Highly reliable quantum dot laser directly grown on CMOS compatible Si (001) substrate

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Abstract: We present highly reliable InAs/GaAs quantum dot lasers directly grown on CMOS compatible Si (001) substrate without any predefined pattern or intermediate material. Under 300mA driving current, the continuous wave optical power reaches 91mW and 70mW at 25℃ and 85℃, respectively, with no obvious thermal rollover. Whilst operating at 85℃ 100mA, the lasers have demonstrated lifetime beyond 3000 hours and the observed optical power deterioration is less than 5%.

1. Introduction

Silicon photonic technology has gone through rapid development in last two decades. It has the potential for large-scale optical integration, low-cost high-volume production, and tightly integration with electronics for low I/O power consumption [1]. The lack of energy-efficient and reliable light source is one of the challenges it faces, because the indirect bandgap of silicon prevents in-situ realization of laser. Among various light source solutions, monolithically growth of III-V laser material on silicon has been regarded as the ultimate solution with the promises of low cost and large scalability [2]. However, two technical problems need to be resolved before practical implementation of the idea, i.e. the reliability of the grown III-V laser and the efficient coupling from III-V laser to silicon waveguide. The reliability challenge is due to the defects originated from the mismatch between silicon and III-V materials in terms of polarity, lattice constant and coefficient of thermal expansion (CTE). The defects, especially those exist in laser active region, act as non-radiative recombination centers and lead to early device failure [3]. Owing to their discrete in plane distribution, quantum dot (QD) active materials have been shown to be less vulnerable to threading dislocations than quantum wells [4]. Many efforts have been put into the direct growth of quantum dot laser on silicon in last decades, and rapid progress in laser performance and reliability has been demonstrated. Very recently, about 10% degradation for 1200 hours aged at 80℃ biased at two times threshold current has been reported, pushing the reliability of QD lasers on silicon close to the requirement of data center applications. [5]

In this paper, we demonstrate further reliability improvement of monolithically grown GaAs-based O-band QD lasers on 3-inch nominal (001) Si substrate. The proposed Fabry-Perot (FP) laser was designed to have single transverse mode. High temperature operating life (HTOL) aging of twenty samples at 85℃ 100mA shows power deterioration of less than 5% up to 3000 hours. To our knowledge, this is the best reliability result of QD laser monolithically grown on silicon so far.

2. Laser design and epitaxy

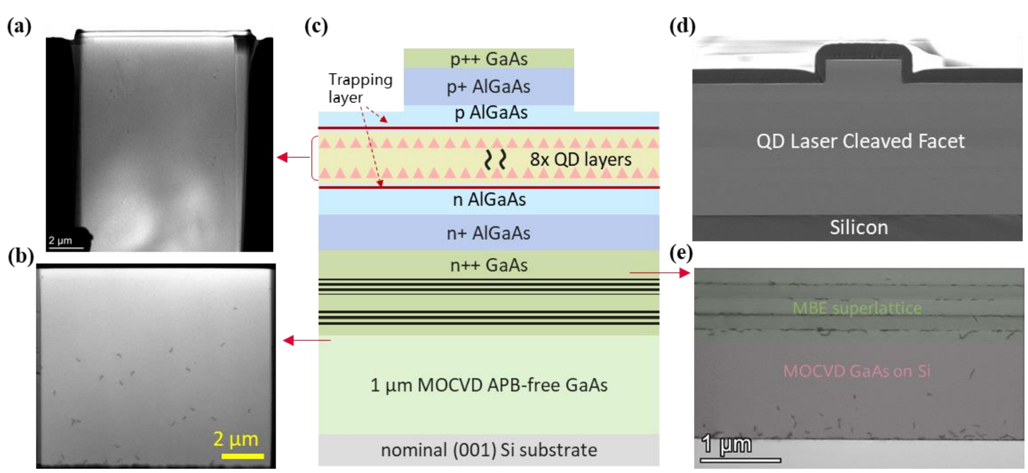

Fig. 1. Planar-View Transmission Electron Microscopy (PV-TEM) image at (a) 8 quantum dot layers without trapping layers (b) surface of the 1 μm APB-free GaAs. (c) Schematic view the epi-design of the proposed QD laser. (d) Scanning Electron Microscopy (SEM) image of the cleaved facet. (e) Cross-Section TEM image of the GaAs/Si growth interface and dislocation filtering superlattice.

A schematic view of the laser design is shown in Fig. 1(c). Metal-Organic Chemical Vapor Deposition (MOCVD) is used to grow 1 μm thick GaAs on the nominal (001) planar surface of silicon substrate. High temperature hydrogen atmosphere thermal annealing is used on silicon surface to form double atomic steps before GaAs growth to avoid antiphase boundaries (APBs). As shown in Fig. 1(e), there is no intermediate material like GaP or V-groove pattern at GaAs/Si interface. During the 1 μm GaAs growth, multiple steps of thermal cycle annealing are used to filter threading dislocation. The threading dislocation density (TDD) is $2 \times 10^{7}\ cm^{-2}$ after MOCVD epitaxy, as shown by the PVTEM image in Fig. 1(b). Afterwards, the wafer is sent to Molecular Beam Epitaxy (MBE) for quantum dot laser growth. Two sets of InGaAs/GaAs superlattice layers are used to further filter threading dislocations, as shown in Fig .1(e). Trapping layers are used to remove misfit dislocation from the 8 layers of quantum dots. The final TDD achieved at the 8 QD layers is $7.5 \times 10^{6}\ cm^{-2}$, and no misfit dislocations can be seen, as shown in Fig. 1(a). Residual tensile strain due to CTE mismatch between silicon and III-V materials is carefully managed and the whole device thickness is controlled to be 5.2 μm. As a result, no crack lines appear after the whole device epitaxy. Shallow etched ridge waveguide of 2.5 μm width is used for single transverse mode operation. After fabrication, 1 mm long laser bars are cleaved and coated with 95% high reflection films on rear and 30% reflectivity single-layer film on front for testing and aging. Perfectly cleaved III-V facet can be seen in Fig. 1(d).

3. Laser performance and reliability

Light-Current characteristics of the sample were tested under 25 ℃ and 85 ℃. The threshold currents are 18 mA and 30 mA, respectively. As shown in Fig. 2(a), the optical power reaches 91 mW at 25 ℃ 300 mA and 70 mW at 85 ℃ 300 mA, and no rollover is seen. Fig. 2(b) shows that ground state lasing of quantum dots around 1290nm can be maintained up to 85 ℃ 280mA, which is critical for reliability of QD lasers grown on silicon [6].

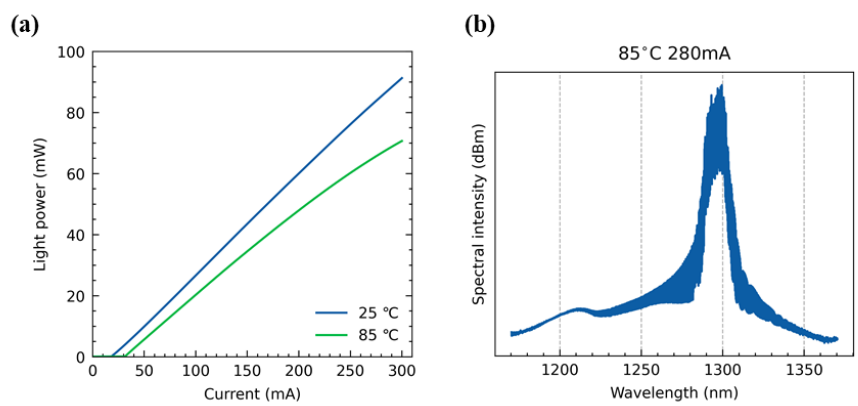

Fig. 2. (a) Light-Current characteristics and (b) Optical spectrum at 85℃ 280 mA of the proposed QD laser.

For the HTOL aging test, 20 chips were cleaved from bars and mounted p-side up on AlN carriers. All the samples were aged at 85 ℃ ambient temperature and 100mA injection current, corresponding to optical power about 20 mW. The samples are tested every 100 hours before 1000 hours and every 500 hours before 3000 hours. The results are shown in Fig. 3. Optical power change were tested under 120mA. For the median performance of all the samples throughout 3000 hours, the optical power performance at 25 ℃ show less than 2% deterioration. The threshold current degradation is less than 5%. The 85℃ performance also show less than 5% optical power deterioration and less than 10% threshold current degradation. Further improvement of the performance and reliability can be expected by lowering the optical loss which was tested to be about 6 cm^{-1} of current samples.

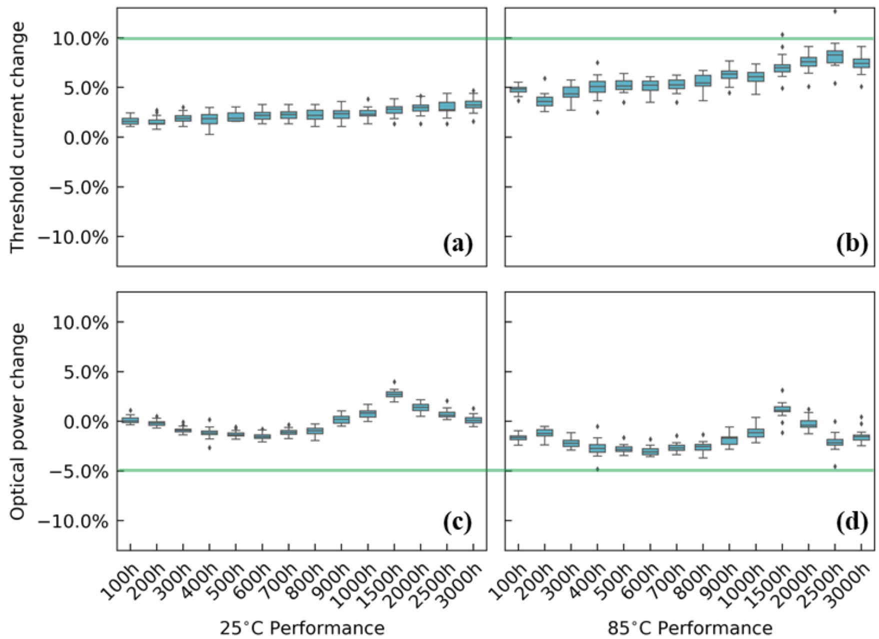

Fig. 3. Box plot of percentage change of threshold current at (a) 25 ℃ and (b) 85 ℃. Percentage change of optical power biased at 120 mA of (c) 25 ℃ and (d) 85 ℃. The sample consist of 20 chips, all aged at 85 ℃ 100mA.

4. Conclusion

We demonstrate highly reliable quantum dot laser monolithically grown on nominal (001) silicon substrate. APB-free III-V growth on silicon was accomplished by MOCVD, and the quantum dot growth was accomplished by MBE. Low TDD of $7.5 \times 10^{6} cm^{-2}$ was achieved at the quantum dot region. No thermal crack appears after the whole device epitaxy. The fabricated FP QD laser has single transverse mode and reach 70mW fundamental state lasing at 85℃ 300mA. The laser chips show state of the art reliability with less than 5% high temperature optical power deterioration throughout the 3000 hours 85℃ 100mA aging.

5. References

[1] N. Margalit, C. Xiang, S. M. Bowers, A. Bjorlin, R. Blum and J. E. Bowers, "Perspective on the future of silicon photonics and electronics," *Applied Physics Letters,* vol. 118, p. 220501, 2021.

[2] Y. Han, H. Park, J. Bowers and K. M. Lau, "Recent advances in light sources on silicon," *Adv. Opt. Photon.,* vol. 14, p. 404–454, September 2022.

[3] A. Y. Liu, R. W. Herrick, O. Ueda, P. M. Petroff, A. C. Gossard and J. E. Bowers, "Reliability of InAs/GaAs Quantum Dot Lasers Epitaxially Grown on Silicon," *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 21, pp. 690-697, November 2015.

[4] Y. Wan, J. Norman, S. Liu, A. Liu and J. E. Bowers, "Quantum Dot Lasers and Amplifiers on Silicon: Recent Advances and Future Developments," *IEEE Nanotechnology Magazine,* vol. 15, pp. 8-22, April 2021.

[5] C. Shang, E. Hughes, Y. Wan, M. Dumont, R. Koscica, J. Selvidge, R. Herrick, A. C. Gossard, K. Mukherjee and J. E. Bowers, "High-temperature reliable quantum-dot lasers on Si with misfit and threading dislocation filters," *Optica,* vol. 8, p. 749–754, 2021.

[6] M. Buffolo, L. Rovere, C. D. Santi, D. Jung, J. Norman, J. E. Bowers, R. W. Herrick, G. Meneghesso, E. Zanoni and M. Meneghini, "Degradation of 1.3 µm InAs Quantum-Dot Laser Diodes: Impact of Dislocation Density and Number of Quantum Dot Layers," *IEEE Journal of Quantum Electronics,* vol. 57, pp. 1-8, February 2021.