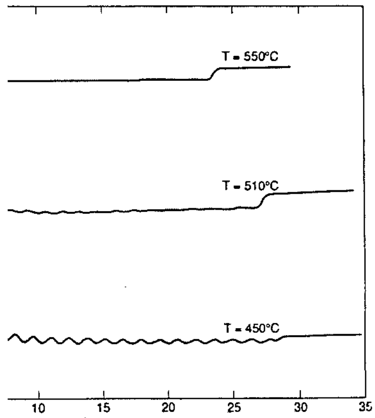

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I. Miles of Hughes Research Laboratories urements on one of the InAs samples, fice of Scientific Research under the grant from TRW.

s. Lett. 53, 2320 (1988)
be published)
ac. Sci. Tech. B, March/April (1989).
5 (1987).
ett. 53, 1648 (1988).
ppl. Phys. A35, 61 (1984).
Grange, J. Cryst. Growth 50, 538 (1980).
ki, J. Vac. Sci. Tech. 17, 603 (1980).
ata, Jap. J. Appl. Phys. 16, 2133 (1977).
ton, J.Appl. Phys. 59, 2895 (1986).
M. Kimata, Jap. J. Appl. Phys. 17, 2091

R.W. Grant, J. Vac. Sci. Tech. B1, 688

ys. D12, 1601 (1979).
Growth 81, 1 (1987).
Grunthaner, J. Vac. Sci. Tech. B4, 560

ELECTRON TRANSPORT IN InAs/AlSb QUANTUM WELLS: INTERFACE SEQUENCING EFFECTS

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ABSTRACT

We present data on electron transport in AlSb/InAs/AlSb quantum wells grown by molecular beam epitaxy. Because both anion and cation change across an InAs/Alsb interface, it is possible to grow such wells with two different types of interfaces, one with an InSb-like bond configuration, the other AlAs-like. Electron mobility and concentration were found to depend very strongly on the manner in which the quantum well's interfaces were grown, with high mobilities seen only if the bottom interface is InSb-like. An As-on-Al sites antisite defect model is postulated for bottom AlAs-like interfaces.

INTRODUCTION

The InAs/AlSb system, first studied by Chang et al.,[1] offers the combination of a large 1.3 eV conduction band offset with the high electron mobilities of InAs,[2] a combination that might be used in a variety of device structures. A particularly promising structure is the AlSb/InAs/AlSb quantum well, in which the the very deep well could be used to contain a high-density, high-mobility two-dimensional electron gas. There have already been reports of low-temperature electron mobilities greater than 2×10^5 $cm^2/V{\cdot}s$ for InAs/AlSb quantum wells,[2] and similar values for the related InAs/(Al,Ga)Sb and InAs/Ga(As,Sb) quantum wells.[3]

However, to the best of our knowledge, there has been no report on one very interesting aspect of this material system: Because both the cation and anion change across an InAs/AlSb (or InAs/GaSb) interface, such quantum wells can have two distinctly different types of interfaces. In one case, the InAs would be terminated with a final layer of In and the adjoining AlSb would start with a layer of Sb, leading to InSb bonds across the interface. We call this the "InSb-like" interface:

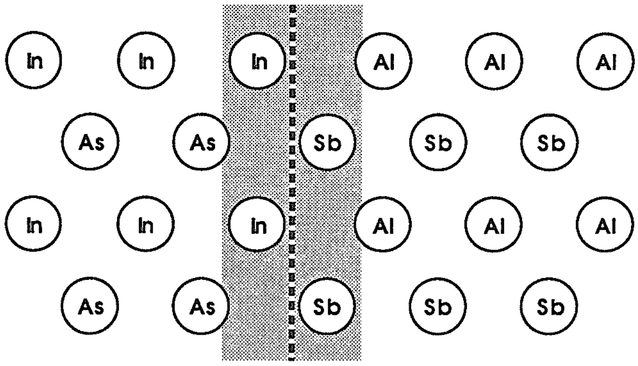

Fig. 1a. InSb-like InAs/AlSb interface

In the other case, the InAs would be terminated with a layer of As atoms, which would bond to Al atoms across the interface. This is the "AlAs-like" case:

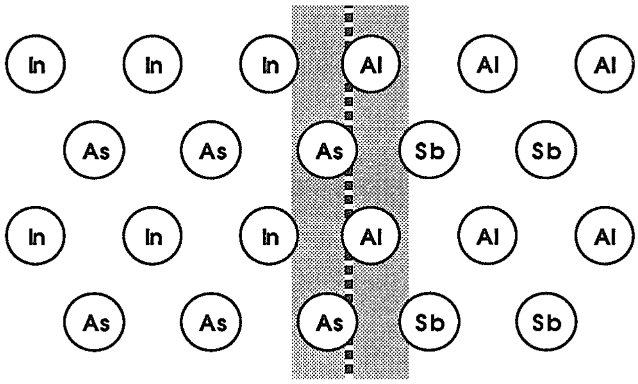

Fig. 1b. AlAs-like InAs/AlSb interface

A similar asymmetry exists at the InAs/GaSb interface, and also at the (Ga,In)As/InP interface. Strain induced by asymmetric interfaces in (Ga,In)As/InP quantum wells has been measured using high resolution X-ray diffraction by Vandenberg et al.[4] But there do not appear to exist any reports of any asymmetries in the electronic properties.

We present here measurements of the electronic properties of AlSb/InAs/AlSb quantum wells with different types of interfaces. To study the effects the differing interfaces on electron transport in the quantum wells, we grew and tested four samples: (*i*) InSb-like interfaces both top and bottom, (*ii*) AlAs-like interface on top and InSb-like on the bottom, (*iii*) inverse of the second with AlAs-like on bottom and InSb-like on top, and (*iv*) AlAs-like interfaces top and bottom. The epitaxial structure and growth conditions of all was identical except for the interfaces.

EXPERIMENTAL

All samples were grown in a Varian modular GEN II MBE machine, equipped with elemental group III and group V sources, the latter producing As_4 and Sb_4 beams. Bulk InAs layers grown in this machine show n-type background concentrations on the order of $1x10^{15}$ cm^{-3}, and 77K mobilities near 60,000 $cm^2/V{\cdot}s$. Not-intentionally doped bulk layers GaSb are p-type at a level of $1x10^{16} cm^{-3}$. Not intentionally doped bulk AlSb layers have an extremely high resistivity, and we have been unable to measure their background carrier concentration or even the residual conductivity type.

All growths were performed on a semi-insulating GaAs substrates. They have an 8% smaller lattice constant than AlSb and, as reported earlier,[2] to obtain good electrical properties, relatively thick GaSb or AlSb buffer layers were necessary. In the structures reported here, we employed a 1μm GaSb buffer layer, followed by a 1μm AlSb buffer, which in turn was followed by a ten-period (25Å+25Å) GaSb/AlSb superlattice, which aids in obtaining a smooth morphology.[5] Based on TEM measurements on other lattice-mismatched structures investigated in our laboratory,[6] we would expect our samples to have at least 10^7 threading dislocations per cm^2.

The initial nucleation of GaSb on the GaAs substrate was characterized by three-dimensional growth which smoothed to two-dimensional growth within approximately 200Å.

This smoothing transition was
to a (1x3) Sb-stabilized pattern.
temperature of 530°C, as measu
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The sequencing of the Al
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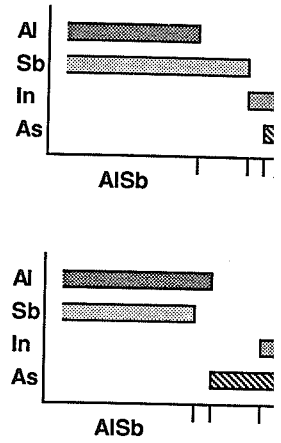

Fig 2. Shutte
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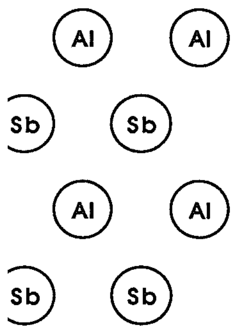

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This smoothing transition was evidenced by an initial spotted RHEED pattern which streaks to a (1x3) Sb-stabilized pattern. The GaSb and AlSb buffer layers were grown at a substrate temperature of 530°C, as measured by infrared pyrometry. The temperature was then lowered to 500°C just prior to the growth of the GaSb/AlSb superlattice, and held there for the remainder of the growth.

The quantum wells consisted of 150Å of InAs sandwiched between a 200Å AlSb barrier on the lower side and a 500Å AlSb barrier on the top. The As flux was pre-set to a level intended to keep the InAs growth just barely on the As-stable side, as indicated by RHEED reconstruction pattern. Our experience, and that of others,[7, 8, 9] has shown that minimizing the As excess is a necessary condition for obtaining high-mobility InAs. In the growths reported here, neither the AlSb barriers nor the InAs quantum wells were intentionally doped. To protect the AlSb from reaction with the water vapor in the air, a 50Å GaSb cap layer was grown on top of the structure.

The sequencing of the Al, Sb, As, and In shutters used to obtain the two types of interfaces is shown in Fig. 2:

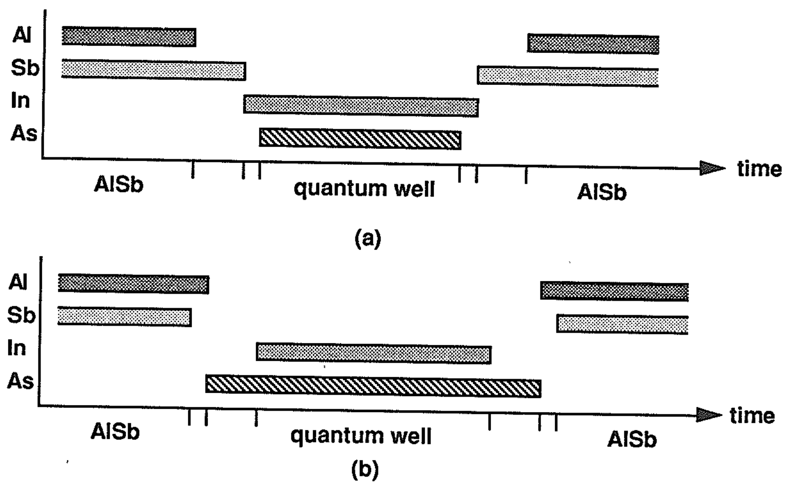

Fig 2. Shutter sequence for InAs/AlSb quantum well:
(a) InSb-like interfaces. **(b)** AlAs-like interfaces.

To grow a quantum well with InSb-like interfaces, the Al shutter is closed on completion of the lower AlSb barrier layer. The Sb shutter is left open during a 15 second growth interrupt and then closed. Simultaneously with shutting off the Sb beam, the In shutter is opened and the amount of In needed to grow one monolayer of InAs is deposited, after which the As shutter is opened and the InAs growth commences. At the top interface, the process is reversed: The As shutter is closed and one monolayer's worth of In is deposited. The In is then shut off, and the Sb shutter is opened. After a 15 second interrupt, the Al shutter is opened and the top AlSb barrier is grown. AlAs-like interfaces are obtained in similar fashion, with As substituted for Sb during the interrupts and the deposition of one monolayer of Al at each interface.

The sheet concentrations and mobilities for these four samples over a temperatures range from 300K to 15K are shown in Fig. 3.

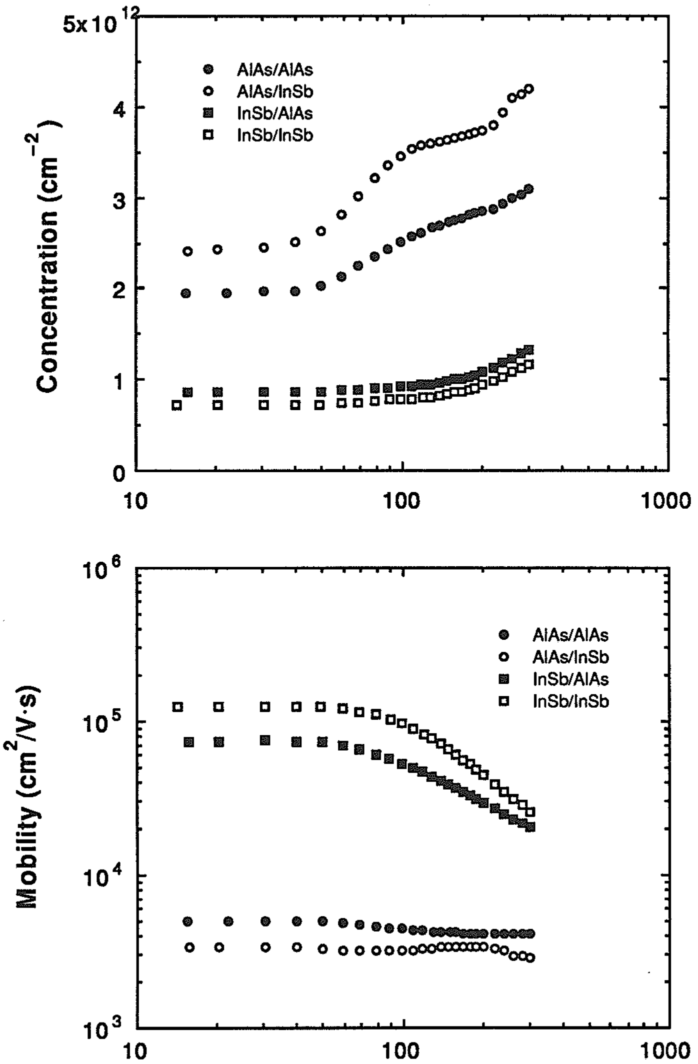

Fig 3 (a) Electron concentration and (b) mobility for InAs/AlSb quantum wells with AlAs-like interfaces both top and bottom (AlAs/AlAs), AlAs-like bottom and InSb-like top (AlAs/InSb), InSb-like bottom and AlAs-like top (InSb/AlAs), and InSb-like both top and bottom (InSb/InSb).

These data were obtained
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DISCUSSION

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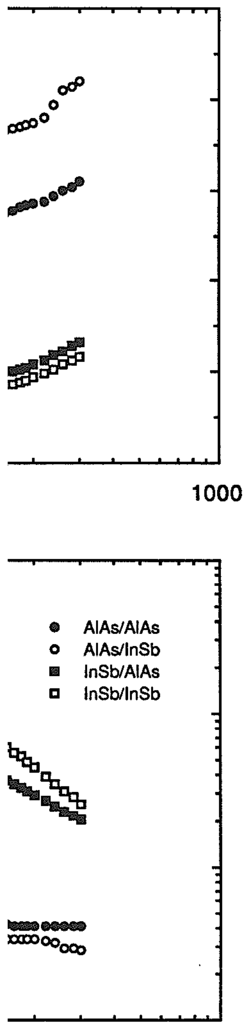

/AlSb quantum wells with AlAs-like
ike bottom and InSb-like top
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(InSb/InSb).

These data were obtained by conductivity and Hall effect measurements employing conventional van der Pauw clover leaf patterns with indium alloyed to the samples to form electrical contacts. These contacts almost certainly alloyed through to the underlying buffer layers. However the low mobilities and carrier concentrations in these layers would have a small, if not negligible, effect on the measurements.

DISCUSSION

It is evident from Fig. 3 that the transport properties of the wells are very sensitive to the nature of the interfaces employed. The data clearly fall into two groups, depending on the nature of the *lower* of the two interfaces. If the lower interface is an InSb-like interface, carrier sheet concentrations of the order $10^{12}\,cm^{-2}$ are found, together with high mobilities, over 20,000 $cm^2/V{\cdot}s$ at room temperature, and increasing with decreasing temperature in the way characteristic of a high-mobility two-dimensional electron gas. The nature of the upper interface in these cases has almost no effect on the carrier concentration, and its effect on the mobility is of the order of the sample-to-sample variations we have found in our earlier work on quantum wells in which *both* interfaces were InSb-like interfaces.[2]

On the other hand, the two samples with AlSb-like interfaces have carrier concentrations between a factor two and four higher, combined with mobilities that over an order of magnitude lower, drastically lower than one would expect for an InAs well. Again the nature of the upper interface in these cases has only a minor effect.

It is clear from these observations that the AlAs-like interface has itself drastically varying properties, depending on whether it is an upper or a lower interface. There is clearly an inequivalence of the two different *growth directions* for the top and bottom AlAs-like interfaces. At first glance, this phenomenon appears to be similar to the well-known growth inequivalence of GaAs/(Al,Ga)As hetero structures, which have different transport properties depending on whether (Al,Ga)As is grown on top of GaAs or GaAs grown on (Al,Ga)As. But on closer inspection there are major differences.

It does not appear possible to explain the data by the assumption that an AlAs-like interface at the bottom is simply much rougher than one at the top, one of the mechanisms that has been invoked to explain the growth inequivalence in the GaAs/(Al,Ga)As system. Firstly, while interface roughness by itself might lower the mobility, it would not create the very large increase in electron concentration, which requires a large concentration of donors-like defects rather than just a geometry effect. Secondly, the growth procedure for InSb-like and AlAs-like interfaces differs only during the growth of less than two monolayers. It is hard to see how that can lead to an increase in roughness of the actual InAs/AlSb interface sufficiently large to cause a reduction in mobility by over an order of magnitude in wells that are over 100Å wide.

It also does not appear possible to explain the data by the assumption that an impurity that has accumulated during the growth of the lower AlSb barrier is dumped into the InAs well, or that an impurity out-diffuses from the lower AlSb barrier, another mechanism that been invoked to explain the growth inequivalence in the GaAs/(Al,Ga)As system. Until the instance of cross-over from AlSb to InAs, the growth procedures for InSb-like and AlAs-like interfaces are identical, and it is hard to see why in one case be a large concentration of impurities would appear at the interface, but not in the other.

We believe that the data call for an interface donor of *stoichiometric* origin, very likely an *antisite defect* of As atoms on Al sites in the last Al plane before cross-over. Such an As_{Al} defect may form on a stagnant AlSb surface during the cross-over phase of the growth of a *lower* AlAs-like interface, during which the Sb flux is already turned off, while the Al-rich AlSb surface is exposed for some time to an As flux before the In flux is also turned on to resume the growth. On the other hand, for an *upper* AlAs-like interface there is no longer a large excess of As molecules impinging on the first Al plane after cross-over.

In bulk AlSb, such antisite donors would almost certainly be deep donors, which remain largely un-ionized. But adjacent to the very deep InAs well, these donors could readily drain their electrons into the well, which is presumably the reason for the large increase in electron concentration.

Because of their close proximity to the charge carriers, a high sheet concentration of antisite interface donors would of course introduce massive charged-impurity scattering into the well, which we believe is the reason for most of the drastic mobility reduction, with at most a minor contribution from increased interface roughness scattering.

A final comment is in order concerning the origin of the donors contributing the electrons in the case of high-mobility InAs/AlSb quantum wells. From the high mobilities it is clear that the latter donors contribute far less impurity scattering than the antisite interface donors postulated here, and that they must therefore be of a different origin. Numerous indications suggest that they are also located near at the interface,[1,2] but probably at some distance into the AlSb barriers. Their nature also remains to be elucidated.

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REFERENCES

1 C. A. Chang, L. L. Chang, E. E. Mendez, M. S. Christie, and L. Esaki, J. Vac. Sci. Technol. B **2**, 214 (1984).
2 G. Tuttle, H. Kroemer, and J. H. English, J. Appl. Phys., to be published.
3 H. Munekata, L. Esaki, and L. L. Chang, J. Vac. Sci. Technol. B **5**, 809 (1987).
4 J. M. Vandenberg, M. B. Panish, H. Temkin, and R. A. Hamm, Appl. Phys. Lett **53**, 1920 (1988).
5 G. Griffiths, K. Mohammed, S. Subbanna, H. Kroemer, and J. L. Merz, Appl. Phys. Lett. **43**, 1059 (1983).
6 T. Y. Liu and P. M. Petroff, unpublished.
7 W. J. Schaffer, M. D. Lind, S. P. Kowalczyk, and R. W. Grant, J. Vac. Sci. Technol. B **1**, 688 (1983).
8 B. R. Hancock and H. Kroemer, J. Appl. Phys. **55**, 4239 (1984).
9 S. M. Newstead, R. A. A. Kubiak, and E. H. C. Parker, J. Cryst. Growth **81**, 49 (1988).