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Effect of interfacial layer on the crystal structure of InAs/AlAs$_{0.16}$Sb$_{0.84}$/AlSb quantum wells

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Ion channeling technique using MeV C^{2+} ions and high resolution X-ray diffraction were used to study the crystal quality of an InAs/AlSb-based quantum wells. We found that the InAs quality has a strong dependence on the type of the interface used. With the addition of the InSb-like interface, the crystal quality of the InAs channel was greatly improved. The InAs lattice was fully strained and aligned with the lattice of the buffer layer without any lattice relaxation. On the other hand, if the interface was of the AlAs type, the lattice of the InAs quantum well was relaxed and the crystal quality was poor. This explains why a superior InAs quantum well with high electron mobility and good surface morphology can be achieved with the use of the InSb interface. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4872138]

I. INTRODUCTION

Semiconductor heterostructures based on AlSb/GaSb/InAs material system have attracted much attention in recent years due to the potential applications in the high-speed, low-power electronic devices,[1–3] and long-wavelength optoelectronic devices.[4] However, the interfaces in such heterostructures differ from those in the typical GaAs/(Al, Ga)As and (In, Ga)As/(In, Al)As systems. It is possible to grow two different types of interfaces between InAs and (Al, Ga)Sb,[1,5] because both the anion and cation have to change at the interface.[6] One is the InSb-like interface, where In atoms from the InAs side bond to Sb atoms on the (Al, Ga)Sb side. The other is the (Al, Ga)As-like interface formed by the As atoms from the InAs side bonding to the group III atoms of the Sb compound. There have been plenty of studies on the difference of these two types of interfaces and its impact on the optical and electrical properties of the grown structures.[5,7–11] All the results indicated that the InSb-like interface is superior to the (Al, Ga)As-like interface. In a molecular beam epitaxy (MBE) system, the choice of the interfacial type in the grown structure can be readily achieved through the shutter control of the source materials. Although it is known that the InSb-like interface is better than the other, there is no direct proof on its superiority from the structure point of view.

In this work, we used the Rutherford backscattering spectrometry (RBS) with channeling measurements to characterize the two different types of interfaces mentioned above. We chose the 4 MeV C^{2+} ions instead of the commonly used He^{+} ions to achieve a better depth resolution in the RBS and channeling spectra.[12] With the C^{2+} beam, we were able to demonstrate clearly the structural difference between the two interfaces and its effect on the quality of the quantum well. High resolution X-ray diffraction (HRXRD) was used to quantify the amount of strain in the InAs channels with different types of interfaces. The combination of these two techniques provided us a very clear picture on the structural difference between these two types of quantum wells and explains why the electrical property is better one over the other.

The heterostructure used in this study was a AlSb/AlAs$_{0.16}$Sb$_{0.84}$/InAs/AlAs$_{0.16}$Sb$_{0.84}$/AlSb quantum well grown on a GaAs substrate. Because of the additional AlAs$_{0.16}$Sb$_{0.84}$ layer, it is a type-I quantum well. It has been used in our InAs FET devices, where the quantum well provides both electron and hole confinement for improved output conductance. Although the AlAs$_{0.16}$Sb$_{0.84}$/InAs heterostructure is not identical to an antimonide/arsenide structure, the AlAs$_{0.16}$Sb$_{0.84}$ alloy, where most of the group V atoms are Sb, basically has the same structural property as AlSb and the hetero-interface has the same problem mentioned above.

II. EXPERIMENT

Two samples were grown by a solid-source MBE system on (001) semi-insulating GaAs substrates. The layer structures used in this study are shown in Fig. 1. Sample A was prepared with the AlAs-like interface while sample B was grown with the InSb-like interface between InAs and AlAs$_{0.16}$Sb$_{0.84}$. As_2 and Sb_2 beams were controlled by cracker cells with needle valves. A GaAs buffer layer of 100 nm was first grown to obtain a smooth surface. A 1.3 μm relaxed metamorphic AlSb buffer layer grown at 520 °C was followed to accommodate the lattice mismatch between the channel layer and the GaAs substrate. The active layers were then grown on top of the buffer layer. These layers, from the bottom to the top, consisted of a 4 nm-thick AlAs$_{0.16}$Sb$_{0.84}$ bottom barrier, a 13 nm-thick strained InAs channel, and a 4 nm-thick AlAs$_{0.16}$Sb$_{0.84}$ layer. A 6 nm-thick AlSb top barrier and a 4 nm-thick highly lattice-mismatched In$_{0.5}$Al$_{0.5}$As

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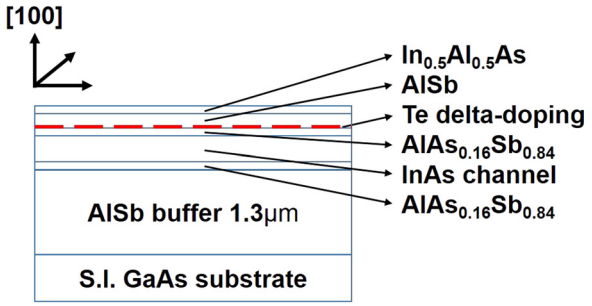

FIG. 1. The layer structure used in this study. The active layers were grown on top of the buffer layer. These layers, from the bottom to the top, consisted of a 4 nm-thick $AlAs_{0.16}Sb_{0.84}$ bottom barrier, a 13 nm-thick strained InAs channel, and a 4 nm-thick $AlAs_{0.16}Sb_{0.84}$ layer. A 6 nm-thick AlSb top barrier and a 4 nm-thick highly lattice-mismatched $In_{0.5}Al_{0.5}As$ cap layer were then grown.

cap layer were then grown. The $In_{0.5}Al_{0.5}As$ layer keeps the underlying layers from oxidation and forms a good Schottky barrier with the metal gate. All of them were grown at 500 °C except the InAs channel, which was grown at 470 °C. The carriers in the channel were provided by a Te delta doped layer ($\sim 1 \times 10^{12}$ atoms/cm^2) at the upper $AlAs_{0.16}Sb_{0.84}$/AlSb interface.

The difference between sample A and sample B and how they were grown are separately shown in Figs. 2(a) and 2(b), which show the sequence of shutter control of all the elements. For sample A, where the interfaces were AlAs-like, the shutters for the group V elements were closed first while the shutter for Al was left open for an additional 2 s to make sure the surface was covered by Al atoms. The As shutter was then opened to form an AlAs interface layer. The growth was then interrupted for 5 s to smooth out the surface before the In shutter was opened for InAs growth. The sequence was reversed for the upper interface of the quantum well. For sample B, the Sb shutter was left open for 10 s after the growth of the $AlAs_{0.16}Sb_{0.84}$ layer. The In shutter was then opened for the growth of a single InSb atomic layer. After that the Sb shutter was closed and the As shutter was opened for the InAs growth.

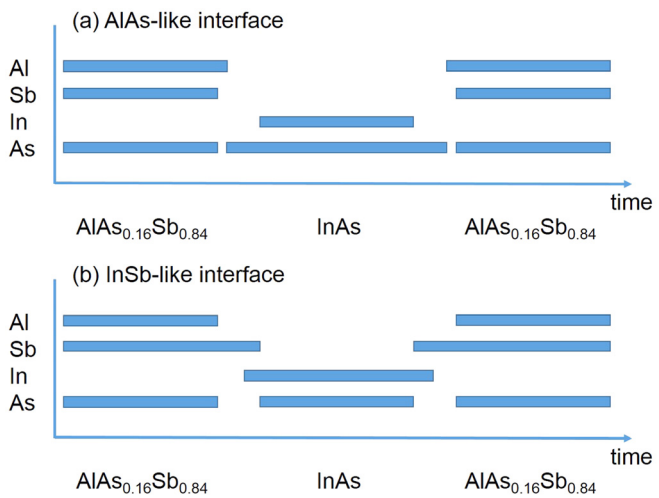

FIG. 2. The sequence of shutter control of all the elements for (a) sample A and (b) sample B, respectively.

The HRXRD measurements were conducted using Cu-Kα radiation. The samples were placed on a three-axis rotary plane with a precision of ~0.005°. RBS and channeling measurements were performed with 4 MeV C^{2+} ions using a 9SDH-2 Tandem accelerator. The samples were mounted on a four-axis (three rotation and one translation) goniometer with an accuracy better than 0.01°. Backscattered particles were detected at an angle of 160° with respect to the incident beam. The energy resolution of the system, determined by fitting the GaAs edge of the energy spectrum, was around 40 keV. Channeled RBS was conducted by aligning the incident beam with the [100] axis of GaAs substrate.

III. RESULTS AND DISCUSSION

We have performed the X-ray diffraction measurement on our samples to evaluate the crystal quality and the amount of strain in the lattice. Fig. 3 shows the high-resolution XRD $\omega - 2\theta$ scans around the (004) direction for samples A and B. The peaks from right to left correspond to GaAs substrate, InAs quantum well, and AlSb buffer layer. The position of the AlSb peaks indicates that the 1.3 μm AlSb buffers for both samples were fully relaxed with the lattice constant the same as that of AlSb bulk material. The peak height and width are about the same for both samples indicating they have the same crystal quality. The most apparent difference in the spectrum between the two samples is the InAs signal. For sample B, a clear InAs peak is seen in the spectrum. But for sample A, the InAs signal is barely seen near the marked InAs bulk diffraction position. While some of the signal is visible, a large portion is hidden behind the noise level and the large AlSb signal. So clearly, the quality of the InAs channel is much better for sample B, where the InSb-like interface was used. The position of the InAs peak is 31.06° to the right of that of a perfect InAs crystal (marked by the blue line). So the InAs lattice is compressed in the vertical direction (perpendicular to the layers). In other words, the InAs channel is under tensile strain to accommodate the larger lattice spacing of the buffer layer underneath. Based on the peak position and the Poisson's ratio (~0.35),[13] the calculated lateral lattice spacing for InAs is 6.136 Å, which is the same as that of the bulk AlSb. But for sample A, the

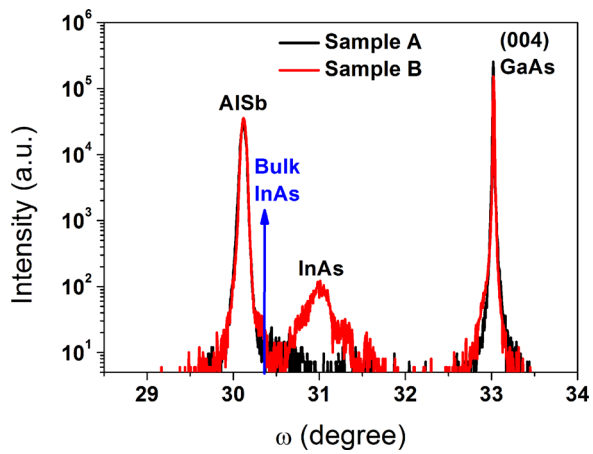

FIG. 3. The high-resolution XRD $\omega - 2\theta$ scans around the (004) direction for sample A and sample B.

position of the weakly seen InAs peak indicates that the InAs layer is nearly relaxed.[10]

Ion beam analysis combined with the channeling technique has also been used to determine the crystalline quality. Fig. 4 shows the aligned RBS spectra taken at the exact [100] direction for sample A and sample B. The random RBS spectrum, which is nearly identical for the two samples, taken at 4° off the normal direction is also shown in the figure for comparison. Again it shows clearly that sample B has a much better crystal quality because of relatively low backscattered yields. The peaks in the spectra correspond to the In and As signals. While these peaks are from all the layers containing In and As, the main sources are provided by the InAs layer. The broad background (up to the right edge) is due to Sb, which is the heaviest element and is in most of the layers in our samples. Comparing the minimum yields, defined as the yield ratio of the aligned spectrum and the random spectrum, we can see clearly the difference of the two samples. At the surface of the AlSb buffer, marked by the vertical line U in the spectra, the calculated values for samples A and B are around 0.14 and 0.08, respectively. Based on our XRD results, however, the crystal quality of AlSb buffer layer for the two samples is not significantly different. So the difference in the minimum yield is probably due to the different dechanneling behaviors. For sample A, because of the less ordered InAs layer, the channeled ions interact with the displaced atoms that are on top of the AlSb buffer layer giving rise to enhanced dechanneling and backscattering.[14–16] Thus, a worse minimum yield for sample A is obtained.

Fig. 5 shows the extracted As signals in the RBS spectra with and without channeling. They were obtained by subtracting the Sb background from the original spectra. There are two peaks (marked by R and L) in the As spectra in Figs. 4 and 5. They mainly correspond, respectively, to the As signals of the top $In_{0.5}Al_{0.5}As$ layer and that of the InAs quantum well. The minimum yields calculated from the fitted curves for the InAs quantum well were 0.34 and 0.08 for sample A and sample B, respectively. Although these values may also be affected by the dechanneling effect, the effect should be small as compared to that on the AlSb buffer

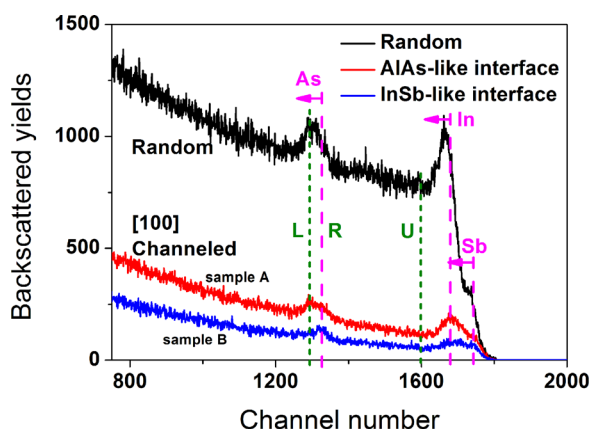

FIG. 4. The aligned RBS spectra taken at the exact [100] direction for sample A and sample B. The random RBS spectrum taken at 4° off the normal direction is also shown for comparison.

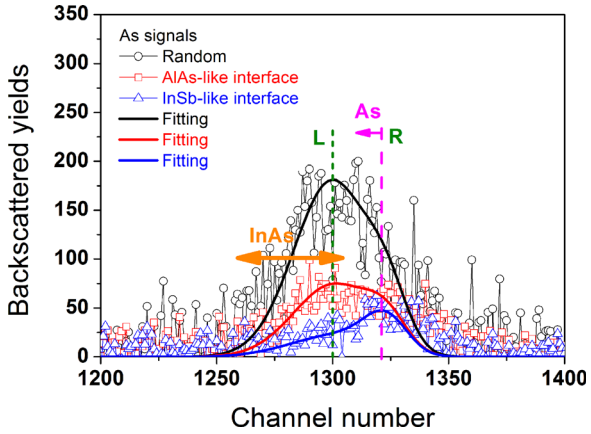

FIG. 5. The extracted As signals in the RBS spectra with and without channeling.

because there are much fewer displaced atoms above the InAs channel. So the low minimum yield from the InAs channel for sample B does reflect that the crystal quality is much better. Comparing these values with those calculated from the Sb signal at the surface of the AlSb buffer layer, we can see that there is a drastic change in crystal quality from the buffer/active layer interface to the InAs quantum well for sample A where the minimum yield changes from 0.14 to 0.34. But for sample B, where the InSb-like interface was used, the minimum yield stays low at 0.08. For InAs and AlSb perfect crystals, the minimum yields for low index axes are typically around 0.05.[14,15] The value of 0.08 for sample B is close to that of a perfect crystal. With the insertion of the InSb-like interface between the InAs channel and the $AlAs_{0.16}Sb_{0.84}$ barrier, the crystal quality of the InAs channel is greatly improved. This result is consistent with the result observed from the XRD measurement.

Figs. 6(a) and 6(b) show the 2D mapping images of the backscattered ion yield as a function of the channel number (sample depth) and the tilted angle for sample A and sample B, respectively. The angle was tilted toward the incident beam direction making an angle of 3° with the [100] axis and measured relative to the surface normal direction. The color scale shows the amount of the backscattered yield. Comparing these two figures, we can see sample B, which had InSb-like interfaces, had a much stronger contrast and the middle blue (low yield) region goes much deeper than sample A. The arrow indicates the location of the InAs channel. This stronger channeling effect is a clear indication that sample B had a superior crystal quality than sample A.

The InSb-like interface clearly helps the InAs lattice to align with the lattice of the buffer layer. When the layer is fully strained to be in line with the lattice underneath, the defects caused by lattice mismatch are reduced and the crystal quality improved. We have also used an atomic force microscope to measure the roughness of the sample surface. Sample B had a very smooth surface with a root mean square variation of only 0.5 nm, while that for sample A was ~2 nm. This again shows that the overall crystal quality of sample B is superior to that of sample A. The difference in the quality of the InAs channel is also reflected in the mobility measured. The room-temperature electron mobility for

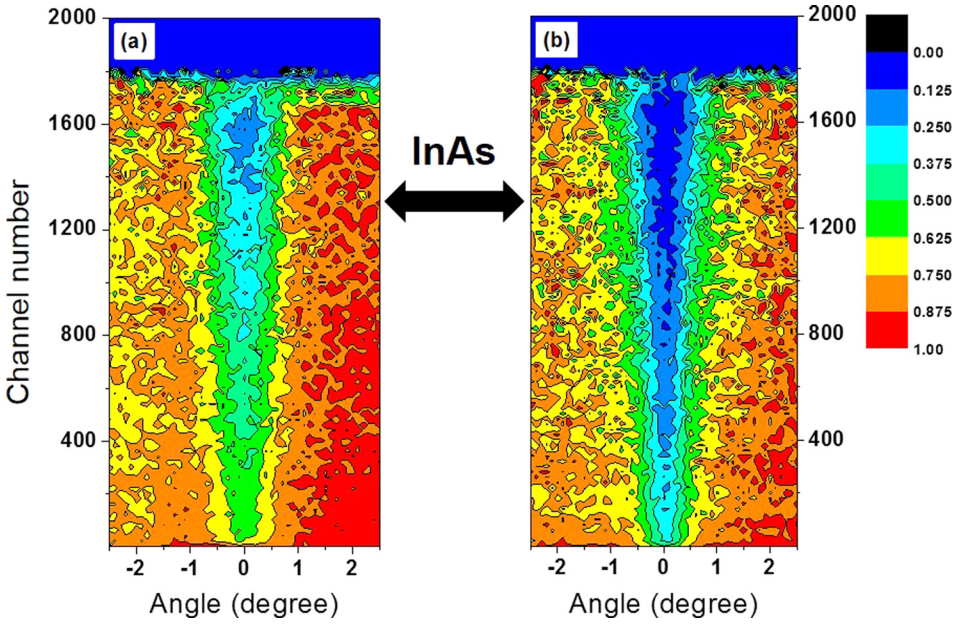

FIG. 6. The 2D mapping images of the backscattered ion yield as a function of the channel number (sample depth) and the tilted angle for (a) sample A and (b) sample B, respectively. The arrow indicates the location of the InAs channel.

samples A and B determined by the Hall measurement were 4000 cm^2/V-s and 18 100 cm^2/V-s, respectively. This high mobility for sample B with the InSb-like interface is a direct result of the superior InAs quality.

IV. CONCLUSIONS

High resolution X-ray diffraction and ion channeling technique using MeV C^{2+} ions were used to study the crystal quality of the InAs quantum wells in an InAs/AlSb-based heterostructure. Because of the use of heavy ions, which provides great depth resolution, we were able to clearly observe the difference in crystal quality between the InAs quantum well and the adjacent buffer layer through the channeling RBS spectra. With the InSb-like interface, the crystal quality of the InAs channel was greatly improved. Based on the XRD results, the InAs lattice was fully strained to align with the lattice of the buffer layer without any lattice relaxation. This is believed to be the reason for the superior InAs crystal quality. The improved electron mobility and surface roughness are direct results of the superior InAs crystal quality.

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