InAs/GaAs quantum dot lasers on exact GaP/Si (001) and other templates

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Keywords: Quantum Dot, Silicon Photonics, Laser Diode, Molecular Beam Epitaxy

Abstract

We demonstrate InAs quantum dot (QD) laser diodes epitaxially grown on exact (001) Si substrates by molecular beam epitaxy. Intentional 4-6 ° offcut substrates have been traditionally employed to avoid formations that stem from the interface between III-V and Si. However, offcut substrates are not fully compatible with the standard CMOS processing. In this work, we employed on-axis GaP/Si and V-groove Si substrates to enable high performance QD laser diodes with output power of more than ~100 mW and continuous wave (CW) threshold current of ~30 mA at room temperature (RT).

INTRODUCTION

The silicon photonics field is advancing rapidly, with many new devices demonstrated recently [1]. Demonstrations have shown significantly improved performance that is now approaching that of devices on native InP substrates. In addition to the many passive devices, including arrayed waveguide gratings (AWGs), isolators, and circulators, active devices including lasers, modulators, amplifiers and photodetectors are reaching higher levels of integration. Over 400 devices have been integrated onto a single waveguide for applications such as integrated transmitters for datacom and telecom, true time delay photonic integrated circuits (PICs) for phased array radars, and LIDAR. However, realizing an efficient light source on Si remains still challenging, and more cost-effective integration may be possible by avoiding heterogeneously integrated III-V light sources for Si photonics. III-V QD lasers epitaxially grown on Si are proving to be a promising light source for silicon photonics [1]. Previous demonstrations have relied on intentionally offcut silicon substrates to suppress anti-phase-domains from III-V on Si heteroepitaxy. However, exact on-axis Si substrates are needed for compatibility with CMOS process flows. Here, we demonstrate InAs QD laser diodes epitaxially grown on two different on-axis (001) Si templates [2, 3]. We believe that this is a significant advance toward cost-effective and scalable light source integration for Si photonic circuits.

QD LASERS ON GAP/SI (001)

Fig. 1 (a) shows a GaP/Si template provided by NAsP III-V GmbH. We first grew a smooth GaAs buffer through a two-step growth by molecular beam epitaxy (MBE). The first 100 nm GaAs was grown at 500 C, and the substrate temperature was raised to a typical GaAs growth (630 °C) to further grow a 2300 nm GaAs layer. Then, a GaAs/AlGaAs graded-index

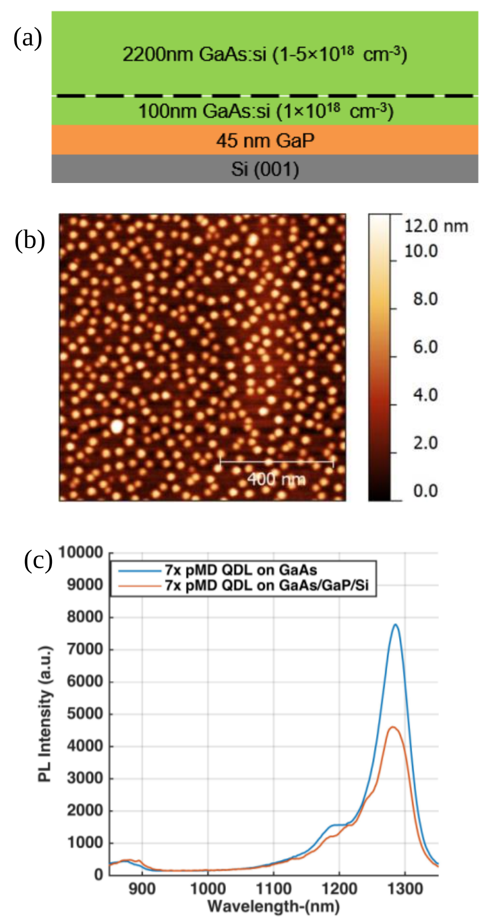

Fig. 1 (a) A schematic illustration of the GaAs/GaP/Si (001) template. (b) A 1 × 1 μm^2 AFM image of InAs QD grown on GaAs. (c) Room-temperature PL spectra from InAs QDs grown on GaAs substrate and on on-axis GaP/Si substrate, separate-confinement heterostructure was grown to form the waveguide and cladding for optical confinement. Optimized InAs QDs were employed as a gain medium for our Si lasers. The AFM image in Fig. 1(b) shows high density (5×10^{10} cm^{-2}) InAs QDs and RT PL (not shown here) reveals ~35 meV full-width at half-max linewidth. The seven layers of QDs with p-doped (5×10^{17} cm^{-2}) GaAs spacers were grown on the GaAs/GaP/Si (001) template by MBE. The 2.75 monolayers of InAs QDs were embedded in an $In_{0.15}Ga_{0.85}As$ quantum wells. The same active structure was also grown on a GaAs substrate for comparison. Fig. 1 (c) shows a RT photoluminescence (PL) comparison of the two as-grown laser structures, showing similar peak wavelengths, while the intensity of the laser on GaP/Si is ~60% that of on GaAs.

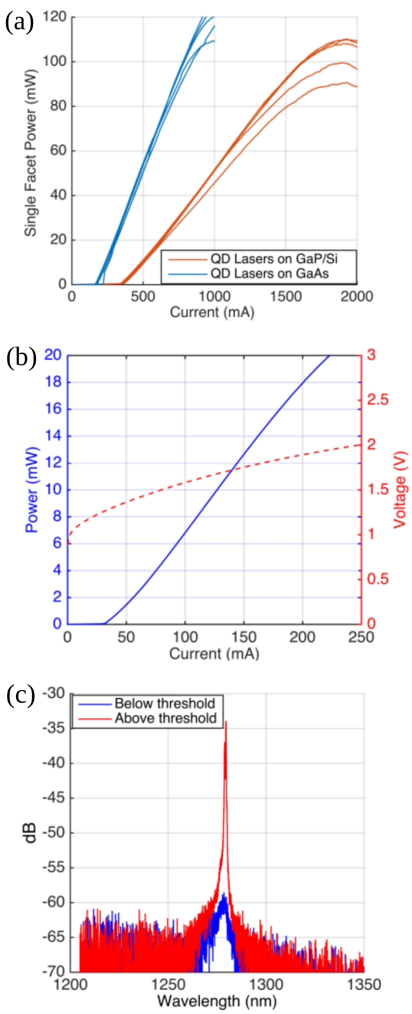

Fig. 2 (a) L-I curves measured from InAs QD broad-area (20 μm) lasers grown on GaAs (blue) and GaP/Si (red), (b) RT CW L-I-V curves and (c) lasing spectra from GaP/Si laser diode.

The laser epi materials were fabricated by standard dry etching and metal deposition techniques. Fig. 2 (a) shows RT continuous wave (CW) light-current (L-I) comparisons of 20 μm × 2 mm broad lasers on GaAs (J_{th} = 475 A/cm^2) and on GaP/Si (J_{th}=862 A/cm^2), both with as-cleaved facets. Note that the threshold current from the Si laser is about 1.8× higher than that of the GaAs laser, suggesting that the disparity comes from the higher dislocation densities in the GaP/Si laser than the GaAs laser. We expect to lower the threshold current density from the Si laser by optimizing the growth conditions of the GaAs/GaP/Si template. Fig. 2 (b) shows light-current-voltage (L-I-V) curves from a narrow ridge-waveguide laser (750 μm × 4 μm) on GaP/Si. The facets were polished and coated by high-reflection films. The CW threshold current is 32 mA at RT. CW lasing spectra measured from a device on GaP/Si is shown in Fig. 1 (c), and the lasing wavelength is ~1280 nm at RT. CW lasing from the lasers with high-reflection coatings persisted up to 90 °C with characteristic temperature of ~100 K between 20 – 40 °C. The maximum CW RT output power was measured to be ~110 mW.

QD LASERS ON V-GROOVE SI (001)

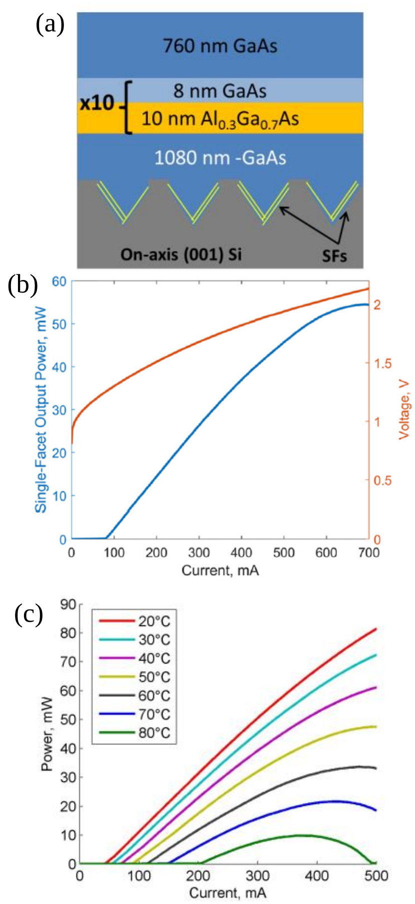

Fig. 3 (a) A schematic of GaAs template on V-groove Si (001). (b) L-I curves from the quantum laser diodes grown on V-groove Si. (c) Temperature-dependent CW L-I curve from an 8 × 1200 μm^2 HR coated device.

High quality anti-phase-domain free GaAs templates were grown on Si (001) by metal-organic chemical vapour deposition for another QD laser template as shown in Fig. 3 (a). Most of the stacking faults that arise from the interface between the GaAs and Si are trapped in the diamond-like Si pockets [3]. We performed an electron channeling contrast imaging technique to survey the defects in the template and found that the GaAs layer has densities of 7×10^7/cm^2 for threading dislocations and 2×10^7/cm^2 for stacking faults. The initial GaAs seed layers were coalesced to form a smooth surface on top of the V-groove Si substrate. Atomic force microscopy (AFM) revealed a root-mean-square (RMS) roughness of ~1 nm from a 10×10 μm^2 scan (not shown here).

Five layers of InAs QDs were grown in a similar structure to that presented above, except for the omission of p-doping in the GaAs layers and minor optimizations to the QD growth conditions. We fabricated narrow ridge-waveguide laser diodes with a 95% high-reflection coating on a facet. Fig. 3 (b) shows CW L-IV curves from a 9×1200 μm^2 device with a RT threshold current of 81mA. The lowest threshold current was 36 mA from a 6×1200 μm^2 laser bar, corresponding to ~500 A/cm^2 RT CW threshold current density. The laser diode grown on the V-groove on-axis Si substrate showed maximum operating temperature up to 80 °C as shown in Fig. 3 (c). The characteristic temperature was ~40 K between 20 – 80 °C, and the maximum out power reached ~107 mW. Note that we have not optimized the growth condition of the GaAs buffer layer. So, we believe that the performances of our preliminary QD lasers grown on the on-axis Si substrates will be improved further by lowering the threading dislocation densities in the GaAs layer to ~10^6/cm^2.

CONCLUSIONS

In conclusion, we demonstrated QD laser diodes epitaxially grown on exact (001) GaP/Si and V-groove (001) Si substrates, and the results are summarized in TABLE I. Both laser structures showed high performance lasing characteristics with over 100 mW CW output power and low threshold currents of ~30 mA. There are five reasons quantum dot lasers may finally replace quantum well lasers on Si: 1) reduced sensitivity to dislocations (important for growth on Si), 2) higher temperature operation, 3) low threshold, 4) reduced reflection sensitivity, 5) reduced sensitivity to surface recombination, allowing smaller, lower power lasers. A comparison of QW and QD lasers will be summarized in the presentation.

ACKNOWLEDGEMENTS

This work was supported by ARPA-E award (DE-FOA-0001261) and AIM photonics.

TABLE I
Summary of InAs QD lasers on Si (001) templates

		GaP/Si	V-groove Si
GaAs template	TDD	3×10^8 cm^{-2}	7×10^7 cm^{-2}
	SFD (cm^{-2})	N/A	2×10^7 cm^{-2}
	AFM RMS roughness	5 nm	0.9 nm
Active region	# of QD layers	7	5
	p-doping (cm^{-3})	5×10^7	N/A
Laser	λ at RT	1280 nm	1250 nm
	Lowest I_{th} (CW RT)	30 mA (3×750 μm^2)*	36 mA (6×1200 μm^2)*
	Lowest J_{th} (CW RT)	862 A/cm^2 (20×2000 μm^2)	498 A/cm^2 (12×1000 μm^2)*
	Output power (CW RT)	110 mW (20×2000 μm^2)	107 mW (8×1200 μm^2)*
	Max T (CW)	80 °C**	80 °C

* Indicates HR coated devices.
**Indicates Max T for ground state lasing.

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ACRONYMS

AFM: Atomic force microscopy
AWG: Arrayed waveguide grating
CW: Continuous wave
LIDAR: Light detecting and ranging
MBE: Molecular beam epitaxy
PIC: Photonic integrated circuit
PL: Photoluminescence
QD: Quantum dot
RT: Room temperature
RMS: Root-mean-square
SFD: Stacking fault density
TDD: Threading dislocation density