Heterointegration of III-V Device Structures on Si Substrates via Direct MBE Growth

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Abstract

Recent progress on the heterointegration of III-V device structures on large-mismatched substrates via direct MBE growth will be reviewed. Focus will be on comparing InP- and GaSb-based optical and IR device structures grown on native substrates with the same structure on GaAs and Ge-coated Si (Ge/Si) substrates.

INTRODUCTION

Heterogeneous integration of III-V semiconductor devices with Si CMOS circuitry has attracted significant interest for its potential in next generation monolithic hybrid integrated circuits and Si photonics applications. Successful implementation of this approach can provide the combined advantages of high level integration and volume production of Si-based electronic circuitry with superior high speed and optical performance of III-V components. Various technologies have been explored, from pick-and-place die transfer to full wafer bonding to direct growth of III-V's on Si, but all require the implementation of high-quality III-V epilayers on CMOS-compatible Si host substrates. In this work, we will review our progress on the monolithic integration of III-V with Si.

Recent advancement in low threading dislocation Ge/Si substrate technology enables high quality III-V devices to be grown with comparable performance to those grown on native and intermediate-mismatched substrates [1]. Material characterization and device data on InP-based resonant-tunneling diode (RTD), InP-based quantum cascade laser (QCL), and GaSb-based mid-wave infrared (MWIR) photodetector structures grown on Ge/Si substrates will be discussed.

EXPERIMENTAL

All Si substrates used in this work were (100) oriented with a 6° offcut toward the [111] to help suppress anti-phase domain formation originating from polar (III-V) semiconductor on non-polar (Si) semiconductor growths [2]. Ge provided the first 4% step in lattice constant transition, and was employed because it has about the same lattice constant as GaAs, making it a good transition layer to the III-V semiconductors. The Ge layers were grown by chemical vapor deposition using an ASM E2000 tool. III-V epitaxy were performed on a variety of multi-wafer production molecular beam epitaxy (MBE) platforms. GaAs-on-Ge nucleation and metamorphic buffer (M-buffer) layers were primarily grown on our multi-6" Veeco GEN2000 production platform. Details of this GaAs-on-Ge growth process have been published previously [3]. These GaAs on Ge/Si templates were then transferred to either Oxford-VG V-100 or V-150 production MBE systems for the growth of the InP-and GaSb-based M-buffer and active layers.

Surface morphology, structural quality, and uniformity are critical first-pass evaluations of epiwafer quality, especially for the mismatched growths, as any abnormalities may result in fabrication problems and degraded device parameters. Optical-based defect mapping, Nomarski microscopy, and Atomic Force Microscopy (AFM) were used to evaluate epiwafer morphology. Structural quality was measured using High Resolution X-ray Diffraction (HRXRD). Optical properties of the GaSb-IRPD material were assessed by low temperature photoluminescence (LT-PL) using a Nicolet FTIR-8700 spectrometer and MCT detector.

METAMORPHIC INP-RTD ON SI SUBSTRATES

RTD device is the fastest pure solid-state electronic devices with room-temperature operation in the THz range [4, 5]. It is a promising candidate for energy-efficient and compact ultra-broadband short-range wireless communication transceiver technology need to support future network usage requirements. RTDs require very low power consumption and unlike traditional transistor technologies, they exhibit an intrinsic gain provided by its negative differential resistance (NDR) region which allows for a simple and energy efficient implementation [6]. Supported by the EU iBROW project [7], IQE explored the feasibility of growing InP-RTD structures on Ge/Si substrates as a potential for very high-speed and low-cost solution to enable ubiquitous ultra-broadband wireless communications.

The RTD structures under consideration are based on an InGaAs/AlAs double barrier quantum well design [5,7]. Following the growth of the GaAs buffer, an InAlAs M-buffer with a linear grade to a high In concentration was used, followed by a thinner inverse grade back to the target device composition [8]. The inverse graded step was used to compensate for residual strain in the epilayer as proposed in Ref. 9. Figure 1 schematically depicts this lattice constant progression from Si to the InP-based device layers.

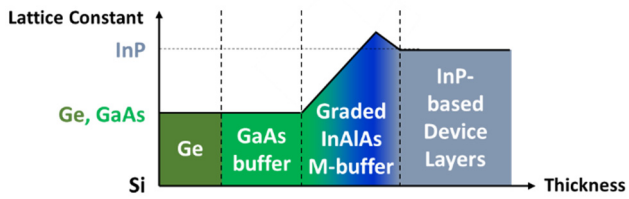

Fig. 1. Schematic of lattice constant progression from Si substrate to the InP-based epilayers (not to scale).

As a consequence of increasing lattice mismatch and strain relaxation, slightly elevated surface roughness and degree of cross-hatching becomes apparent for RTD layers grown on non-native substrates (Fig, 2). Despite the degradation in morphology, functional RTD devices exhibiting the expected N-shaped IV characteristics with a well-defined NDR region were obtained on structures grown on large-mistmatch substrates using this metamorphic growth approach (Fig. 3).

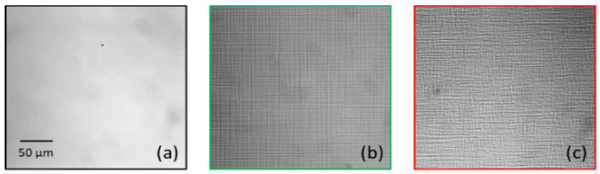

Fig. 2. Nomarski images of InP-RTD structures grown on (a) InP, (b) GaAs, and (c) Ge/Si substrates.

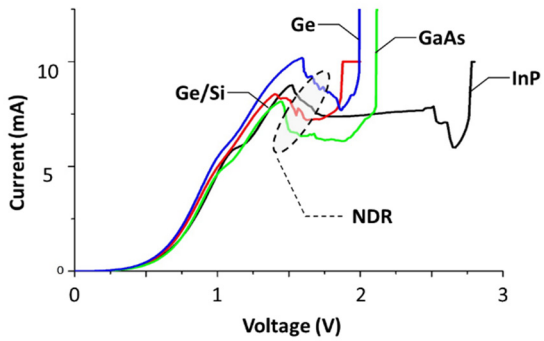

Fig. 3. IV curves of 9µm^2 RTD devices* on InP, GaAs, Ge, and Ge/Si substrates, all demonstrating NDR characteristics [11] (*with different epilayer designs).

METAMORPHIC INP-QCL ON SI SUBSTRATES

InP-based QCLs have demonstrated the highest performance essentially throughout the entire MWIR and longwave (LWIR) spectral regions [11]. The monolithic integration of these structures onto Si substrates paves the way for the development of ultra-compact and potential low cost infrared platforms with QCL elements used for chip-level wireless communications, sensing, and illumination. QCLs grown directly on Si substrates using an InAs-based alloy system targeting LWIR (~11 µm) operation was demonstrated recently [12]. Our work here reports on an InP-based MWIR QCL structure grown directly on a Si substrate [13]. The 40-stage QCL design utilized $Al_{0.78}In_{0.22}As$ barriers and $In_{0.73}Ga_{0.27}As$ quantum wells in the active region, both highly strained relative to InP waveguide layers surrounding the active region (-2.04% and 1.34%, respectively). The employment of the high strain active region layers increases the band offset, which improves carrier confinement for MWIR QCLs and, as a consequence, increases material gain.

As in our InP-RTD/Si work discussed above, direct growth of InP-QCL structures on Si substrates is challenging due to the large lattice-mismatch. The resultant mechanical stress is released via formation of threading dislocations whose presence in the active region leads to a reduced laser performance. We have earlier demonstrated the growth of the same QCL structure onto intermediate lattice-mismatched GaAs substrate, achieving room-temperature lasing at 4.4 µm [14]. Extending this to growth on Si substrate using the same scheme depicted in Fig. 1 turned out to be more challenging, partly because of the highly-strained design. While the active region was designed to have a net zero strain relative to InP, the strain of the individual layers plus any residual net strain in the active region can create more growth challenges.

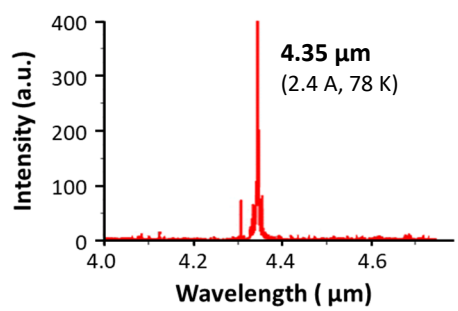

Fig. 4. 78K emission spectrum of a 3 mm × 40 µm ridge-waveguide QCL on Ge/Si device with with lateral current injection and high-reflection coating [13].

Surface morphology of the QCL on Si epiwafer was evaluated at various stages of the epi-stack growth, and degradation at the onset of the growth of the highly-stained

active layer was visible. Device performance and yield was impacted but we were still able to achieve lasing up to 170K [13]. The emission spectrum (Fig. 4) was centered at about the same 4.35 µm wavelength obtained on the QCL-on-GaAs wafer, demonstrating that despite the complexity of state-of-the-art QCL structures, an emission wavelength for a specific active region design can be reproduced for epi-growth on substrates having a wide range of lattice-mismatch by using appropriate M-buffer schemes.

ADVANCEMENT IN GE/SI QUALITY

In addition to the M-buffer, the quality of the Ge growth on the Si substrate also plays a crucial role in determining the quality of the active III-V device layers on top. The threading dislocation densities (TDD) in the Ge layer used for the RTD and QCL growths is in the mid 10^7 cm^{-2} range, so our best estimate for TDD in the InP layers is mid 10^8 cm^{-2}. Improvements in device can be expected with improved Ge/Si substrate quality.

Traditional evaluation of TDD has relied on cross-sectional and plan-view tunneling electron microscopy (X-TEM and PV-TEM). This is a time consuming and costly exercise which, due to the limited inspection area and the effects of variation in sample thickness, can also be unreliable especially when defect density drops below 10^7 cm^{-2}. IQE has developed an in-house wet etching metrology technique to quantify etch pit density (EPD), providing a fast, cost-effective alternative that offers improved accuracy for lower defect density measurements.

We started our development program with a measured EPD of ~7×10^7 cm^{-2} in our 1st generation Ge/Si substrates. Through careful experimentation and a series of process modifications, significant improvements have been achieved. The latest processes show defect densities of ~5×10^5 cm^{-2}, two orders of magnitude lower than the initial wafers. Progression of defect reduction in Ge/Si substrates is summarized in Table I, and representative Normaski images of substrates used in this work is shown Fig. 5.

TABLE I PROGRESSION IN DEFECT REDUCTION MEASURED BY IQE IN-HOUSE EPD METHOD, X-TEM AND PV-TEM.

Process	Defect Density (cm^{-2})		
	EPD	X-TEM	PV-TEM
1	**7×10^7**	**6.6×10^7**	**1.1×10^8**
2	1×10^7	1.0×10^7	
3	8×10^6	4.0×10^6	
4	4×10^6		
5	**$1\sim2\times10^6$**		
6	$\sim5\times10^5$		

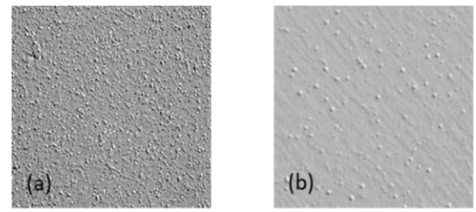

Fig. 5. Etched surface microscopy images showing improvement in Ge/Si template quality: (a) Process 1 templates used for RTD and QCL growths and (b); Process 5 templates used for GaSb IRPD growths.

METAMORPHIC GASB-BASED IR PHOTODETECTORS ON SI

Using the newly improved Ge/Si template technology based on process 5, we expanded our Si integration effort to include GaSb-based IR detector structures [15]. IQE has previously demonstrated a MWIR IRPD production MBE growth process in multi-wafer configurations on GaSb substrates as well as via a metamorphic process on GaAs substrates [16]. The same standard bulk InAsSb/AlAsSb barrier detector design with cutoff wavelength ~4 µm was used as the test vehicle as shown in Fig. 6.

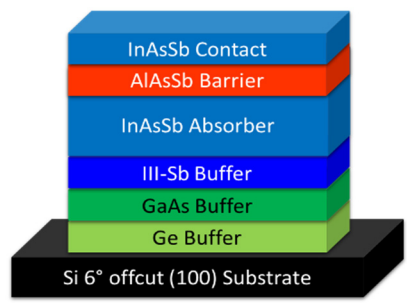

Fig. 6. Schematic of GaSb-IPRD grown on Ge/Si substrate (not to scale).

GaSb IRPD structures grown on 6" GaSb and GaAs revealed the expected mirror-like and mound-like (orange-peel) surfaces, respectively, with AFM rms roughness of 7 and 2 Å. The same structure grown on 6" Ge/Si substrates revealed a higher density of mounds, with an AFM rms value of 15 Å. As expected, the roughness increased as the mismatch between the device layers and the substrate material increased (Fig. 7a), but such levels of uniform roughness are more than acceptable for device fabrication. Excellent structural and optical uniformity of the GaSb-IRPD/Ge/Si epiwafers was verified by multi-point HRXRD and LT-PL measurements across the wafer. The InAsSb absorber composition varied by less than 0.005 Sb-mole fraction and the peak wavelengths were within 4.05±0.05 µm. across the wafer. Such epiwafer uniformity is important as it leads to the fabrication of FPAs with very uniform performance.

Large area mesa detector structures were fabricated at IQE from epiwafers grown on Ge-Si, GaAs, and GaSb substrates, all showing comparable 160K diode characteristics demonstrating high operation temperature capability. The low dark current (Jd) value of 5×10^{-5} A/cm^2 for the IRPD-on-Ge/Si sample was only slightly elevated compared to the other two samples. The spectral response curves also demonstrated consistent high-quality performance across all 3 samples, with a strong QE of about 60% (uncorrected for substrate and with no AR coating) and with cutoff wavelength in the expected 4.0–4.2 µm range. Finally, the IRPD-on-Ge/Si was fabricated into an FPA using a standard 640×512 pixel, 15 µm pitch process at QmagiQ. An image taken from this FPA, together with the corresponding visible image are shown in Fig. 8. QE from the AR-coated and fully packaged FPA is 80% with operability close to 100%. These results offer a potential technological path toward next-generation large format FPA IR detector applications.

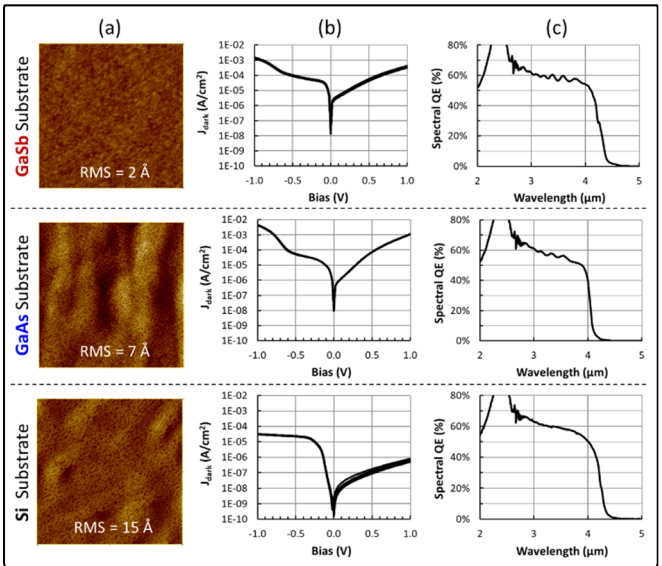

Fig. 7. (a) AFM images, large-area diodes (b) IV and (c) spectral response curves from GaSb-IRPD grown on the GaSb, GaAs, and Ge/Si substrates.

Fig. 8. IR image taken from an FPA fabricated from a Sb-based MWIR detector structure grown on Ge/Si template. The corresponding visible image is shown on the inset (courtesy QmagiQ LLC)

Conclusions

We have summarized some of IQE's on-going efforts in the area of heterogeneous integration of III-V semiconductor devices with Si by direct MBE growth on Ge-coated Si substrates. This M-buffer architecture was successfully applied to InP-based RTDs and QCLs, and to GaSb-based IRPD's. With optimization of the Ge/Si EPD levels, device structures grown on the Ge/Si substrates demonstrated performance characteristics comparable to the same devices grown on native lattice-matched substrates. This represents an important potential technological path toward next-generation heterointegration technologies.

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