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# Study of the morphology of the InAs-on-AlSb interface

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Using an atomic force microscope, we studied various InAs-on-AlSb interface structures grown by molecular beam epitaxy. We found marked differences between the effects of the two interface bond configurations—InSb-like and AlAs-like—on the morphology of the subsequent InAs layer. In general, InSb-like interfaces lead to a much smoother InAs overgrown layer with clearly resolvable monolayer terraces. AlAs-like interfaces, on the other hand, lead to increasingly rougher InAs growth with longer As exposure. Previous studies have demonstrated a strong correlation between the interface configuration and the electron mobility in the InAs quantum well. The morphology and transport results we obtained indicate one reason for the influence of the interface configuration—a rough InAs layer. © *1997 American Institute of Physics.* [S0021-8979(97)01522-3]

## INTRODUCTION

Much work has been done to improve the quality of (Al,Ga)Sb–InAs quantum wells (QWs) in order to achieve higher electron mobilities as promised by the low electronic effective mass in InAs. One important issue is the quality of the interfaces on either side of the QW. Since growing InAs on AlSb involves changing both the anion and the cation, two possibilities for the interface bond configurations arise: an InSb-like interface or an AlAs-like interface. Previous studies[1–6] have pointed out a strong influence of the interface configuration on the properties of the InAs QWs, particularly the bottom interface. However, direct measurements of the effect of this bottom interface on the subsequent growth of the InAs layer have not been performed. In the present work, we used atomic force microscopy (AFM) to directly measure the morphology of InAs layers grown on top of different InAs-on-AlSb interface growth sequences. We then performed transport measurements on the corresponding QW structures to establish the correlation between the interfacial morphology and the electron mobility in the channel.

## EXPERIMENT

Four pairs of samples with different growth sequences for various InAs-on-AlSb interface configurations were grown on semi-insulating GaAs(001) substrates in a solid-source Varian Gen II molecular-beam epitaxy (MBE) chamber. Each pair of samples consisted of one AFM sample and a transport sample. A schematic of the growth structure is shown in Fig. 1(a), in which the growth of the AFM samples was terminated 1.5 nm into the InAs layer; whereas the full structure was used for the transport samples. The respective growth rates for GaSb, AlSb, and InAs were 2.81, 2.56, and 0.76 Å/s. Both $As_2$ and $Sb_4$ had beam equivalent pressures (BEPs) of about $2\times10^{-6}$ Torr. The substrate temperature during the GaSb buffer was 530 °C as measured by an infrared pyrometer. After the GaSb buffer layer, the substrate was cooled to 510–520 °C during the bottom superlattice barrier and cooled further to 490–500 °C while the bottom interface and the InAs layer were being grown. Apart from the growth sequence for the bottom interface, all samples were grown as identically as possible, which included the top interface being InSb-like in all the QW samples.

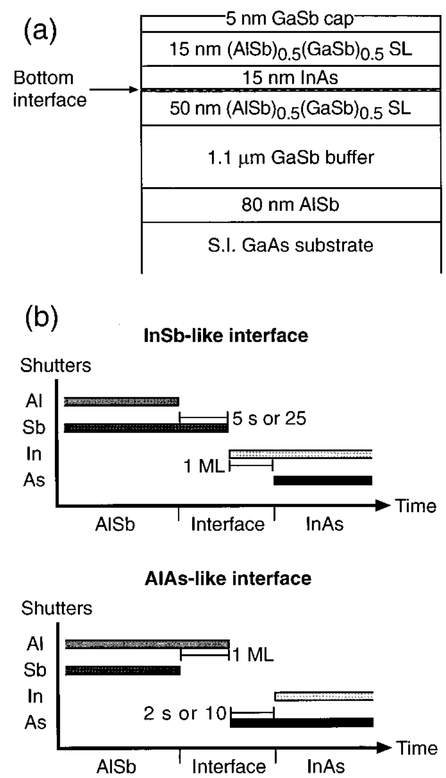


FIG. 1. Schematics for (a) the layer structure of the transport samples and (b) the shutter sequences for the two interface configurations used for the bottom interfaces. For our AFM samples, we stopped the growth 1.5 nm into the InAs layer.

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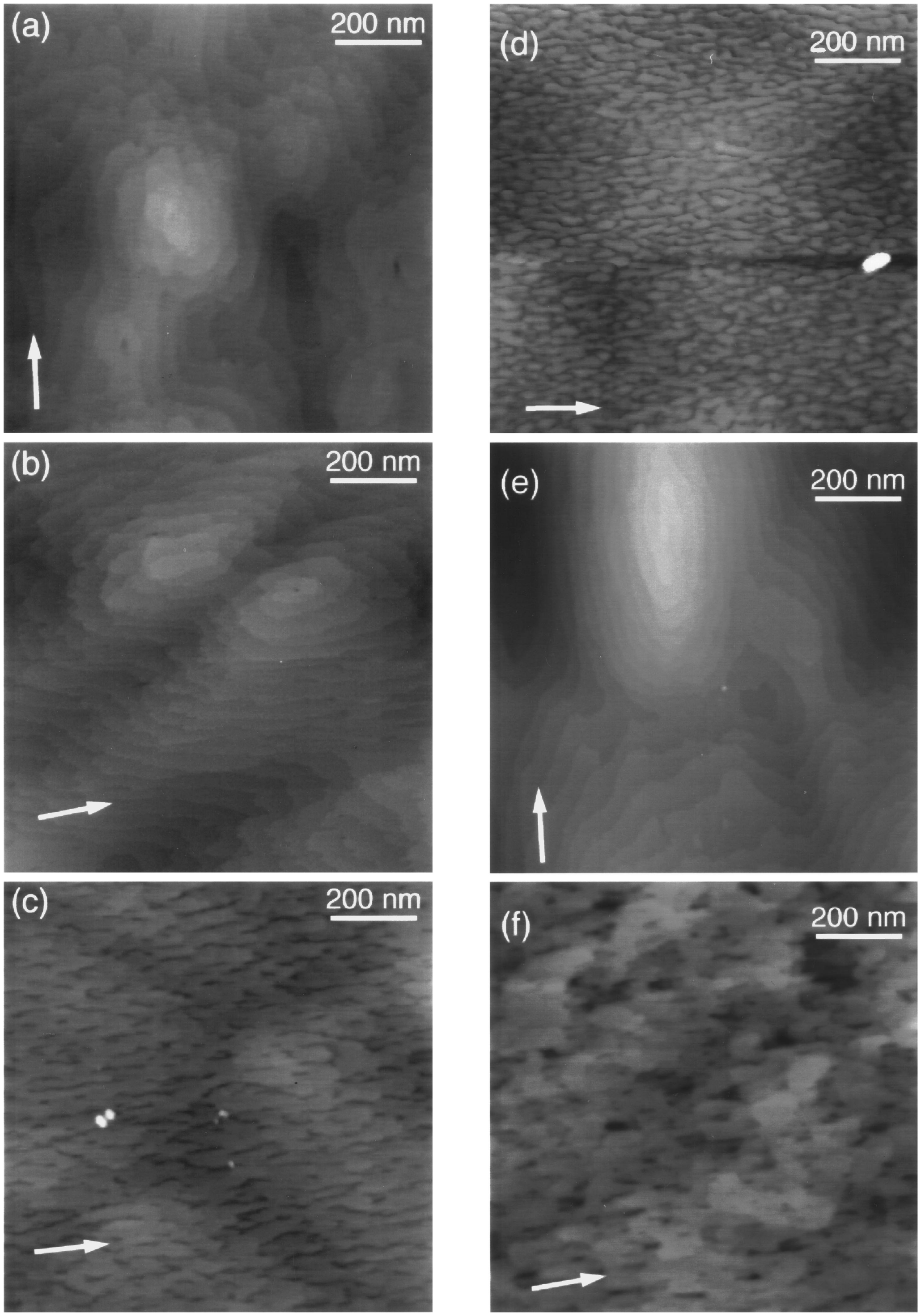


FIG. 2. 1 $\mu$m$\times$1 $\mu$m AFM scans of the as-grown surfaces of six samples: InSb-like interfaces with (a) 5 and (b) 25 s Sb soaks; AlAs-like interfaces with (c) 2 and (d) 10 s As soaks. (e), (f) Samples similar to (c) and (d), respectively, but these samples have a cap layer of 15 nm instead of 1.5 nm InAs. The arrows indicate the [$\bar{1}$10] azimuth and the vertical scale on all images is 10 nm from black to white.

Figure 1(b) shows the shutter sequences used to produce the two interface configurations. In both cases, the deposited group III element nominally constituted one monolayer while the group V exposure was varied: The Sb soak time was 5 s for sample A and 25 s for sample B, while the As soak was 2 s for sample C and 10 s for sample D. A thin layer (1.5 nm) of InAs was grown on top of the interface to protect the underlying AlSb layer while keeping a close proximity to the interface for the AFM measurements, which were performed within a few hours of removal from vacuum.

## RESULTS

Figure 2 shows 1 $\mu$m$\times$1 $\mu$m AFM scans of the InAs surface on the various interfaces. The images were obtained with a Digital Instrument Nanoscope III AFM using tapping-mode AFM. Immediately noticeable are the similarities between the samples with the same interface configuration and the sharp differences between the two configurations. In the InSb cases [Figs. 2(a) and 2(b)], one can clearly resolve the individual monolayer (~0.3 nm) terraces stacked up to form elongated islands. On closer examination, many of these islands terminate in a spiral form. This type of spiral growth was reported elsewhere;[7] it was attributed to screw dislocations at the center of the island. On wider-area scans, we obtain an areal island density of $\sim 4\times 10^8$ cm$^{-2}$ for sample A and $\sim 2\times 10^8$ cm$^{-2}$ for sample B. This agreed well with what was reported by Brar and Leonard,[7] suggesting that InAs grows in a layer-by-layer fashion on top of the InSb-like interface, preserving the morphology of the underlying buffer layer.

The two samples with AlAs-like interfaces [Figs. 2(c) and 2(d)] show very different morphologies when compared to the InSb-like ones. AFM scans at different magnifications reveal that there are two types of roughness for these AlAs-like samples. There is a long-range roughness similar to that found on the InSb-like samples. This roughness is clearly inherited from the underlying buffer layer. On top of this long-range roughness is a high-density short-range roughness on a length scale similar to the width of the terraces (~50 nm) found on the InSb-like samples. This suggests that the growth of InAs on an AlAs-like interface does not progress in a smooth two-dimensional manner but, instead, a ''nanoroughness'' develops as growth progresses. Comparing the images for samples C and D reveals a couple of important differences. The AFM image of sample C appears to have a remnant terrace structure with a high density of directional voids in the terraces. Sample D shows far less order and appears to have entered a three-dimensional growth regime, although the electron diffraction pattern during growth suggested a two-dimensional growth. The exact nature of the roughening process requires further investigation, but using the above differences, we propose a plausible scenario: Exposure of the AlSb surface to an As flux causes an exchange reaction to occur,[8] swapping out Sb atoms and producing an Sb-rich surface. This surface Sb has been shown to persist during the growth of InAs by various groups.[8,9] The existence of surface Sb alters the surface chemistry and, as a result, the InAs layer does not grow via step-flow growth but via island coalescence. From Fig. 2(f), it is evident that such island coalescence is incomplete, producing voids in the InAs layer. A prolonged exposure to an As overpressure, as in sample D, can produce more Sb atoms at the growth surface, disrupting layer-by-layer growth even further, and producing smaller islands. Indeed, Fig. 2(d) appears to support such a scenario.

The corresponding QW samples, used in the Hall measurements, tell the effect of interface morphology on electron transport in the InAs layer. All of the QWs are only 20 nm away from the surface and are effectively doped by the pinning of the Fermi level at the GaSb surface.[10] Figure 3 shows the electron mobilities and sheet concentrations of the four samples. Samples A, B, and C have essentially the same electron sheet concentrations. Their mobilities, however, have some notable variations. At 12 K, the two samples with InSb-like interfaces have very similar mobilities, agreeing

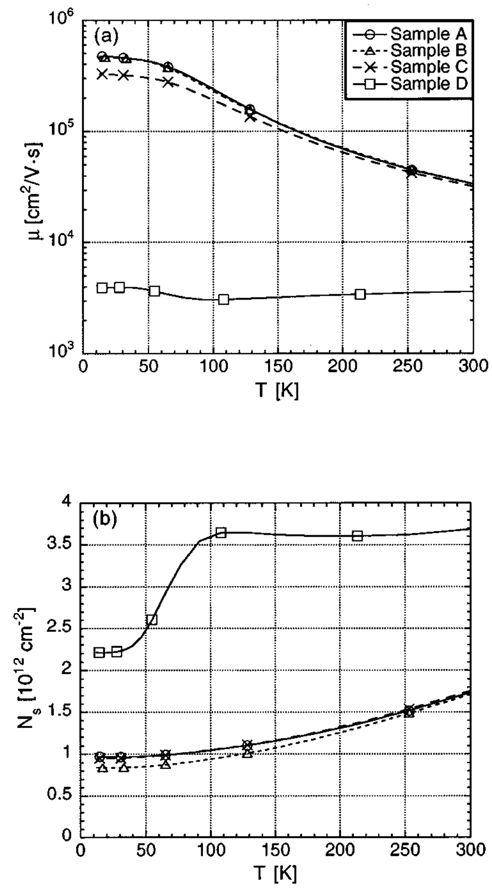


FIG. 3. Electrical characterizations for four samples showing (a) mobility variations and (b) electron sheet density variations.

with their similar morphologies. Sample C shows a noticeable decrease in mobility at 12 K—reaching only about 70% of the mobility of sample A. This decrease can be attributed to the increased roughness at the interface with an average roughness length scale of about 30 nm, on the order of the Fermi wavelength (about 25 nm) for these devices.

Sample D, on the other hand, has a significantly different electron sheet concentration *and* mobility. First of all, the electron concentration increases from about $1\times 10^{12}$ to $3\times 10^{12}$ cm$^{-2}$ at 12 K. Previous studies[4] have attributed this increase in electron density to the formation of As-on-Al ($As_{Al}$) antisite defects which have been shown to be deep donors in AlSb layers. This sharp increase in electron density due to $As_{Al}$ defects alone would result in a decrease in the mobility due to ionized impurity scattering. However, the electron mobility in this sample is suppressed by two orders of magnitude and we believe there is another contributing factor to this strong suppression: rough interfaces. Not only is the bottom interface rough as shown in Fig. 2(d), but we believe the top interface is also rough. To substantiate this claim, we grew two more AFM samples (samples E and F) with 2 and 10 s As soaks, respectively. Instead of just 1.5 nm of InAs growth, these samples have the full 15 nm InAs layer as in a QW sample. Figures 2(e) and 2(f) show that the morphologies at the top of the 15 nm InAs layer are very different for the 2 and 10 s of As exposure. In the case of a

2 s As soak, the growth surface has essentially recovered from the rough start shown in Fig. 2(c). The surface roughness is comparable to that found in samples A and B, with slightly enhanced island-height fluctuations, producing narrower terraces. However, with a 10 s As soak, the surface fails to recover and, in fact, many voids are visible in the InAs layer shown in Fig. 2(f). As pointed out by a recent study on the effect of the buffer layer on these QWs,[11] electron mobilities can decrease by an order of magnitude simply by using an AlSb buffer which produced a significantly rougher morphology on the length scale of the Fermi wavelength. Inasmuch as these QWs are surface doped,[10] the electrons in the channels are strongly driven towards the top interface, and a rough top interface would then have a strong detrimental effect on the electron mobility. This could explain the relatively weak influence of a 2 s As soak on the electron mobility even though the AFM picture suggests a rather rough bottom interface. The AFM scan of sample E further supports our belief that the growth of InAs on top of an AlAs-like interface does not progress in a smooth layer-by-layer fashion, but through a rough three-dimensional island coalescence process that leaves behind voids in the InAs layer.

## CONCLUSIONS

To summarize, we observed a roughening of the growth of InAs grown on AlSb when the interface was AlAs-like. The duration of the As soak had a strong influence on the morphology of the InAs overlayer. Even a mere 2 s exposure to As flux (at a BEP of $2\times10^{-6}$ Torr) caused the InAs layer to grow considerably rougher than in the case of the InSb-like interface. Prolonged exposure led to a significant reduction in adatom mobilities on the growth surface, resulting in a rough three-dimensional growth mode with incomplete surface coverage, even the top interface after the QW layer was very rough. This together with the formation of $As_{Al}$ antisite defects decreased the low temperature electron mobility by two orders of magnitude. On the other hand, the growth of InAs on the InSb-like interface proceeded in a smooth layer-by-layer growth, leading to an atomically smooth interface. We saw a slight smoothening of the interface when the Sb soak was extended to 25 s, but the effect on the electron mobility was minimal because, on the scale of the Fermi wavelength, samples A and B were equally smooth.

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