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Materials growth and band offset parameters of the $Al_2O_3/In_{0.28}Ga_{0.72}Sb/AlSb/GaSb/GaAs$ heterostructure

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Abstract

High quality $In_{0.28}Ga_{0.72}Sb/AlSb/GaSb/GaAs$ heterostructure grown by metalorganic chemical vapor deposition (MOCVD) using an interfacial misfit dislocation (IMF) GaSb buffer layer is demonstrated. A smooth surface and low threading dislocation density are achieved to be 1.0 nm and 6.2 × 10^6 cm^{-2}, respectively. The band alignment of the heterostructure integrated with Al_2O_3 high-*k* dielectric is also determined by X-ray photoemission spectroscopy (XPS) measurement, where the valence band and conduction band offset between the $In_{0.28}Ga_{0.72}Sb$ epilayer and Al_2O_3 layer are 3.21 and 3.11 eV, respectively.

1. Introduction

As downsizing of Si complementary metal oxide semiconductor (CMOS) devices comes to a standstill, III-V compound semiconductor has been attracting extensively as a promising alternating material for realizing ultra-high speed and low power consumption transistors. Specially, the integration of $In_xGa_{1-x}Sb$ materials on GaAs or Si substrate has been considered as a single channel CMOS applications due to its both high electron and hole mobilities, very low effective mass, controllable band gap [1]. However, due to the large lattice mismatch (>8%), the epitaxial material has to relieve strain energy through misfit dislocations, threading dislocations (TDs), and other defects. Recently, interfacial misfit dislocation (IMF) growth technique has been explored for the growth of InGaSb/GaAs by metalorganic chemical vapor deposition (MOCVD) [2][3], which can relieve almost the strain energy by periodic 90^0 misfit dislocation arrays located at the InGaSb/GaAs interface. As a result, fully relaxed InGaSb epilayers with low dislocation density (~10^6 cm^{-2}) were obtained. In this study, we demonstrate the growth of $In_{0.28}Ga_{0.72}Sb/AlSb/GaSb$ heterostructure on GaAs substrate by MOCVD method. While a thin GaSb buffer layer was grown using IMF growth mode to relieve partially the lattice strain between the epilayer and substrate, the AlSb layer was utilized as a bottom barrier layer to prevent the back leakage current in MOS devices due to its high bandgap. The band-offset parameters of the $Al_2O_3/In_{0.28}Ga_{0.72}Sb$ interface were investigated for realizing InGaSb-based CMOS application.

2. Experimental

The $In_{0.28}Ga_{0.72}Sb/AlSb/GaSb$ heterostructure was grown on SI-(001) GaAs substrate by Aixtron 2400 MOCVD. First, a 110-nm thick IMF GaSb buffer layer was grown under the optimized growth condition [3]. Then, 30-nm thick AlSb bottom barrier layer was grown at 650 ^oC with a V/III ratio of 1.5. Next, 125-nm $In_{0.28}Ga_{0.72}Sb$ epilayer was grown on the AlSb layer at 600 ^oC with a V/III ratio of 2.5. The surface morphology of the epilayer was observed by AFM D3100. HR-XRD Bede D1 along with HR-TEM Cryo JOEL JEM 2010 was employed to investigate the structural properties and the heterointerfaces of the sample. For the XPS measurement (MICROLAB 350 system), the sample were passed through a typical cleaning process, and then 1.5 nm (for $In_{0.28}Ga_{0.72}Sb/Al_2O_3$ interface analysis) and 12.0 nm (for bulk oxide analysis) Al_2O_3 deposition were deposited by Cambridge NanoTech Fiji 202 DSC atomic layer deposition ALD system at 250 ^oC [3]. The band-offset parameters of the $Al_2O_3/In_{0.28}Ga_{0.72}Sb$ interface were determined by using Kraut's model [4].

3. Results and discussion

Figs. 1(a)-(c) show the surface morphology of each layer of the $In_{0.28}Ga_{0.72}Sb/AlSb/GaSb/GaAs$ heterostructure, where the surface roughness of the GaSb, AlSb, and $In_{0.28}Ga_{0.72}Sb$ layer was 0.54, 2.10, and 1.01 nm, respectively. The (004) XRD data of the heterostructure are shown in Fig. 1(d), where the (004) $In_{0.28}Ga_{0.72}Sb$ peak located at -11643 arc-sec with a FWHM rocking curve of 391 arc-sec. Meanwhile, the GaSb peak located at -9697 arc-sec indicates that the GaSb buffer layer was completely relaxed due to the formation of the IMF array at the GaSb/GaAs

interface [2, 3]. (224) asymmetric reciprocal space map (RSM) XRD scan of the heterostructure showed in Fig. 1(e) indicates that the large lattice strain of the InGaSb epilayer was fully relieved with a relaxation degree of 98.6%.

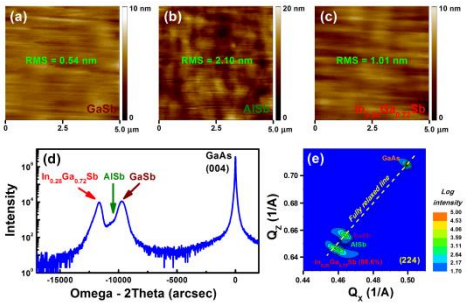

Figure 1. (a) AFM image of (a) GaSb, (b) AlSb, and (c) $In_{0.28}Ga_{0.72}Sb$ surface, (d) (004) ω-2θ XRD scan, and (e) (224) RSM image of the whole heterostructure.

HR-TEM micrograph of the heterostructure is shown in Fig. 2(a). The thickness of the IMF GaSb buffer layer, the AlSb barrier layer, the $In_{0.28}Ga_{0.72}Sb$ epilayer, and the Al_2O_3 high-*k* dielectric were 110 nm, 30 nm, 125 nm, and 12 nm, respectively, in consistent with the Auger depth profile data illustrated in Fig. 2(b). The Auger depth profile data also showed the intermixing of As-Sb atoms at the GaSb/GaAs interface, which was attributed to the intermixing of IMF array located along the [1-10] direction. The thickness of the intermixing IMF layer was estimated to be 6.0 nm. A well-defined 12-nm-ALD $Al_2O_3/In_{0.28}Ga_{0.72}Sb$ heterointerface can be observed in Fig. 2(c). It is note worth that most of threading dislocation (TD) was terminated at the AlSb/GaSb interface as can be observed in Fig. 4(a), resulting in very low TD density of the $In_{0.28}Ga_{0.72}Sb$ epilayer. From the plan-view HR-TEM (Fig. 2(d)), the TD density of this epilayer was approximately 6.2×10^6 cm^{-2}.

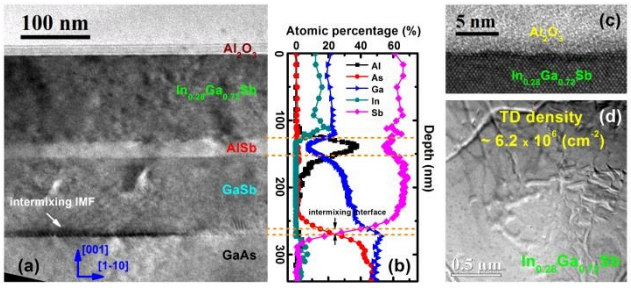

Figure 2. (a) Cross-sectional HR-TEM image and (b) Auger depth profile of the $Al_2O_3/In_{0.28}Ga_{0.72}Sb/AlSb/GaSb/GaAs$ heterostructure, (c) High magnification HR-TEM image at the $Al_2O_3/In_{0.28}Ga_{0.72}Sb$ interface, and (d) Plan view HR-TEM image of the $In_{0.28}Ga_{0.72}Sb$ top epilayer.

The valence band offset (VBO) of the high-*k* dielectric $Al_2O_3/In_{0.28}Ga_{0.72}Sb$ heterojunction was indicated by Kraut's model [4] as described:

$$\Delta E_V = \left(E_{CL}^{InGaSb(b)} - VBM^{InGaSb(b)}\right) - \left(E_{CL}^{Al_2O_3(b)} - VBM^{Al_2O_3(b)}\right) - \left(E_{CL}^{InGaSb(i)} - E_{CL}^{Al_2O_3(i)}\right) \quad (1)$$

Herein, the Al $2p_{3/2}$, Sb $4d_{5/2}$ core levels (CLs) in bulk and interface and valence band maximum (VBM) value of bulk InGaSb and Al_2O_3 layer were applied to Eq. (1), which is shown in Figs. 3(a)-(c).

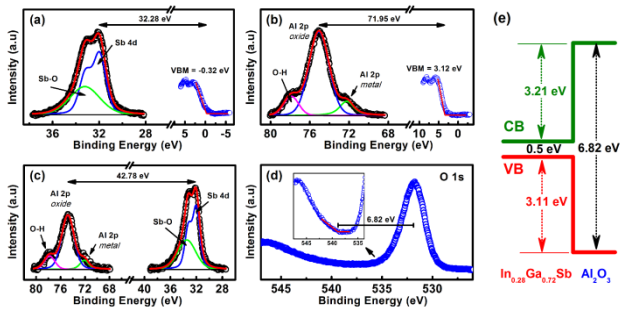

Figure 3. XPS data of (a) Sb 4*d* and VBM from the 125 nm $In_{0.28}Ga_{0.72}Sb$ epilayer, (b) Al 2*p* and VBM from the 12.0 nm Al_2O_3, (c) Sb 4*d* and Al 2*p* from the interface of 1.5 nm $Al_2O_3/In_{0.28}Ga_{0.72}Sb$, (d) O 1*s* peak from the 12.0 nm Al_2O_3 and (e) Band alignment of the $Al_2O_3/In_{0.28}Ga_{0.72}Sb$ heterointerface.

As a result, the VBO of the $Al_2O_3/In_{0.28}Ga_{0.72}Sb$ interface was indicated to be 3.11 eV. By using the Al_2O_3 bandgap of 6.82 eV indicated from O 1*s* spectrum (Fig. 3(d)) and the $In_{0.28}Ga_{0.72}Sb$ bandgap of 0.5 eV (referenced from bulk value), the conduction band offset (CBO) of the interface was determined to be 3.21 eV. The values of VBO and CBO obtained in this study are relatively high, which makes it enable for both n-channel and p-channel MOS application. The band alignment of the $Al_2O_3/In_{0.28}Ga_{0.72}Sb$ heterointerface is described in Fig. 3(e).

4. Conclusions

In conclusion, high quality $In_{0.28}Ga_{0.72}Sb$ epilayer was grown on GaAs substrate by MOCVD method using a very thin IMF GaSb buffer layer. The fully relaxed $In_{0.28}Ga_{0.72}Sb$ epilayer has a surface roughness of 1.01 nm with an FWHM of 391 arc-sec, and very low TD density of 6.2×10^6 cm^{-2}. The optimized conditions for the MOCVD growth of AlSb epilayer on GaSb/GaAs surface were also found to be 650 °C at a V/III ratio of 1.5. The band offsets of the $Al_2O_3/In_{0.28}Ga_{0.72}Sb$ interface extracted from XPS analyses were 3.11 eV for VBO and 3.21 eV for CBO. The results provide important information for future MOCVD growth technique and single channel InGaSb-based CMOS device.

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