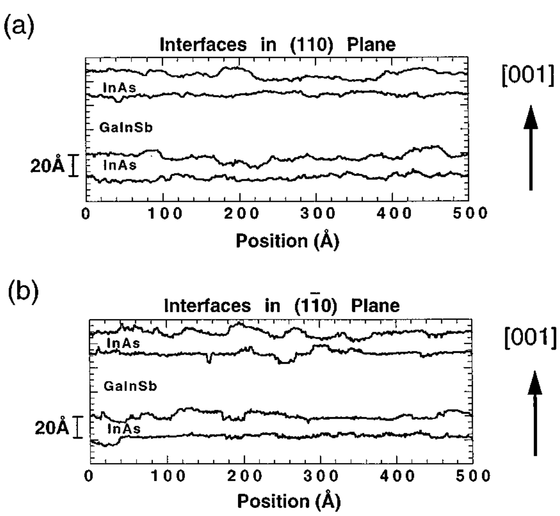

FIG. 2. Representative interface profiles obtained from (a) (110) and (b) (110) cross-sectional STM images of the $Ga_{1-x}In_xSb/InAs$ superlattice sample. The [001] growth direction is indicated.

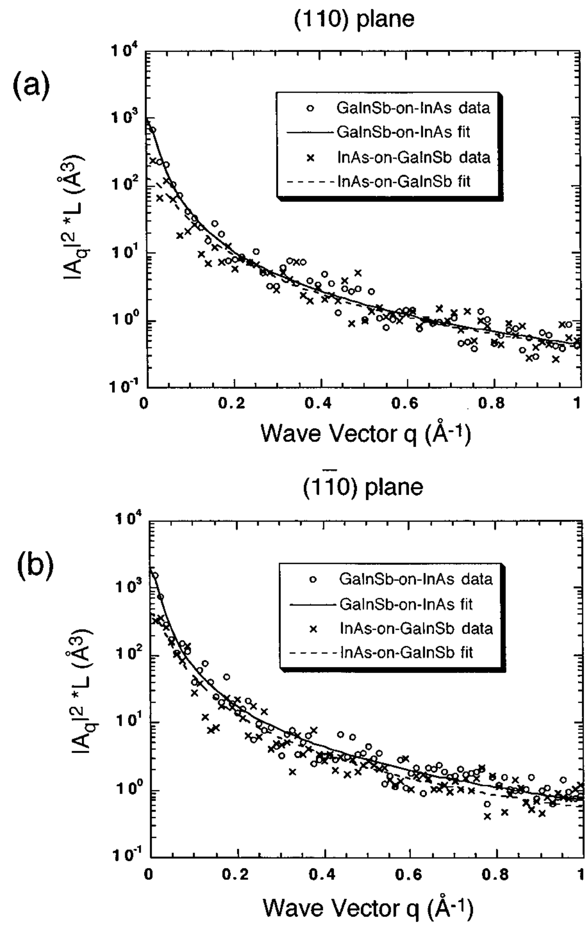

FIG. 3. Interface roughness power spectra (symbols) and Lorentzian fits to the spectra (lines) for $Ga_{1-x}In_xSb$-on-InAs and InAs-on-$Ga_{1-x}In_xSb$ interfaces from (a) (110) and (b) (110) cross sections of the superlattice. Roughness amplitudes and correlation lengths for each interface type are listed in Table I.

where $q={}^{2\pi n}/L$, L is the length of the interface, and d is the spacing between data points along the interface (typically 0.5 Å). The power spectrum of each interface, $|A_q|^2$, is fitted to a Lorentzian function,

$$|A_q|^2=\frac{1}{L}\times\frac{2\Delta^2(\Lambda/2\pi)}{1+(q\Lambda/2\pi)^2}, \qquad (2)$$

where Δ is the roughness amplitude and Λ the correlation length. We find the Lorentzian to be a better fit to our data than a Gaussian or other functional forms. The Lorentzian spectral distribution corresponds to an exponential correlation in real space, and is expected for a random distribution of steps at the interface.[10] Figure 3 shows a plot of the power spectra and also of Lorentzian fits to the power spectra for $Ga_{1-x}In_xSb$-on-InAs and InAs-on-$Ga_{1-x}In_xSb$ interfaces from both (110) and (110) cross sections. Table I lists the roughness parameters for each interface type. The spectra shown are averages of individual roughness spectra from at least 6 different profiles for each interface type. Note that interfaces imaged in the (110) cross-sectional surface are oriented parallel to the [110] direction in the sample.

As indicated in Table I, the interfaces in the (110) plane exhibit larger roughness amplitudes and correlation lengths than those in the (110) plane. This observation is consistent

TABLE I. Roughness amplitudes and correlation lengths obtained from fitting a Lorentzian to the interface roughness power spectra calculated for $Ga_{1-x}In_xSb$-on-InAs and InAs-on-$Ga_{1-x}In_xSb$ interfaces from (110) and (110) cross-sectional images. Error estimates are shown.

Cross section	Interface	Amplitude Δ (Å)	Correlation length Λ (Å)
$(1\bar{1}0)$	$Ga_{1-x}In_xSb$-on-InAs	4.3 ± 0.2	327 ± 38
	InAs-on-$Ga_{1-x}In_xSb$	2.8 ± 0.2	174 ± 21
(110)	$Ga_{1-x}In_xSb$-on-InAs	3.2 ± 0.2	301 ± 39
	InAs-on-$Ga_{1-x}In_xSb$	1.9 ± 0.1	112 ± 16

with anisotropic island formation during growth, a phenomenon that has been observed, using both reflection high-energy electron diffraction (RHEED)[11] and STM,[12,13] in growth of (001) GaAs. These studies showed that islands on the GaAs surface tend to be elongated in the [110] direction. Such island formation during growth of the InAs/$Ga_{1-x}In_xSb$ layers should lead to anisotropic interface structure: interfaces from the (110) cross section, which profile the elongated-island cross sections present along the [110] direction, would be expected to contain smaller roughness components in their roughness spectra than interfaces from the (110) cross section, which profile the shorter-island cross sections found along the [110] direction. The quantitative results obtained from our interface roughness analysis are consistent with this interpretation.

The parameters in Table I also show a substantial dependence of interface roughness on growth sequence, with the $Ga_{1-x}In_xSb$-on-InAs interfaces being substantially rougher than the InAs-on-$Ga_{1-x}In_xSb$ interfaces. In earlier studies of InAs/GaSb superlattices using STM, a substantial growth-sequence dependence was also observed, with the degree of asymmetry in interface structure depending upon growth conditions.[6–8] X-ray diffraction analysis of InAs/$Ga_{1-x}In_xSb$ superlattice samples have suggested that the $Ga_{1-x}In_xSb$ layers are terminated with InSb-like bonds, while the InAs layers are terminated by roughly equal numbers of InSb-like and $Ga_{1-x}In_xAs$-like bonds.[5] The $Ga_{1-x}In_xSb$-on-InAs interfaces would then be of mixed InSb-like and $Ga_{1-x}In_xAs$-like in character, while the InAs-on-$Ga_{1-x}In_xSb$ interfaces would be of a more homogeneous InSb-like character. Since STM is sensitive to nanometer-scale changes in electronic structure, differences in interfacial bond structure such as this would be reflected in the roughness as measured by STM, and could account for the observed growth-sequence dependence of interface structure. It should be noted that interfacial bond structure, and therefore interface roughness, has been shown to vary considerably with growth procedures in studies of InAs/AlSb[14] and InAs/GaSb structures.[15]

In summary, we have used cross-sectional STM to investigate directly the atomic-scale interface morphology of InAs/$Ga_{1-x}In_xSb$ superlattices grown by MBE. Spectral analysis of interface roughness observed by STM shows that interfaces in the (110) cross-sectional plane have larger roughness amplitudes and correlation lengths than those in the (110) cross-sectional plane, suggesting the presence of directional anisotropy in the interface structure of the superlattice layers arising from anisotropic island formation during growth. The roughness spectra also indicate the presence of a growth-sequence dependent interface asymmetry: interfaces in which the $Ga_{1-x}In_xSb$ has been grown on InAs have larger roughness components than interfaces in which InAs has been grown on $Ga_{1-x}In_xSb$. This suggests differences in interfacial bond structure depending on growth conditions, and supports earlier observations suggesting a more homogeneous InSb-bond character at the InAs-on-$Ga_{1-x}In_xSb$ interfaces than at the $Ga_{1-x}In_xSb$-on-InAs interfaces.

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