Monolithic Quantum dot Laser for Silicon Photonics

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OPTICS

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Outline

I. Why monolithic III-V lasers on Si and challenges

II. Quantum dots for monolithic III-V/Si integration

III. Monolithic 1.3 μm InAs quantum dot lasers on Si

IV. Conclusion

Outline

I. **Why Monolithic III-V lasers on Si and challenges**
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III. Monolithic 1.3 μm InAs quantum dot lasers on Si
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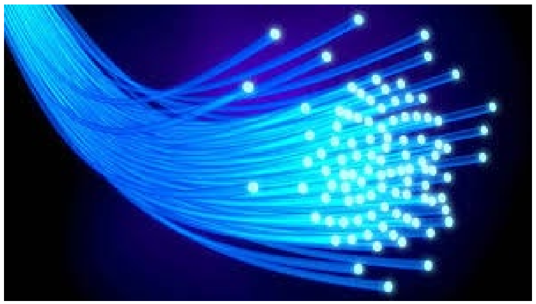
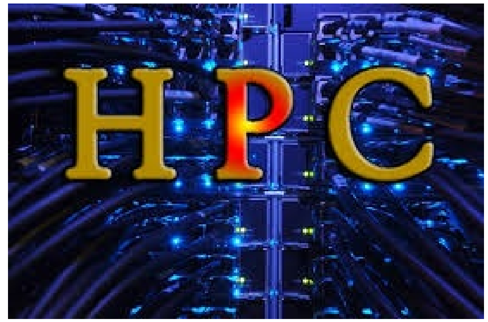
Challenges for today's networks

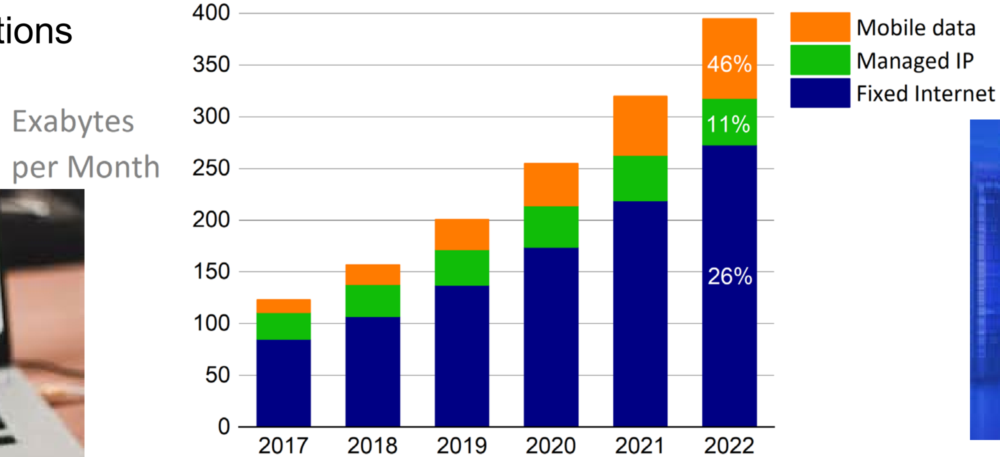


Optical Communications



High-Performance Computing

5 G



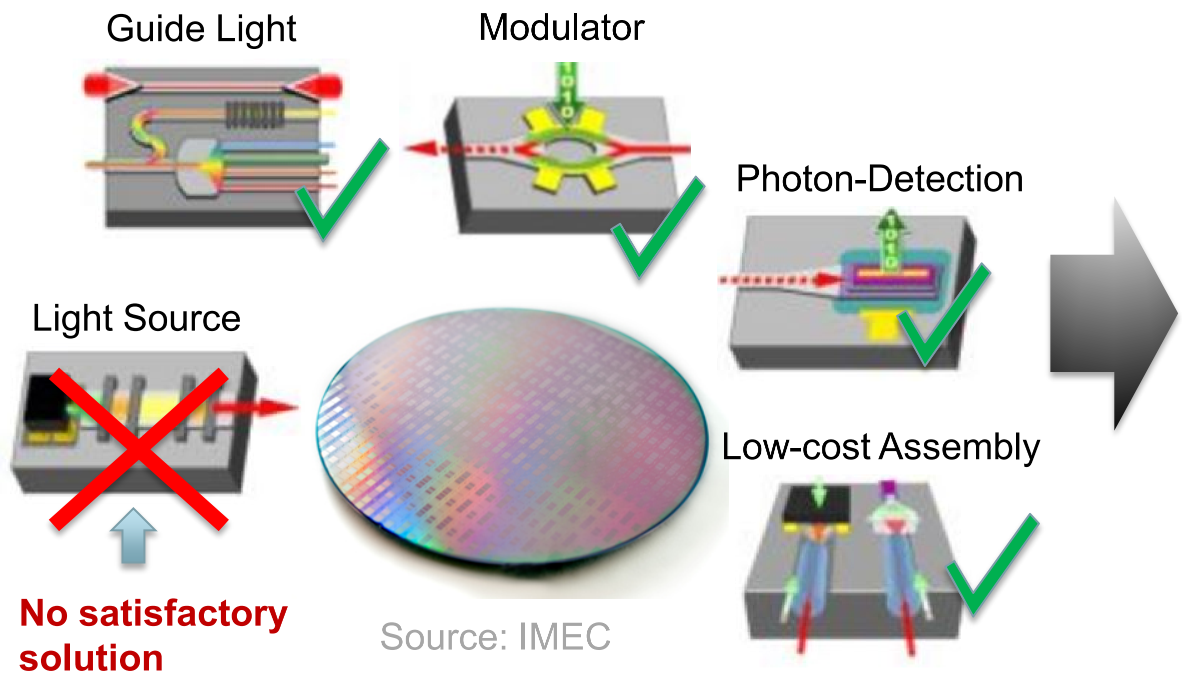
Source: Cisco Global IP Traffic Forecast, 2017-2022

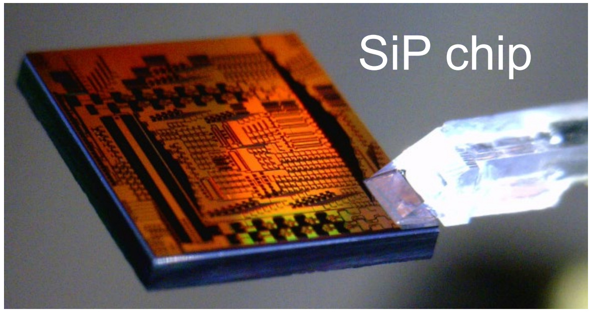
Video downloading

Cloud Storage

- Global IP traffic will increase threefold over the next 5 years
- "Bottleneck" is represented with existing technologies

Why silicon photonics

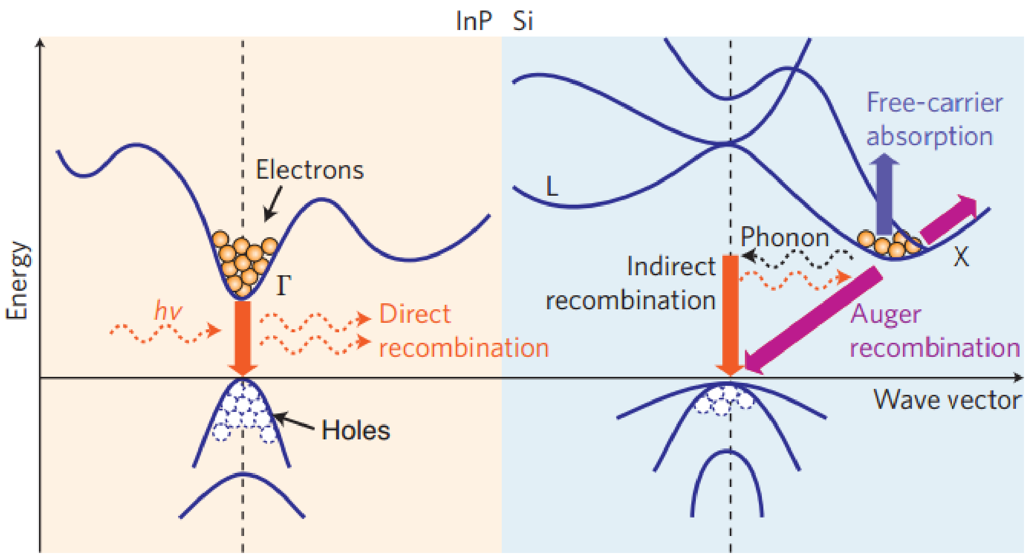




Source: PLCC

- A innovating technology: convergence of photonics and electronics using **standard CMOS fab**.
- The vision: to provide optical connectivity everywhere, ranging from network level to chip-to-chip and to on-chip.
- Many individual building blocks have been realized and embedded at the **SOI wafer level**, except for the **light source**.

Challenges for silicon photonics



Two major non-radiative processes:

- Auger recombination
- Free-carrier absorption

Origin of poor emitter?

- Indirect bandgap
- Extremely **poor** internal quantum efficiency η_i, which is defined as:

$$\eta_i = \frac{\tau_{nonrad}}{\tau_{nonrad} + \tau_{rad}}$$

- and is generally of the order of $\mathbf{10^{-6}}$.

Combine III-Vs and Si

Si

- Cost advantage
- Light routing/modulating/detecting
- Transparent at the infrared wavelengths
- High index contrast
- Poor emitter

III-Vs

- Light emitting
- Dominate for near- and mid-infrared wavelengths
- Expensive
- Small size

Direct epitaxy

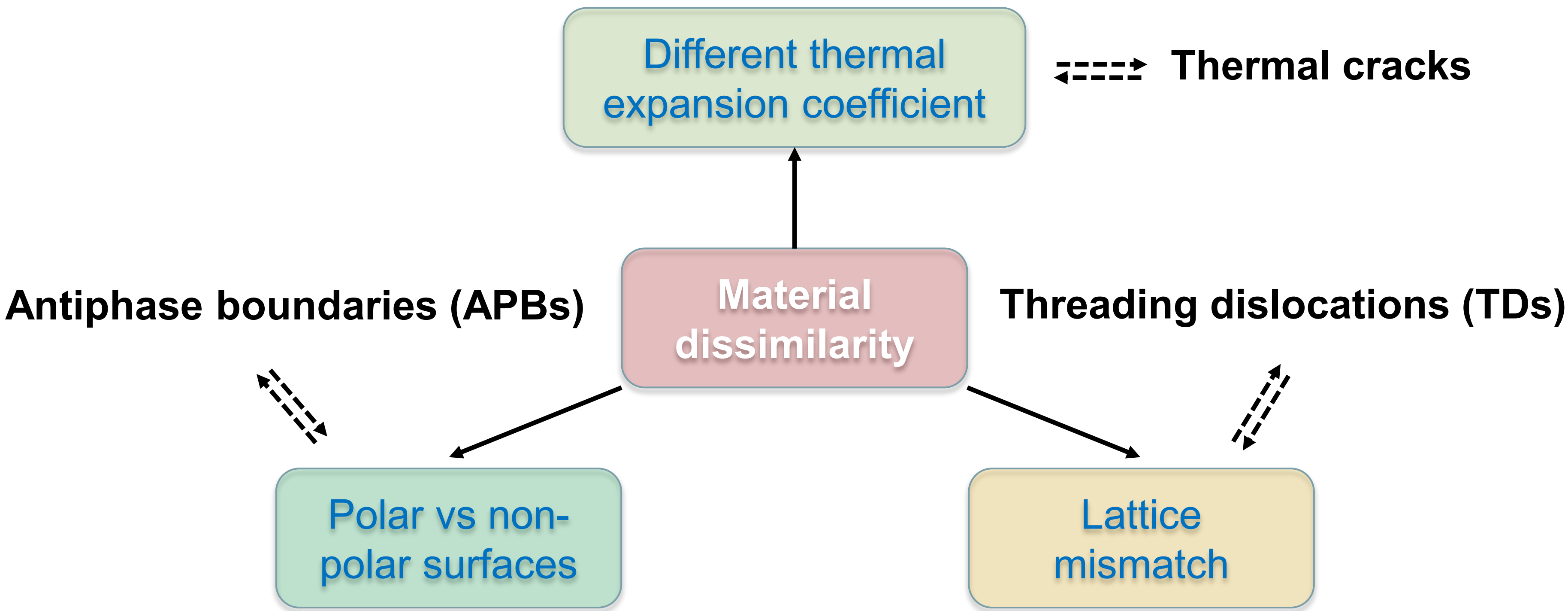
Comparison between different heterogeneous integration strategies on silicon

	Integration density	CMOS compatibility	Cost	Overall maturity
Heterogeneous bonding	Medium	Potentially back-end compatible	Medium	Mature
Transfer printing	High	Potentially back-end compatible	Low	R&D
Epitaxial growth	Very High	Potentially front-end compatible	Potentially very low	R&D
Colloidal QDs	High	Potentially back-end compatible	Potentially very low	Early R&D

- **Wafer bonding**
  – most mature technology
- **Epitaxial growth**
  – cost-effective, massive scalable and streamlined fabrication

Z. Wang et al, **Laser Photonics Rev.** 11, 1700063 (2017)

Challenges for epitaxial growth



- Generate non-radiative recombination centres
- Dramatically undermine the promise of III-Vs

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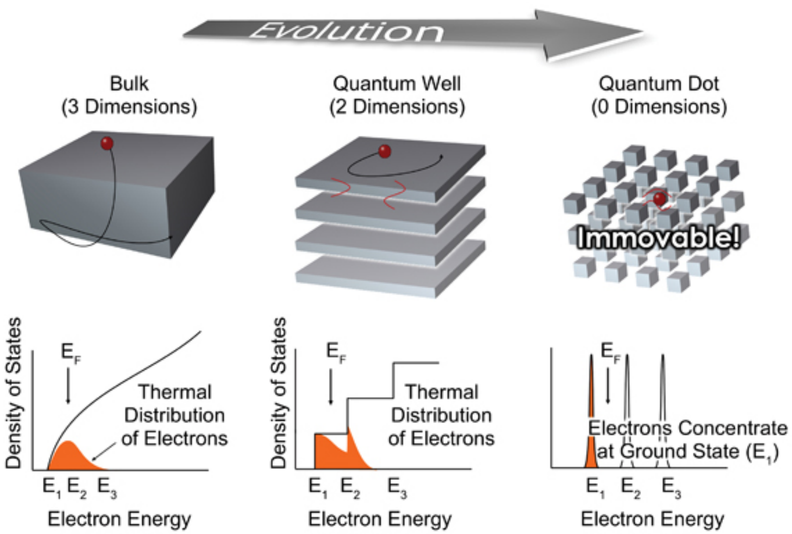
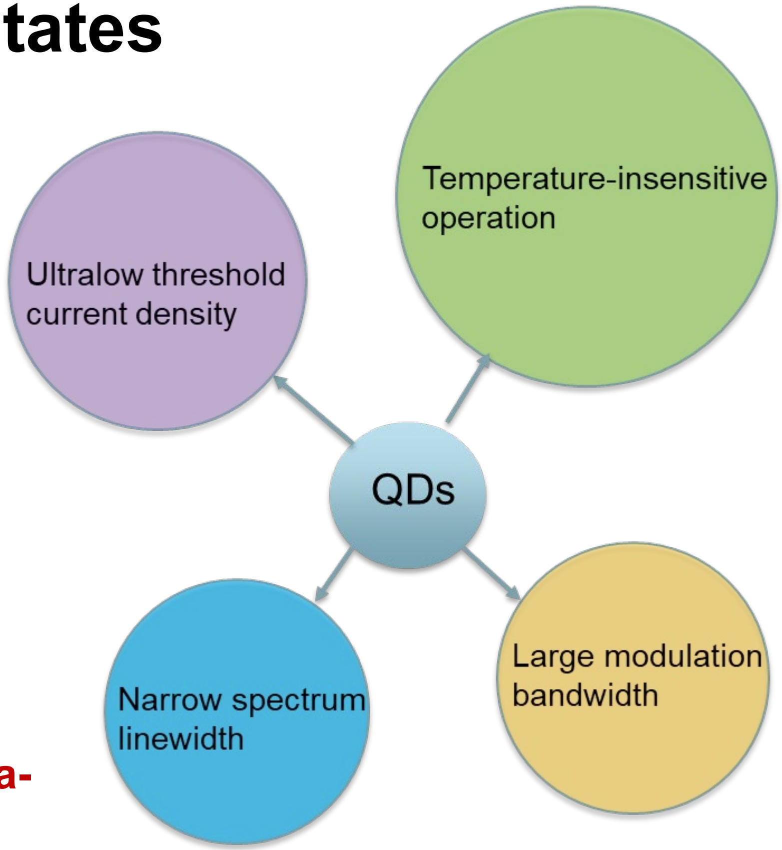
Delta-function density of states



Evolution of density of states



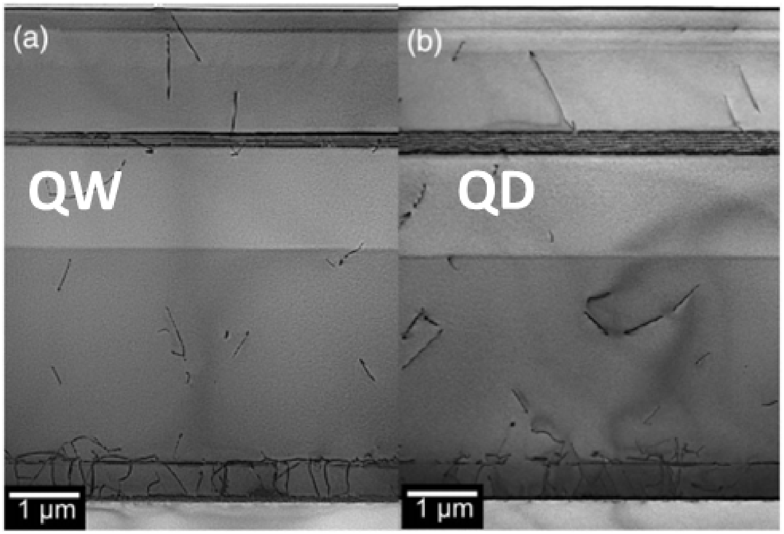
Conventional advantages of QDs

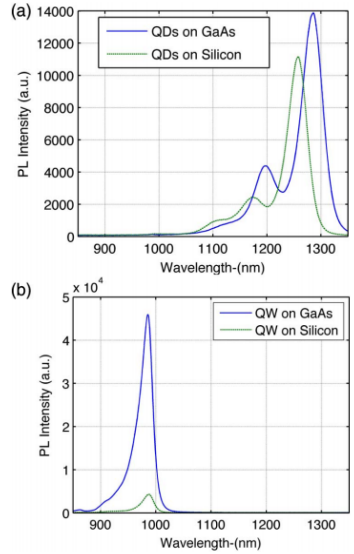
For a QD ensemble, DOS represents a set of **delta-function peaks** centred at the atomic-like energy levels.

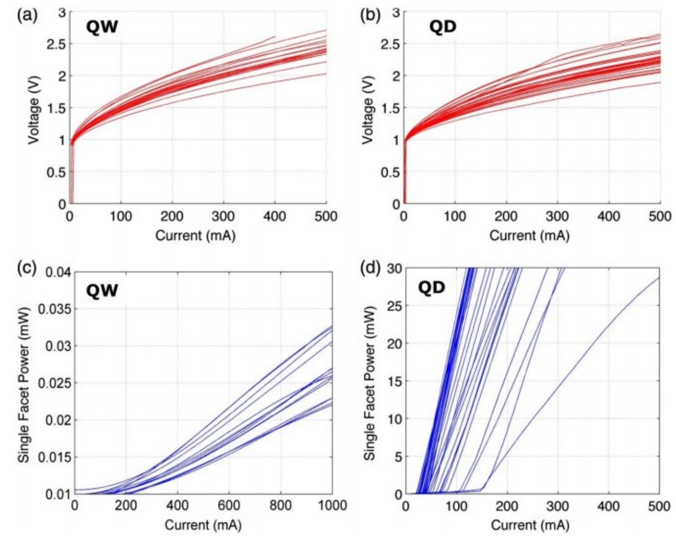
- The density of charge carriers accumulated at the energy of the working transition is significantly enhanced – **Higher differential gain** & **reduced threshold current density**.
- A large energy separation between ground and excited states – **temperature independent operation**.

K. Nishi et al., IEEE JSTQE. **23**, 1901007 (2017)

Unique advantage of QDs - less sensitive to defects







- Direct comparison of QD versus QW lasers grown on Si
- Similar defect density; processing, and measurement techniques were identical

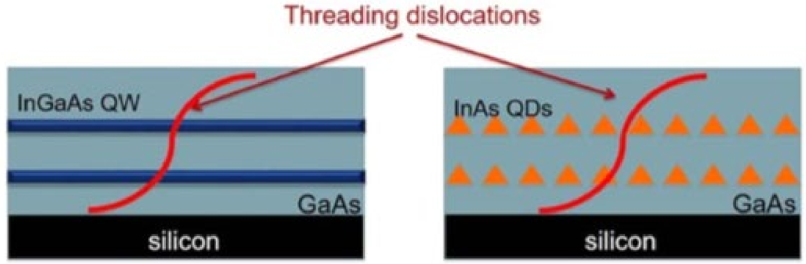
Similar IV characteristics

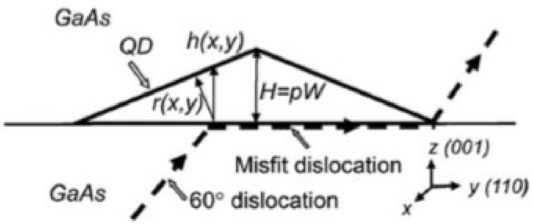
Totally different optical properties and laser performance

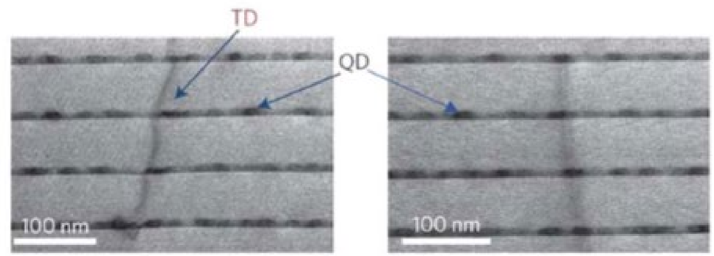
Less sensitive to defects for QDs
Why?

Liu et al., Photonics Research **3**, B1-B9 (2015)

Origin of reduced sensitivity to defects



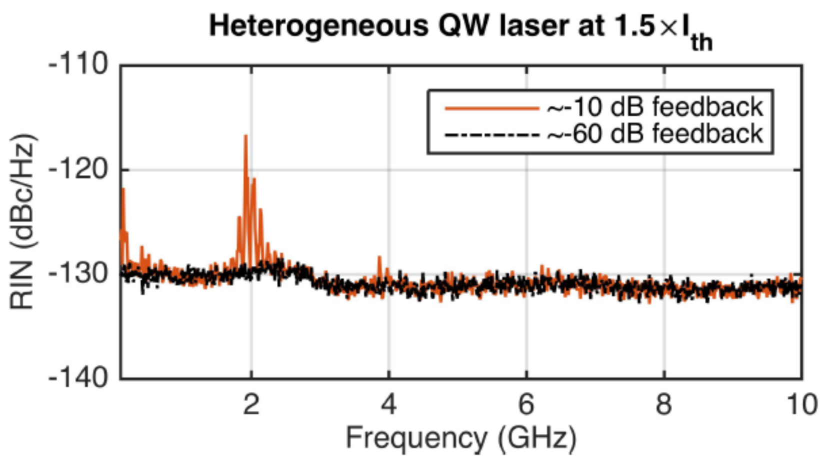


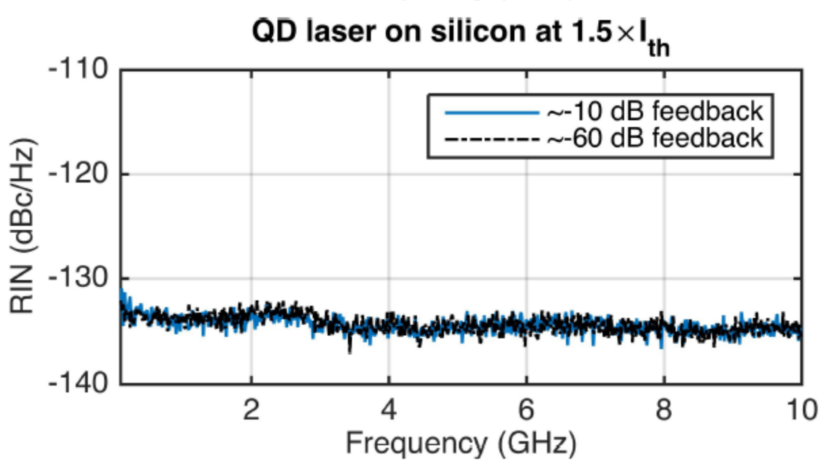


- Carriers are highly localized in QD and hence reduce the probability of interaction with defects
- One TD can only one or a very limited number of dots, while still leaving the rest of dots providing sufficient optical gain – **the number of dots** $\gg$ **the number of TDs**
- The dislocation bending can occur beneath the QDs when strain energy is released through the generation of the misfit dislocation and a TD propagates toward the bottom of a QD. Consequently, the bending of dislocation generated a segment of misfit dislocation gliding below the island.
- The TD can also be effectively propelled away from QDs due to the strong strain field introduced by the QDs.

M. Liao et al., Semicond. Sci. Technol. **33,** 123002 (2018)

Unique advantage of QDs - less sensitive to feedback





The critical feedback level where the laser enters a coherence collapse regime is given by:

$$f_{crit} = \frac{\tau_L^2 (K f_r^2 + \gamma_0)^2}{16|C_e|^2} \left(\frac{1 + \alpha^2}{\alpha^4} \right)$$

where
K: K-factor
α: linewidth enhancement factor

- highly damped relaxation oscillations
- lower amplitude-phase coupling

Liu et al., Opt. Express **25,** 9535 (2017)

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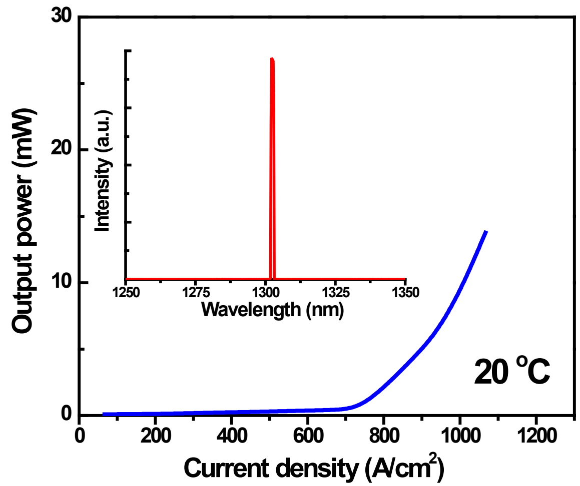
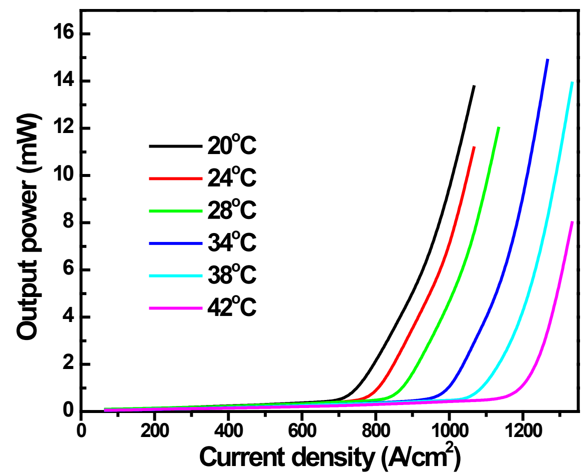
First 1.3 µm III-V QD laser grown on Si

2011





- To present the formation of APBs
  - Offcut Si (100) wafers
- To suppress the propagation of TDs
  - Two sets of InGaAs/GaAs DFLs

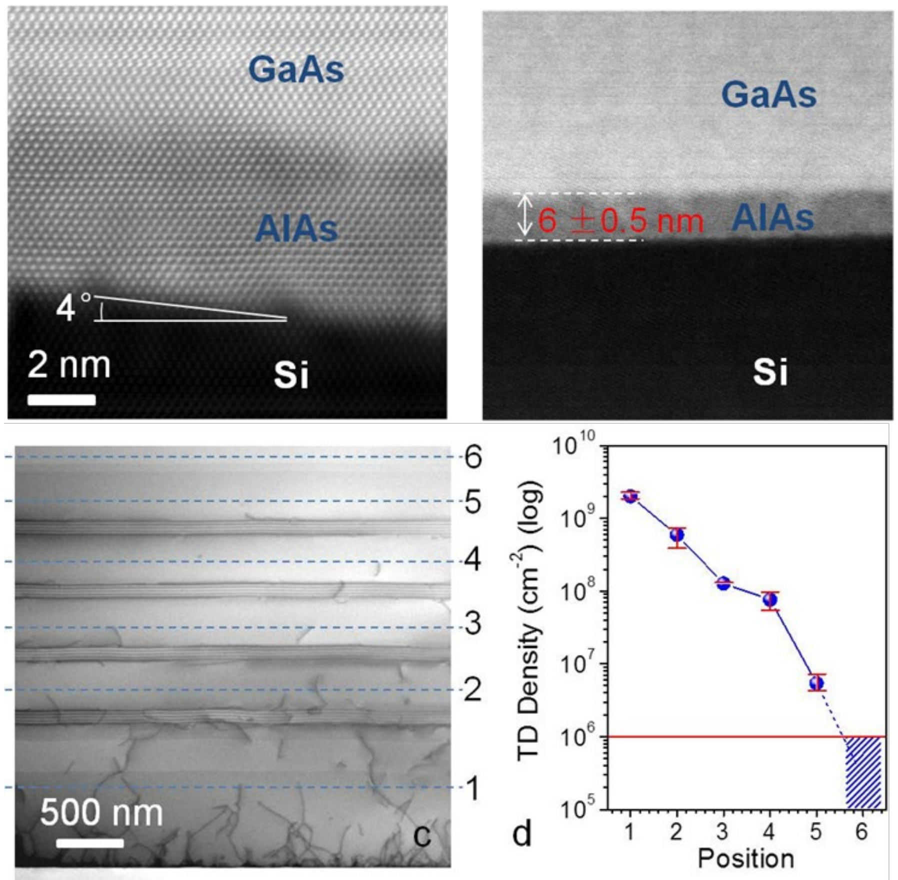
Not good enough

- Off-cut substrate
- Pulsed operation
- J_{th} = 725 A/cm^2 (RT);
- P_{out} =26 mW/facet at (RT)
- λ_{peak} = 1300 nm
- T_{max} = 42 °C

T. Wang et al., Opt. Express **19**, 11381 (2011)

First long lifetime III-V QD laser grown on Si

2016

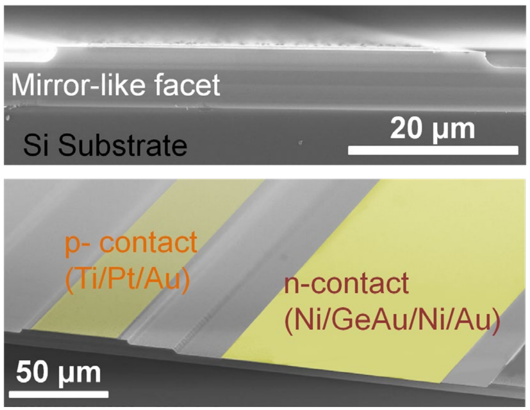


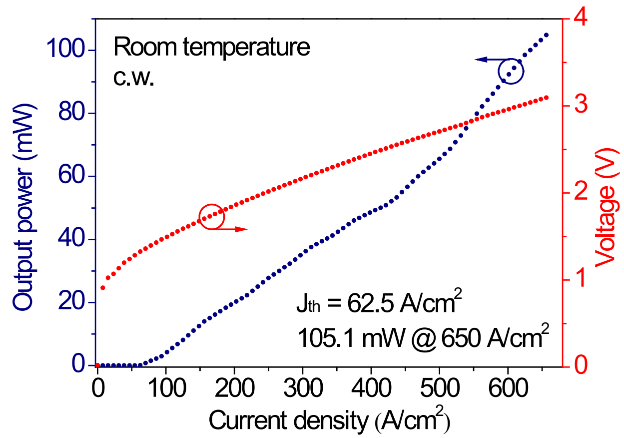
S. Chen et al, Nature Photon. **10**, 307 (2016)

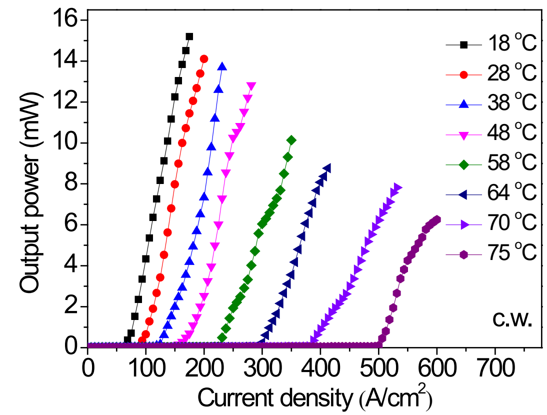
- Si (100) wafers with 4° ***offcut*** to the [011] plane
  - to prevent the formation of APBs
- ***AlAs nucleation layer***
  - to suppress three-dimensional growth
- ***InGaAs/GaAs DFLs***
  - to suppress the propagation of the TDs
- ***In-situ* thermal annealing** of SLS
  - to improve the efficacy of filtering defects.

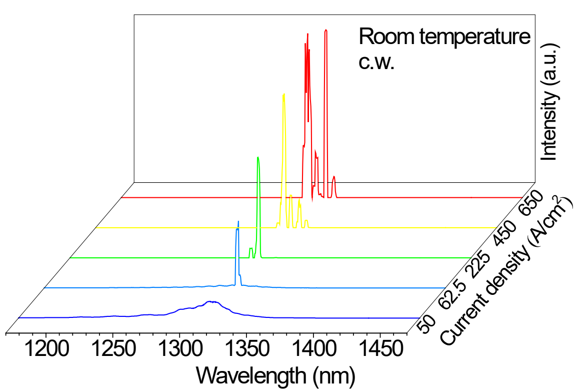
The density of TD has been reduced to the order of ***~10^5 cm^{-2}***.

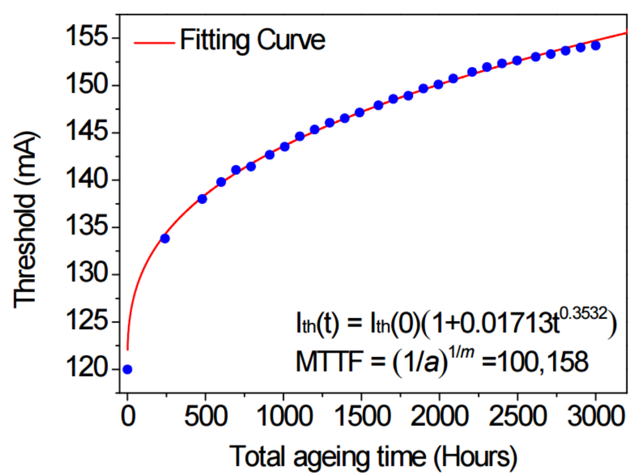
First long lifetime III-V QD laser grown on Si







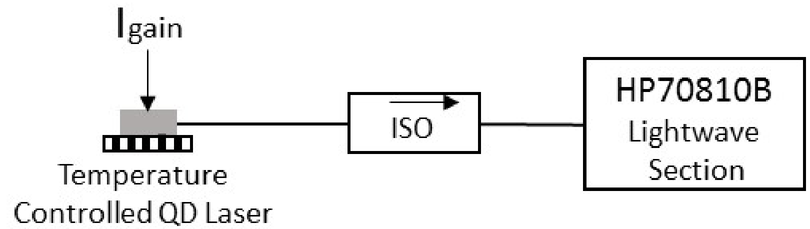


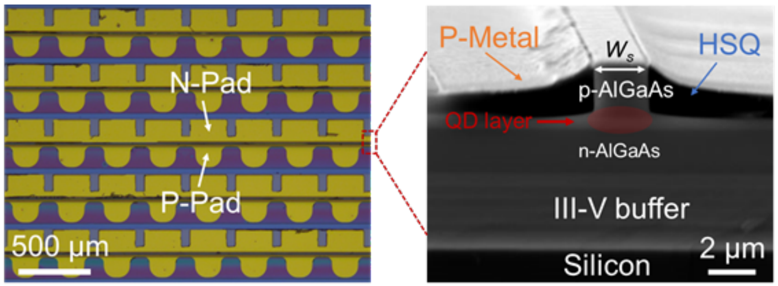


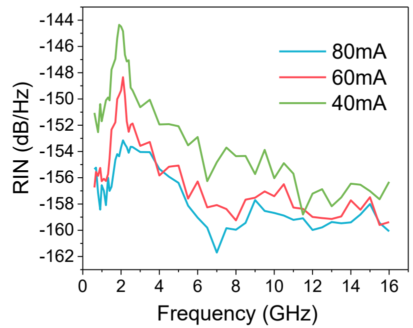
- Broad area laser
- J_{th} = 62.5 A/cm^2 (RT)
- P_{out} =105 mW/facet at (RT)
- λ_{peak} = 1315 nm
- T_{max} = 75 °C (c.w.) 120 °C (pulsed)
- Extrapolated lifetime over 100,000 hours

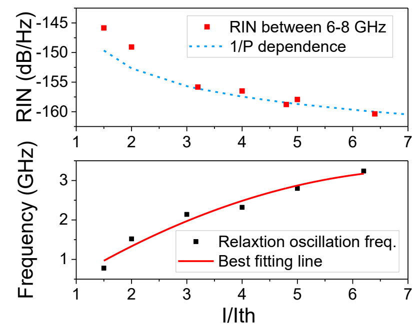
S. Chen et al., Nature Photon. **10**, 307 (2016)

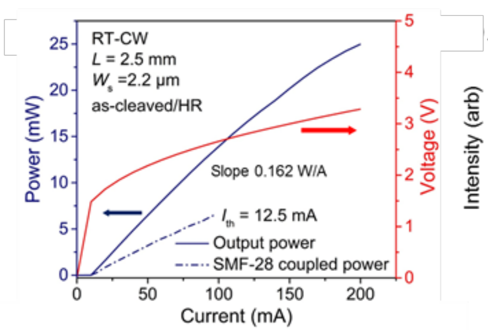
Ridge waveguide laser

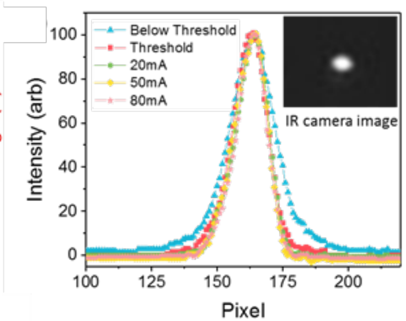


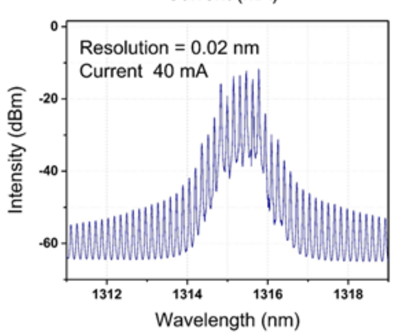


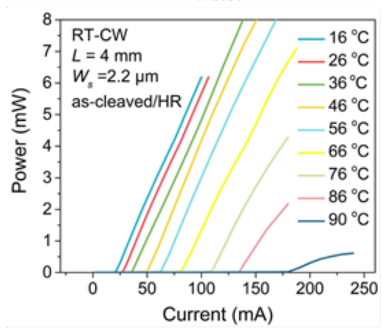








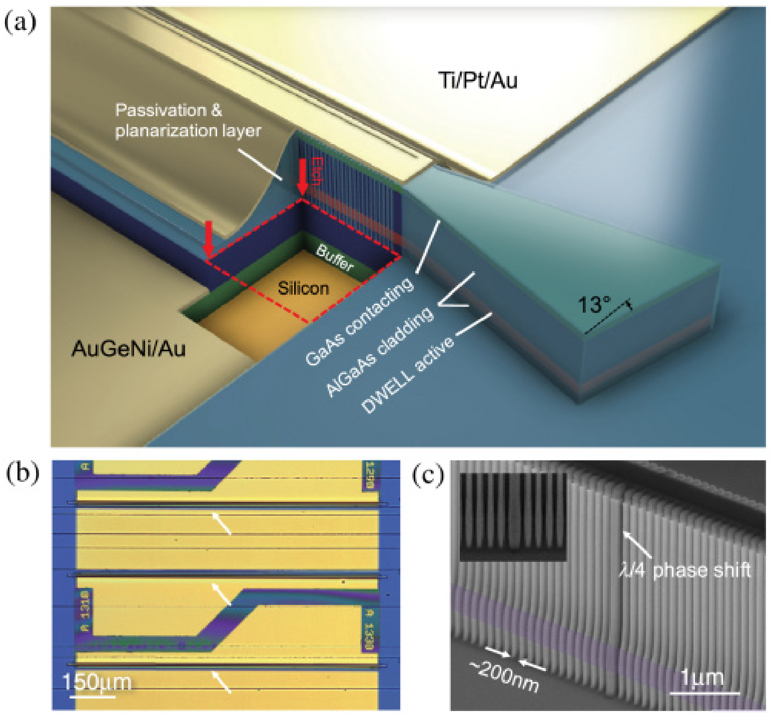


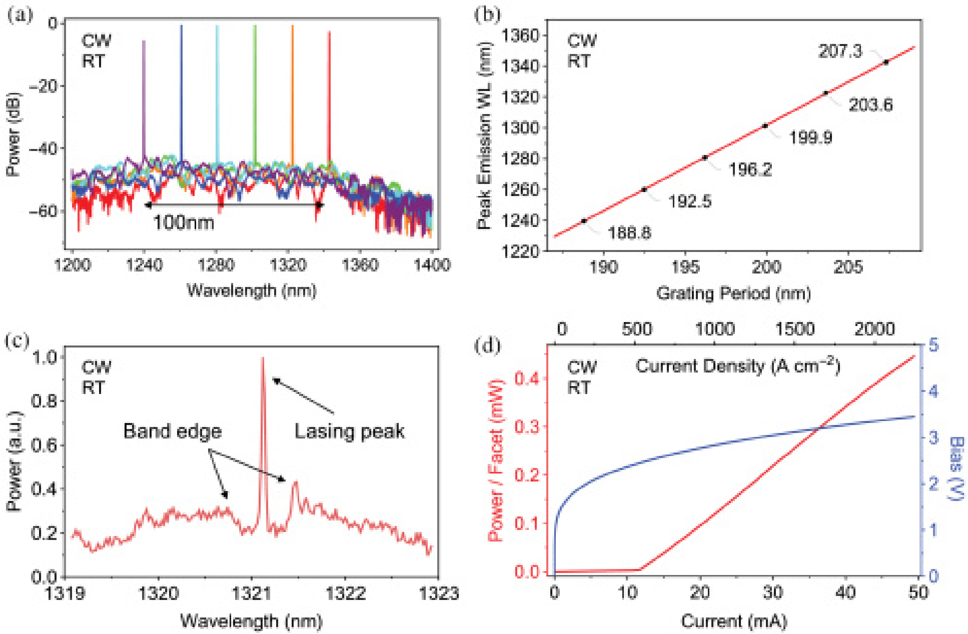


M. Liao et al., Photon. Res. **6**, 1062 (2018)

- Offcut substrate
- I_{th} ~ 12.5 mA @RT (CW)
- T_{max} ~ 90 ^{o}C (CW)
- λ_{peak} ~ 1315 nm (ideal for O-band)
- RIN < -150 dB/Hz.
- The relaxation oscillation frequency (ω_R) from 1 GHz to 3 GHz (20 mA - 80 mA)
- Low ω_R is a result of longer photon lifetime due to its longer cavity length (2.5 mm).

The first QD DFB laser array on Si





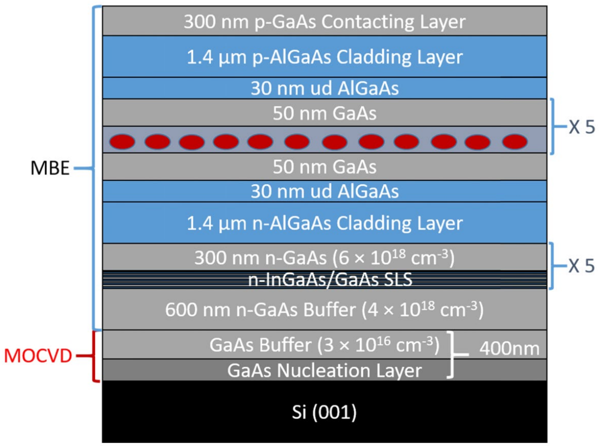
- Lateral surface gratings design (first order)
- λ/4 phase shift
- Different grating periods for λ turnability
- AR-coupler design

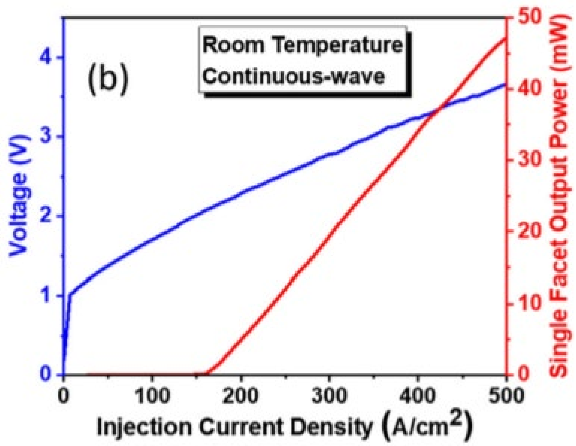
- ➢ Offcut substrate
- ➢ I_{th} ~ 12mA
- ➢ SMSR ~ 50 dB
- ➢ Wavelength coverage ~ 100nm
- ➢ CWDM compatible (20nm spacing)

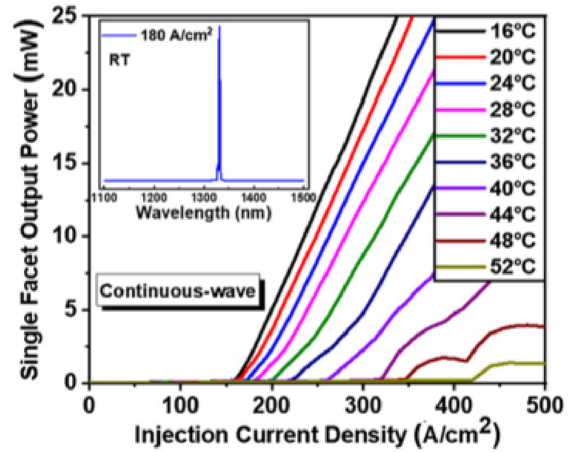
Y. Wang et al., Optica **5**, 528 (2018)

InAs QD laser grown on on-axis Si (001)

2017







Key Features

- Leverage Leti's APB-free GaAs/Si virtual substrate technique
- Combine MOCVD and MBE
- Without any intermediate buffer layer or patterned substrate

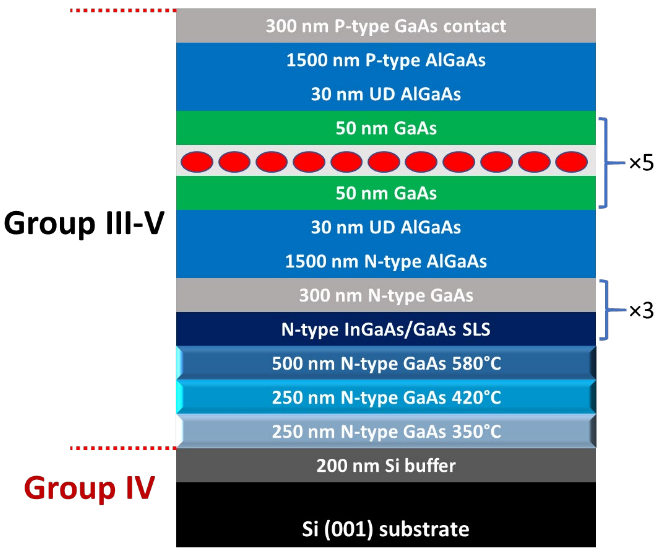
- ➢ On-axis Si (001) substrate
- ➢ CW operation
- ➢ J_{th} = 160 A/cm^2 (RT)
- ➢ λ_{peak} = 1330 nm
- ➢ T_{max} = 52 ^{o}C (CW); 102 (Pulsed)

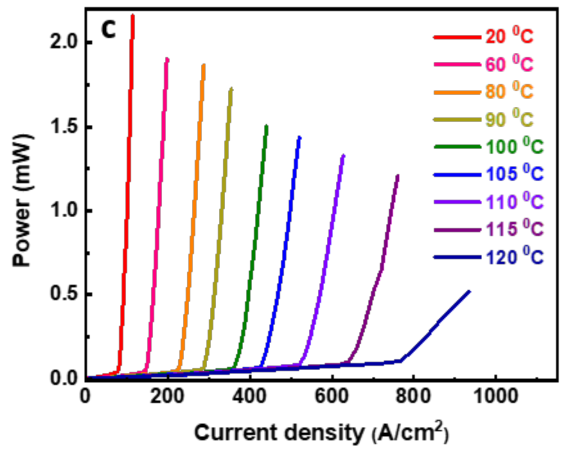
S. Chen et al., **Optics Express** 25, 4632 (2017)

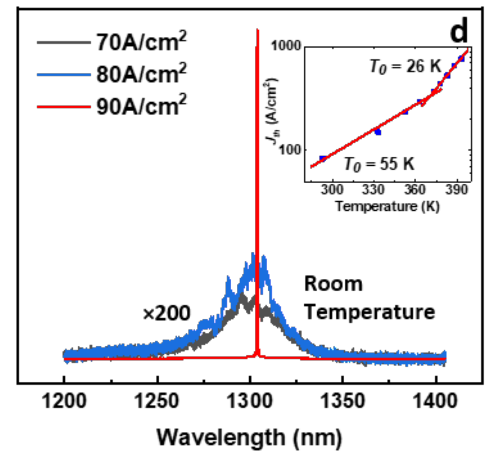
K. Li et al., J CRYST GROWTH **511**, 56 (2019)

All MBE grown QD laser on on-axis Si (001)

2020







Key Features

- All MBE grown
- Si (001) substrates used were not intentionally selected before epitaxy
- Special twin MBE system combining Group-IV and III–V growth chamber

- On-axis Si (001) substrate
- Pulsed operation
- J_{th} = 83.3 A/cm^2 (RT)
- λ_{peak} = 1310 nm
- T_{max} = 120 (Pulsed)

K. Li et al., **Advanced Optical Materials**, 8, 2000970 (2020)

Outline

I. Why monolithic III-V lasers on Si
II. Quantum dots for monolithic III-V/Si integration
III. Review of monolithic III-V quantum dot lasers on Si
IV. Conclusion

Conclusion

- Significance of epitaxial growth of III-V lasers on silicon has been introduced
- Challenges for epitaxial growth of III-V materials on silicon have been discussed
- Unique advantages of using quantum dots as the active for monolithic III-V/Si integration have been discussed
- Recent progress in monolithic 1.3 μm InAs quantum dot lasers on silicon achieved by UCL has been reviewed

UCL

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