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Monolithic, Defect-Free III-V on Si using Self-Assembled AlSb Quantum Dot Nucleation

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1. Introduction

In this paper, we describe unique growth mode of AlSb bulk material on Si (100) based on a monolithic, self-assembled AlSb QD nucleation layer. We show that AlSb follows a unique growth mode established by the combination high lattice mismatch and strong interatomic bond. The AlSb/Si lattice mismatch is sufficient to drive highly crystalline island formation that allows partial relaxation of the interface strain. The strong Al-Sb bond both prevents defect formation during island nucleation and drives island coalescence into a planar, defect-free bulk material within <100 nm of material deposition. Recently, researchers have used the AlSb QDs to nucleate GaSb on Si.[i]

We report and characterize the growth of defect-free AlSb bulk material on Si (001) substrates using a monolithic self-assembled AlSb quantum dot (QD) nucleation layer. During the first few monolayers of AlSb growth on Si, highly crystalline QDs form. With continued deposition, the islands coalesce into a planar material with no detectable defects. The QD nucleation layer facilitates a completely relaxed AlSb within ~100 ML of deposition according to X-Ray diffraction. We attribute the success of AlSb growth on Si to both the large AlSb/Si lattice mismatch ($\Delta a_o/a_o$=13.5%) in combination with the strong AlSb atomic bond. We also demonstrate room temperature photoluminescence from an InGaSb QW grown on the AlSb bulk layer.

2. Growth and Characterization

In preparation for growth, the Si (001) substrate is rinsed in dilute hydrofluoric acid followed by deionized water to remove surface oxide and passivate the Si surface with H atoms. The H atoms are thermally removed in-situ just before growth. Reflection high energy electron diffraction (RHEED) is continuously monitored as a powerful indicator of both Si and III-V surface structure as indicated in Fig. 1 (a)-(c). Before deposition, at T~ 600˚C, the 2x1 reconstruction indicates a H-free Si surface as shown inset in Fig. 1(a). Initial growth of AlSb (3 MLs) results in the RHEED pattern switching from a 2x1 to a chevron-like reconstruction. The connected chevron pattern is characteristic of QDs with an abrupt truncated-pyramidal shape formed under very high lattice mismatch.[ii] Fig. 1(c) (inset) shows the 3x1 pattern associated with the approaching planar growth after 54 ML deposition.

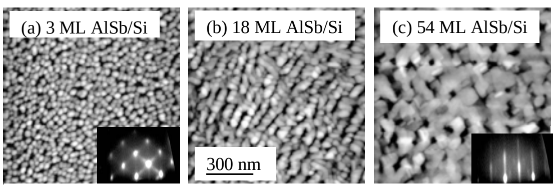

Fig. 1: AFM and RHEED images of AlSb monolithic, self-assembled nucleation layer.

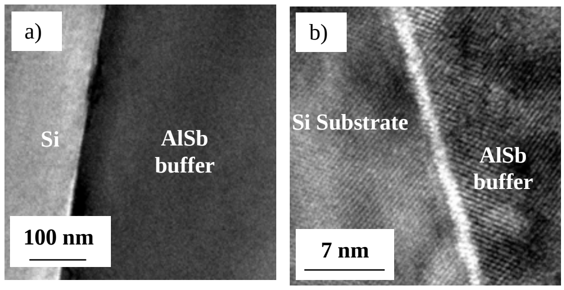

Fig.2: TEM images of the defect-free AlSb/Si bulk and the AlSb/Si interface.

Corresponding AFM images of the AlSb/Si surface are shown in Figures 1 (a)-(c) after 3, 18 and 54 MLs of deposition. At 3 MLs, the QD density is 10^{11} QDs/cm^2 with dot height and diameter of 1-3 nm and 20 nm, respectively. Continued deposition causes the individual islands to coalesce but remain crystallographic in contrast to InAs/GaAs QD growth where island coalescence leads to large defective islands. Fig. 1(b), at 18 MLs, indicates a crystallographic preference of the coalescence along the [110] direction. Figures 1(c) shows continued coalescence towards planar growth with 54 MLs deposition. These results are consistent with the inset RHEED images.

We have used transmission electron microscopy (TEM) to study defect density and material quality of the AlSb/Si interface and AlSb bulk in both the (110) plane and (1-10) plane. While other material systems show asymmetry in the two cleaving planes,[Error! Bookmark not defined.] the AlSb material shows defect-free characteristics along both planes. Figure 2(a) and (b) show TEM images of a thick (500 nm) AlSb bulk layer cleaved along the (110) plane. Figure 2(a) features the Si substrate, Si/AlSb interface and high quality AlSb bulk material ~0.5 μm in thickness. Figure 2(b) is a higher resolution image showing the atomic structure of the Si/AlSb interface. The image shows three notable features. First, the interface is marked by a white region that we are not able to explain presently. Second, some nonuniformity in the crystal alignment is visible. Last, a count of atoms on either side of the interface yields a ratio of ten Si atoms to nine AlSb atoms. Our images are not of sufficient quality to determine the precise lattice constant of the material by real-space mapping.[iii] Hence, we can not calculate the strain (or strain relief) provided by the staggered arrangement of atoms. The formation of QDs does indicate that a

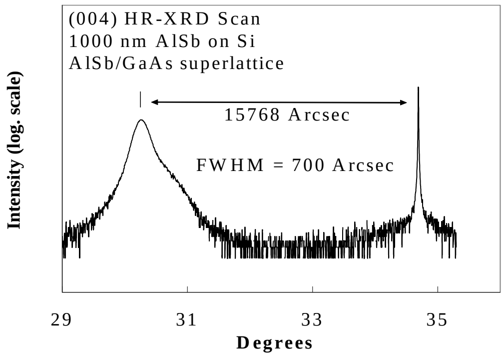

Fig. 3: XRD spectrum from an AlSb buffer layer (1000 nm) on Si.

significant lattice mismatch is still present.

Figure 3 shows an XRD (004) spectrum of a 1000 nm thick AlSb bulk layer peaked at 15768 arcs**ec** from the Si substrate with a full-width at half-maximum (FWHM) of 700 arcsec. The AlSb buffer is grown using a very thin GaSb/AlSb superlattice placed ~100 nm from the AlSb/Si interface to help

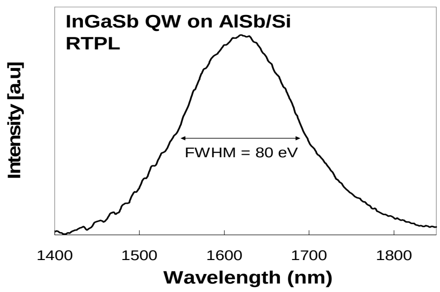

Fig.4: RTPL from an InGaSb QW grown on the AlSb buffer/Si substrate.

align the AlSb lattice. The XRD spectral peak indicates 98% relaxation of the AlSb lattice. The fairly broad FWHM indicates some crystal non-uniformity close to the interface, as shown in Fig. 3(b) that can be reduced by a series of GaSb/AlSb superlattices. Without the superlattices, an XRD of the AlSb buffer results in a FWHM=1500 arcs. We expect the crystalline uniformity to be improved as we optimize the nucleation and coalescence processes. In preparation for laser development, we have grown an $In_xGa_{1-x}Sb$ (x~0.1) lattice-matched quantum well (QW) on a 0.5 µm thick AlSb layer (without superlattice). The 100 Å QW is grown at T=500ºC. The RTPL spectrum, shown in Fig. 4, features a peak wavelength at 1630 nm and a FWHM ~80 meV.

3. Conclusion

We have demonstrated for the first time the monolithic growth of high quality, defect-free AlSb bulk material directly on Si. The nucleation and subsequent coalescence of a self-assembled QD ensemble allows complete lattice relaxation. A planar crystalline surface results within 100 ML of material deposition as indicated by a 3x1 RHEED pattern and narrow XRD after 1000 nm. Material properties that differentiate AlSb from other III-Vs are the very high lattice mismatch and the very strong Al-Sb bond. An InGaSb QW emits RTPL with peak wavelength at ~1.6 µm. The monolithic material nucleation, low temperature growth temperatures (~500°C) and good thermal match to Si makes the AlSb material system very promising for III-V emitters integrated with Si circuitry.

References

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