Comparison of MOCVD Grown GaSb on (001) Si Substrates Using Aspect Ratio Trapping and Interfacial Misfit Growth Methods

Billy Lai, Qiang Li, Kei May Lau

Department of Electronic and Computer Engineering,
Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
e-mail: eekmlau@ust.hk, Phone:+852 2358 7049

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ABSTRACT

Two approaches to integrate GaSb onto silicon were investigated: interfacial misfit growth of GaSb on GaAs-on-Si templates and GaSb-on-V-grooved Si using the aspect ratio trapping technique. GaSb thin films grown on both substrates were found to be highly relaxed and have comparable crystalline quality. The primary defect generation mechanism in both samples was investigated and discussed.

INTRODUCTION

GaSb has many applications in long wavelength devices such as interband cascade lasers and infrared photodetectors [1-2]. Monolithic integration of GaSb-related materials onto silicon is highly attractive to extend the functionality of long-wavelength devices and photonic integration on the silicon platform [3]. Additionally, considering the increasing prevalence of infrared devices, including sensors and projectors, designed in modern smartphones, integration onto Si is an effective solution towards lower manufacturing costs, smaller size, and higher throughput. However, compared to GaAs/Si and InP/Si material systems, GaSb/Si heteroepitaxy is far less established. In this work, with GaSb grown on GaAs substrates as a reference, we investigate two different integration schemes: interfacial misfit (IMF) growth of GaSb on a GaAs-on-Si template and GaSb directly on V-grooved Si using the aspect ratio trapping technique.

EXPERIMENTAL METHODS

Microelectronics standard (001) Si substrates were first patterned with 55 nm wide SiO_2 stripes spaced 75 nm apart. With these patterns, a 1% HF dip was performed to remove native oxide. A 70 °C 45% KOH solution was used to form the V-grooved Si. Lastly, a 10% HCl solution was used to clean the sample. Following these sample preparation steps, the sample was loaded into an AIXTRON 200/4 horizontal metal organic chemical vapor deposition (MOCVD) reactor for epi growth.

The GaAs-on-Si template with a smooth planar GaAs surface is prepared using the method detailed in Ref. [4]. The interfacial misfit growth sequence is then employed to grow GaSb on the template. The IMF growth mode, which forms a 2-dimensional network of 90° Lomer dislocations, is the ideal growth sequence for highly relaxed GaSb films grown on planar GaAs [5]. More specifically, the IMF sequence begins with desorption of As from the GaAs buffer followed by an Sb preflow to form the first monolayer of GaSb and continues with the rest of the GaSb bulk layer. For direct growth of GaSb on nanopatterned V-grooved Si, an ultra-thin GaAs stress relaxing layer approximately a few nm thick is utilized along with the same IMF inspired growth sequence [6]. The notable difference is that an array of 60° misfit dislocations, instead of 90° Lomer dislocations, is formed at the GaAs and GaSb heterointerface inside the Si V-grooves. Following the growth of GaSb nanoridges, SiO_2 pillars are etched away and the nanoridges are coalesced into a 1 μm thin film. The different approaches are shown schematically in Figure 1. X-ray diffraction (XRD) measurements were performed using an Empyrean PANanlytical system operating at 40 kV and 40 mA. Room temperature photoluminescence measurements were performed using a 633 nm laser as an excitation source. Cross sectional transmission electron microscopy (X-TEM) was performed using a JEOL-TEM 2010F operating at 200 kV.

RESULTS AND DISCUSSION

Based on the omega-2 theta peaks obtained from XRD as shown in Figure 2, the relative spacing between the Si substrate peak and the GaSb peak indicates a 101.6% and 100.8% of relaxation for 1 μm thick GaSb grown on the planar GaAs-on-Si template and V-grooved Si substrate, respectively. The residual tensile stress was induced by the thermal mismatch when cooling down from the growth temperature to room temperature. When analyzing the crystalline quality using XRD, 1 μm thick GaSb thin film grown on GaAs-on-Si templates resulted in an omega rocking curve full-width-at-half maximum (FWHM) of 396 arcsec, while the FWHM for an equally thick film grown on a V-grooved Si substrate was determined to be 325 arcsec. Comparing the room temperature photoluminescence (PL) with the reference GaSb layer grown on GaAs, the GaSb layers on GaAs-on-Si and V-grooved Si samples emit similar spectra. With the most intense peak of all three samples centered at 1.6 µm. The GaSb/GaAs-on-Si sample had a slightly higher PL intensity as shown in Figure 3. This lack of correlation between the PL intensity and the omega rocking curve FWHM for the sample grown on V-grooved Si is further examined by measuring an identical sample grown on V-grooved Si, but with the SiO_2 stripes intact during coalescence. The PL intensity is higher than that of the GaAs-on-Si sample. This V-grooved Si sample with the inclusion of the SiO_2 stripes had a similar omega rocking curve FWHM of 318 arcsec as well the same growth parameters as the sample without the SiO_2 stripes since they were grown in the same run. Yet, they have significantly different PL intensities. Further investigation will be required to determine the underlying mechanism for the somewhat weaker PL intensity of the V-grooved Si sample without the SiO_2 stripes.

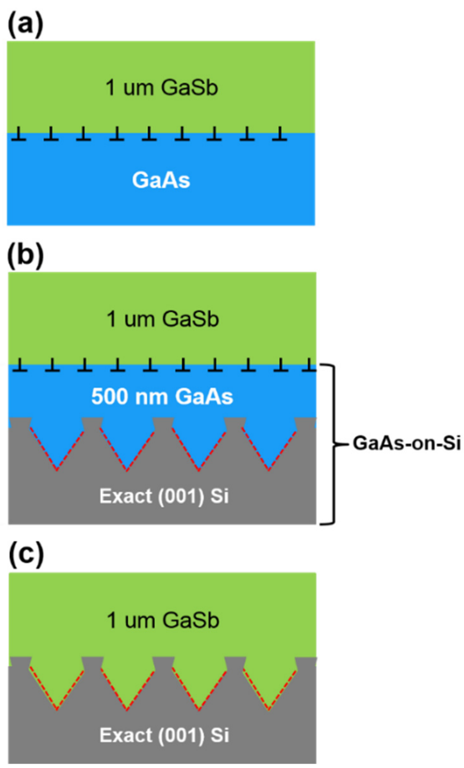

Fig. 1. Schematic showing GaSb grown on different substrates: (a) GaAs substrates; (b) GaAs-on-Si; (c) V-grooved Si.

Figure 4a shows a montage of two TEM images of the 1 µm GaSb grown on a GaAs-on-Si template. There are noticeable defects within the GaAs buffer layer as well as the GaSb. Threading dislocations that form during the growth of the GaAs terminate at the heterointerface, the location of the IMF array. Unfortunately, threading dislocations also form during the GaSb growth. The strain is not completely relaxed by the 90° misfit dislocations and this gives rise to the formation of threading dislocations. A few of these threading dislocations annihilate one another, but others continue to propagate towards the surface. From Figure 4b, upon closer

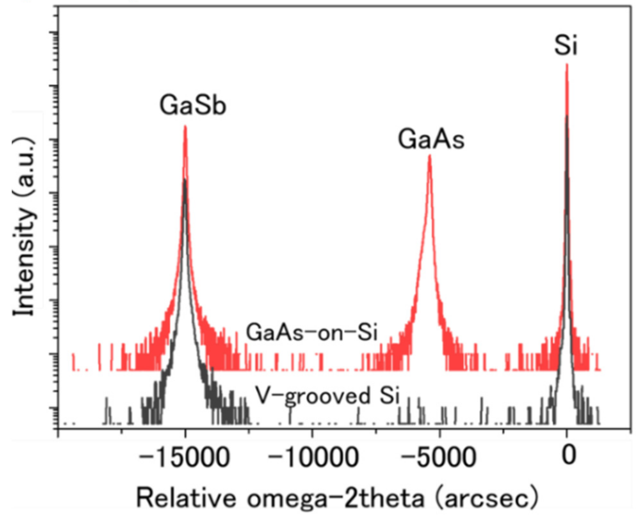

Fig. 2. XRD omega-2θ scans of GaSb grown on GaAs-on-Si template as well as on V-grooved Si

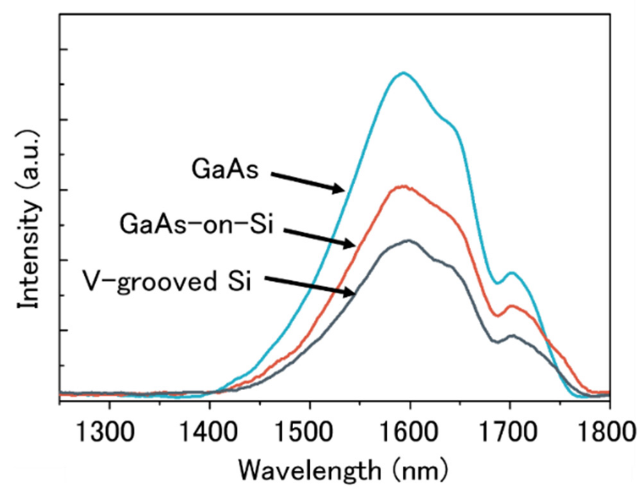

Fig. 3. Room temperature photoluminescence measurements of 1 μm thick coalesced GaSb thin films grown on GaAs, on GaAs-on-Si, and on V-grooved Si.

examination of the heterointerface, the IMF array can be clearly observed. The dark spots lining the heterointerface are the locations of the 90° misfit dislocations. As reported, the average spacing between each of these misfit dislocations is 5.6 nm. From the FFT generated from Figure 4b as shown in Figure 5a, the GaAs and GaSb diffraction spot spacing corresponds to their respective d-spacings. By applying a mask of the (111) and ($\bar{1}\bar{1}\bar{1}$) diffractions spots and generating an inverse FFT, the position of the misfit dislocations can be determined. The presence of an extra half plane in the inverse FFT image gives the exact location. In Figure 5b, the inverse FFT shows that there are approximately 13 GaSb lattice sites between each misfit dislocation. This approximation corresponds to the spacing of an IMF array [7].

X-TEM was also carried out for the GaSb-on-V-grooved Si sample to examine the interface quality and the nature of the defects present in the GaSb film as shown in Figure 6. The voids at the tips of the V-grooves shown in Figure 6a were formed during the coalescence of spatially separated ridges and serve as free surfaces at which threading dislocations can terminate. From Figure 6b, there are threading dislocations that manage to avoid these voids and propagate upwards. Also, there are coalescence defects near the location of the original SiO_2 stripes. These coalescence defects include threading dislocations and stacking faults and are typical for ridge-to-thin film coalescence. It is anticipated that by inserting GaSb/InAs strained layer superlattices (SLS) as dislocation filters, the defect density could be further reduced.

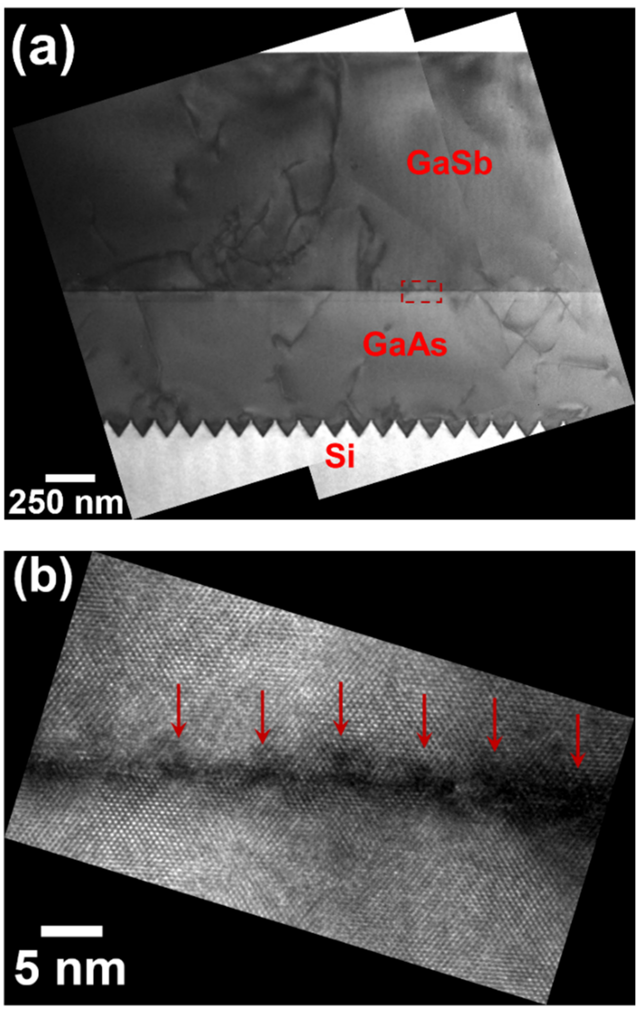

Fig. 4. X-TEM montage of (a) 1µm GaSb thin film grown on GaAs-on-Si template noting the location of (b), a higher magnification X-TEM image of the IMF array formed at the interface between GaAs and GaSb.

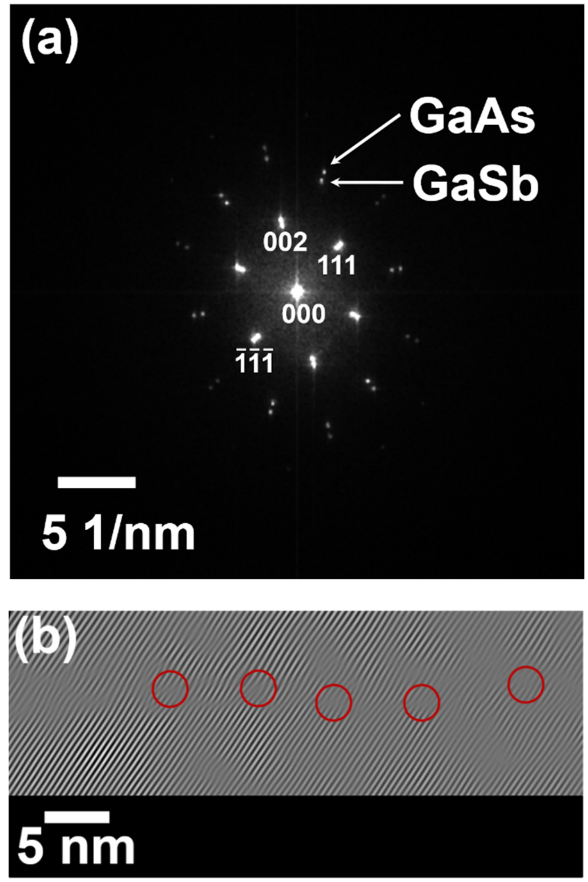

Fig. 5. Generated from Figure 4b, (a) Fast Fourier Transform (FFT) showing the GaAs and GaSb diffractions spots and (b), an inverse FFT generated from masking the (111) and ($\bar{1}\bar{1}\bar{1}$) diffraction spots with misfit dislocations encircled.

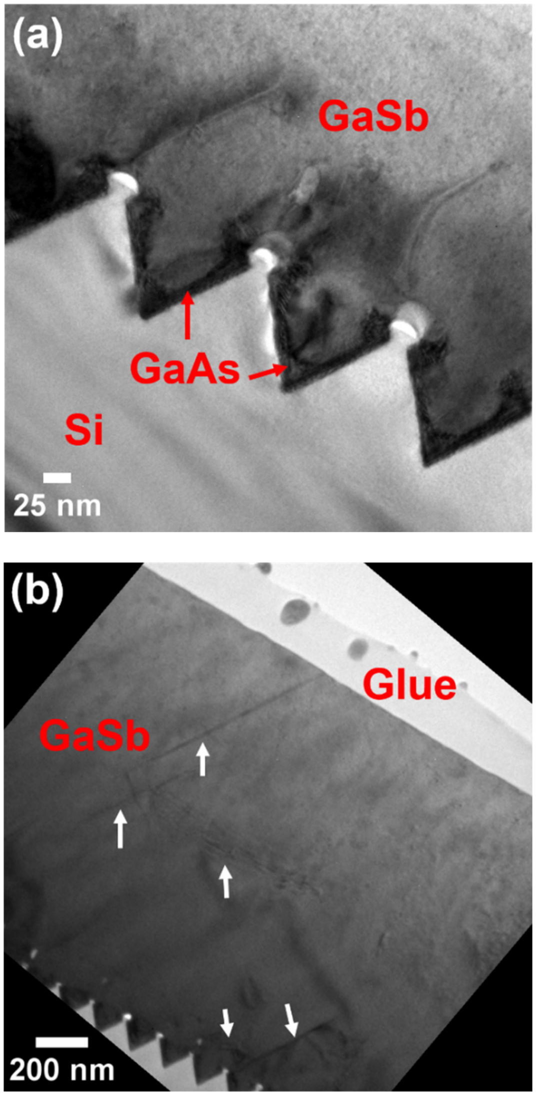

Fig. 6. Cross-sectional TEM images of 1µm coalesced GaSb thin films grown on V-grooved Si (a) zoomed in on the V-groove and (b) zoomed out showing the entire film with arrows indicating planar defects.

Conclusions

Utilizing aspect ratio trapping together with a GaAs stress relaxing layer, highly relaxed GaSb thin films have been grown on Si. Comparing with the GaSb thin films grown on planar GaAs-on-Si substrates, direct growth of GaSb on V-grooved Si offers an alternative path towards good quality templates without resorting to a thick GaAs transitional buffer layer. The primary defect generation mechanism in both samples was investigated. With a preferred method for integrating GaSb onto Si established, further integration of 6.1 Å compound semiconductors will extend the functionality of long wavelength photonic integration platform.

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Acronyms

IMF: Interfacial Misfit
MOCVD: Metal-Organic Chemical Vapor Deposition
XRD: X-ray Diffraction
X-TEM: Cross sectional transmission electron microscopy
FWHM: Full Width at Half Maximum
FFT: Fast Fourier Transform
SLS: Strained Layer Superlattice