Monolithic III-V Quantum Dot Lasers on Si for Silicon Photonics

Siming Chen (RFREng 、Ph.D.)

Department of Electronic and Electrical Engineering
University College London, UK

siming.chen@ucl.ac.uk

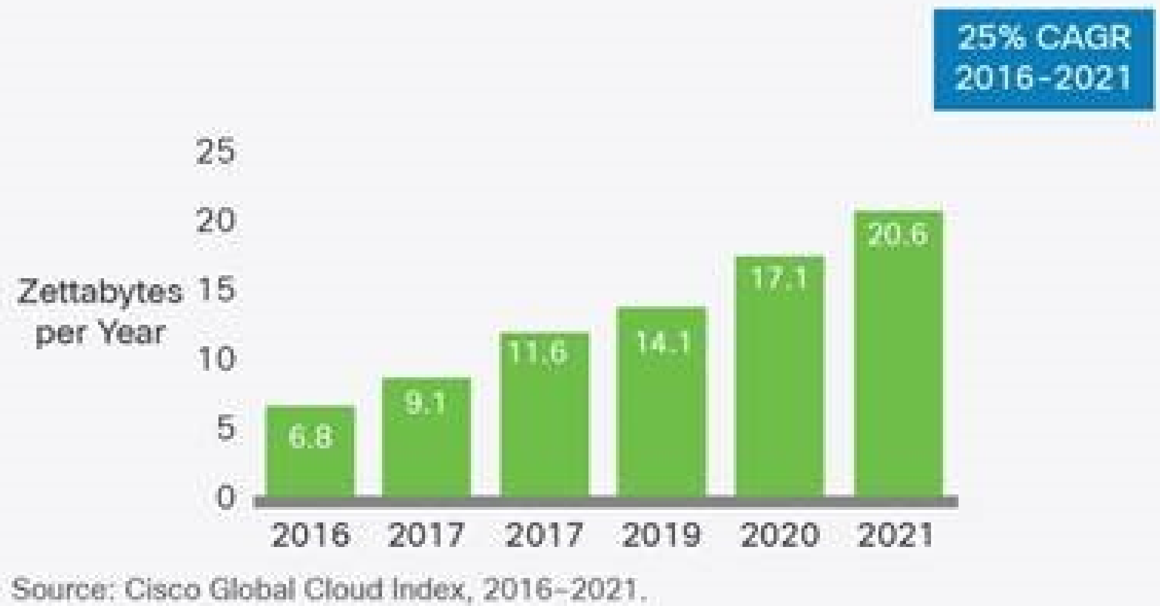
OPTICS

March 23rd 2018, Dresden, Germany

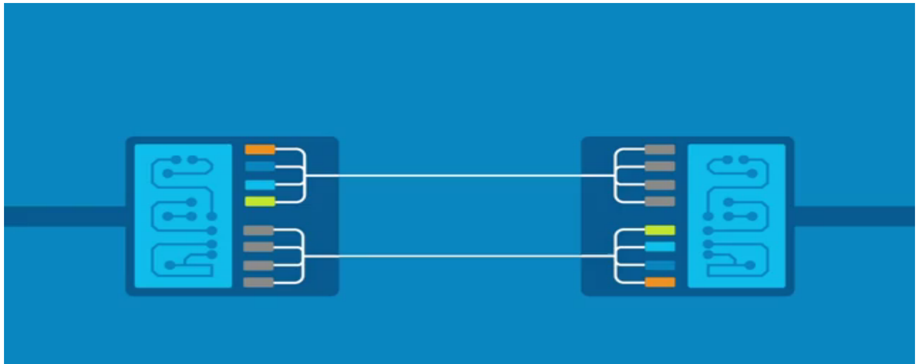
Outline

1. **Why III-V QD laser on silicon**
2. III-V QD FP lasers monolithically grown on Ge and Ge-on-Si substrates
3. III-V QD FP lasers monolithically grown on silicon
4. III-V QD DFB laser array monolithically grown on silicon
5. Summary

Challenge for Data Centre



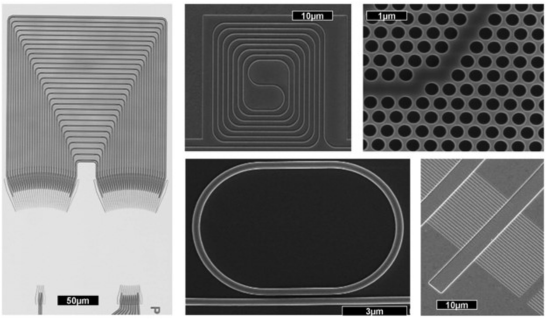
Si Photonics = Optical + Electronic



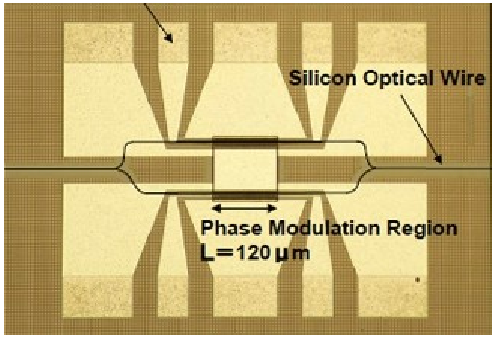
Source: Intel® Silicon Photonics

- **Global data centre traffic is booming**
- **Traditional copper cabling is stifling datacentre evolution**
- **Silicon photonics can solve the slow data transfer problem**

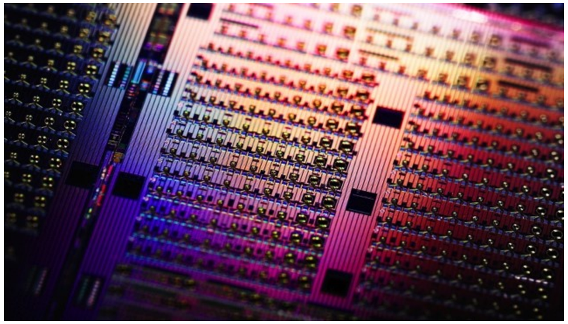
Challenge for Si photonics



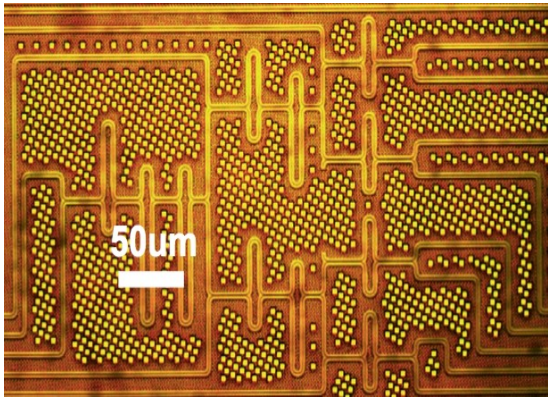
Various Waveguides



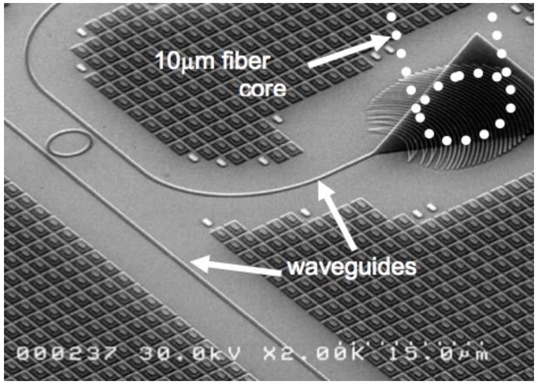
25G Modulator (NEC)



340G APD (Intel)



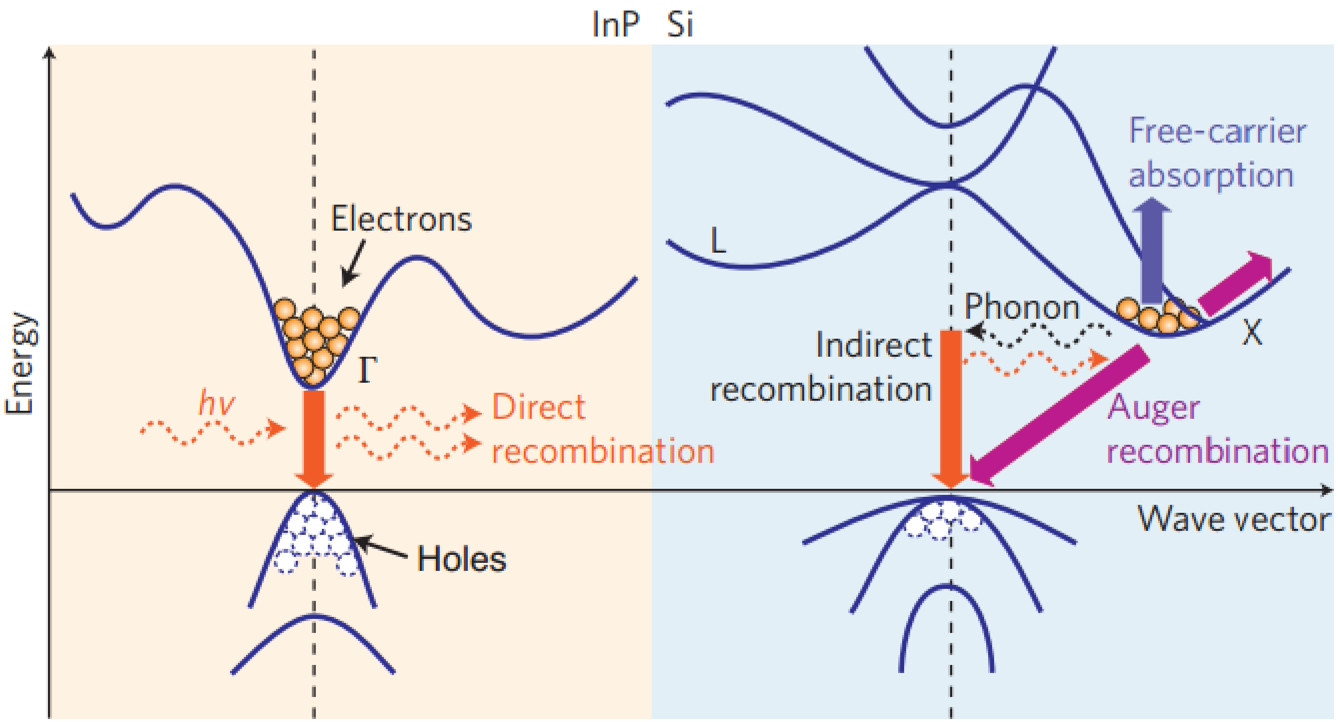
8 channel WDM (IBM)



-0.8dB Vertical Coupler(Helios)

What is missing in silicon photonics?
Electrically-pumped silicon Lasers

Limitation of group-V lasers- 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 10^{-6}.

Two major non-radiative processes:

Auger recombination

Free-carrier absorption

D. Liang and J. Bowers, **Nature Photon. 4**, 511 (2010)

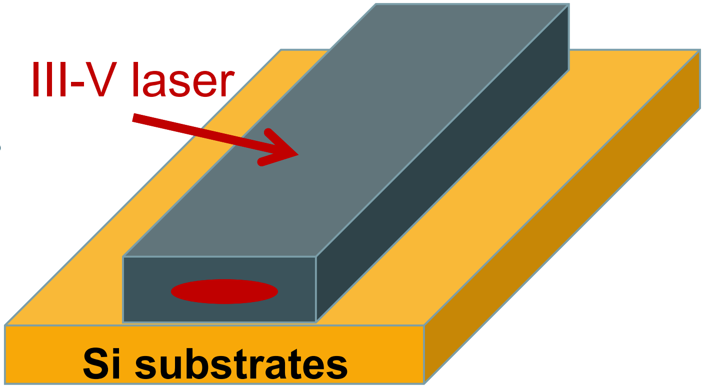
Combine III-Vs and silicon

Silicon

- Pure and have low defect density
- Compatible with CMOS
- Low losses Si waveguide
- High thermal conductivity
- SiO_2 serve as protective layer and a naturally good optical waveguide cladding

III-V compound semiconductors

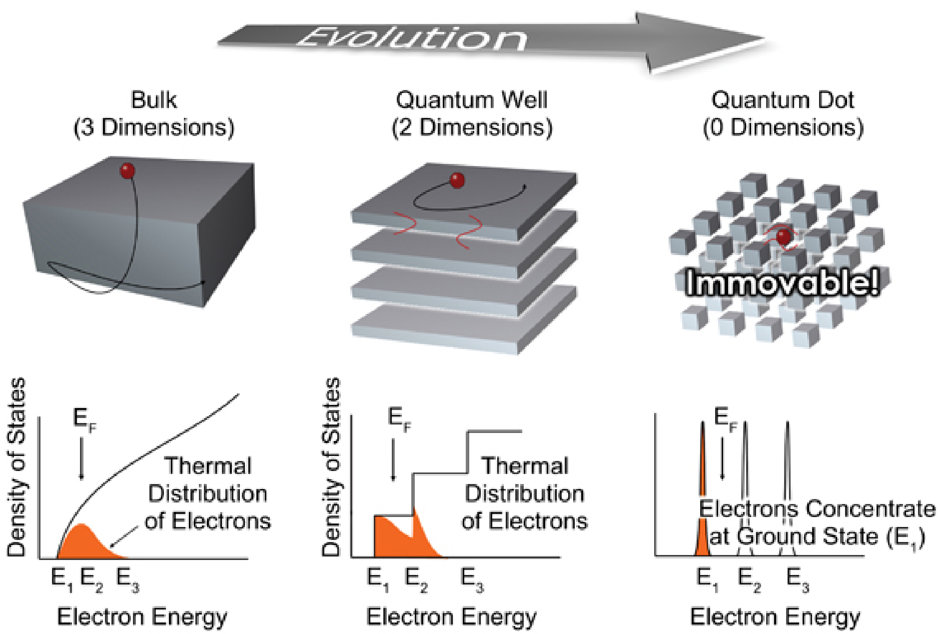
- Mainstays in photonics for light emitters
- Dominance holds for near- and mid-infrared wavelengths
- More expensive than silicon



Solution

- The integration of III-V photonics components with Si microelectronics – ideal solution for Si photonics.
- Wafer bonding – The most successful approach so far
- Monolithic growth – 'holy grail' for cost-effective, massive scalable and streamlined fabrication.

QDs is the better solution!



δ-function peaks centered at the atomic-like energy levels

- **Low** threshold current density
- **Less sensitive** temperature dependent operation
- **Higher speed** in comparison to QW laser
- **Single photon devices** are possible to use quantum dot structure

K. Nishi et al, IEEE J. Sel. Topics Quantum Electronics. 23, 1901007 (2017)

Advantages of QDs- low threshold

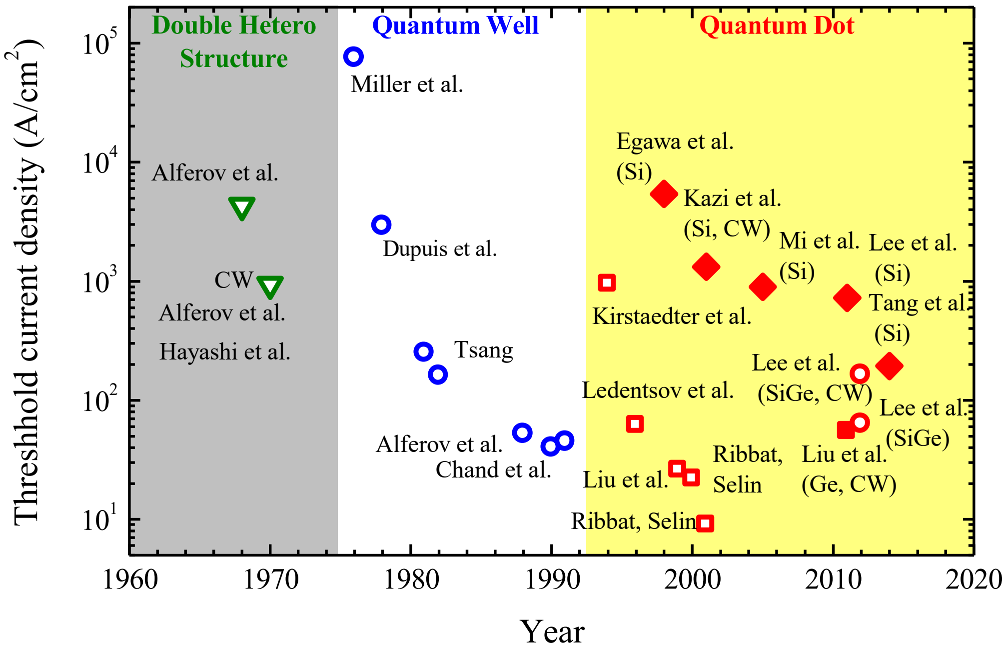
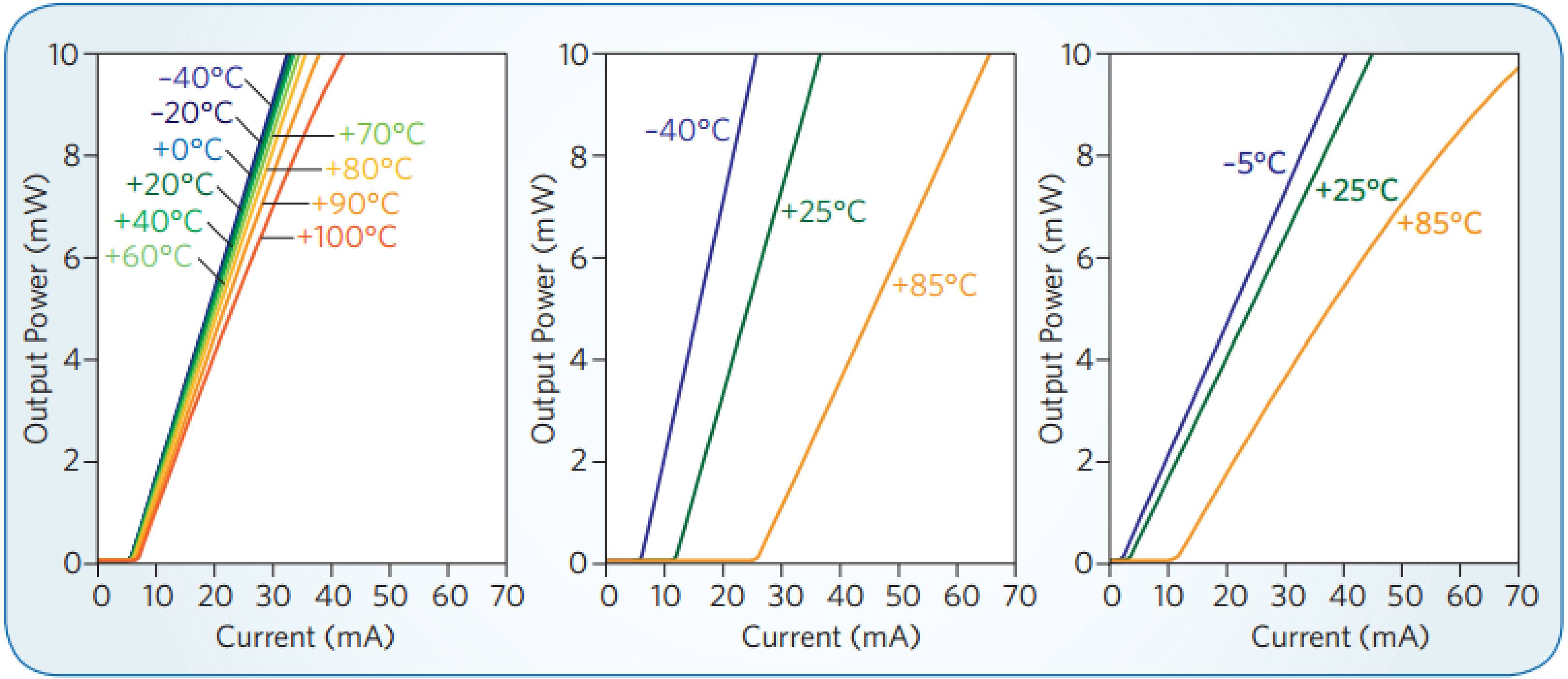


Figure 1. The historical development of heterostructure lasers showing the record threshold current densities at the time of publication (☐ QD laser on GaAs; ■ QD laser on Ge; ○ QD laser on SiGe; ♦ QD laser on Si.) CW indicates that the threshold current values were obtained from QD lasers under continuous operation. The rest were obtained from QD lasers tested in pulse mode.

Jiang Wu et al., **J. Phys. D: Appl. Phys. 48,** 363001 (2015)

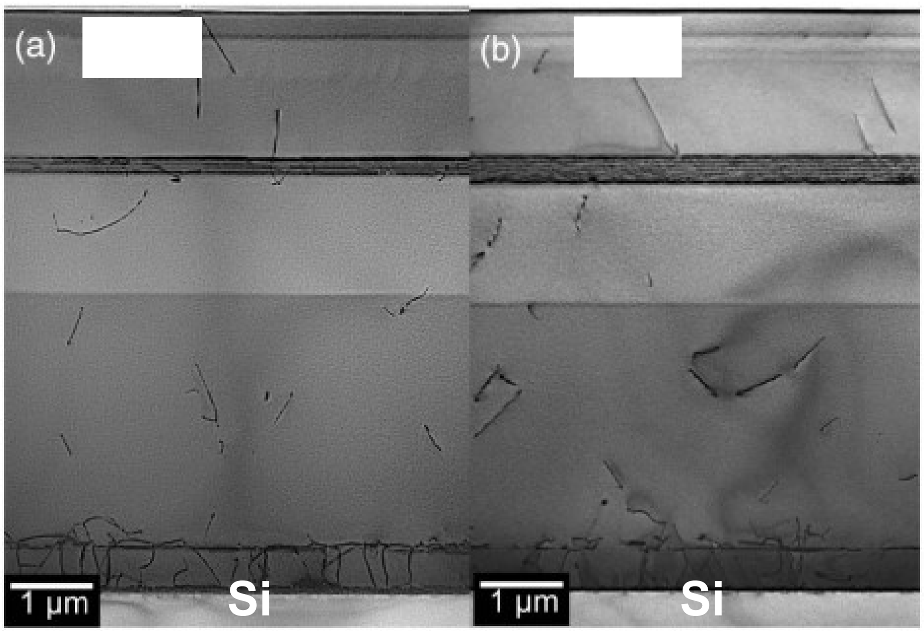
Advantages of QDs- temperature insensitive

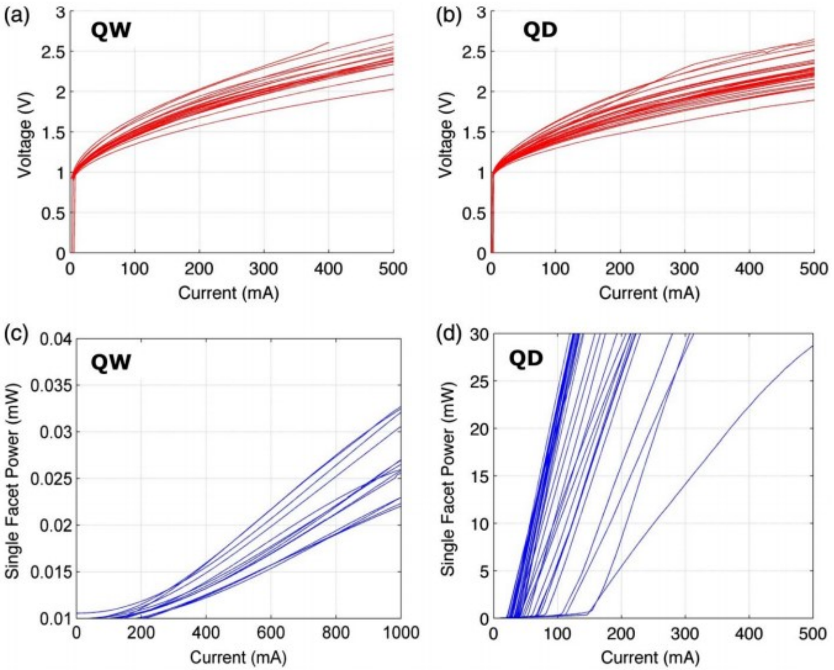


A comparison of typical power–current characteristics of FP lasers. The QD FP laser (left) provides temperature-insensitive operation with almost constant threshold current and slope efficiency. The other two panels show characteristics for two typical conventional quantum well lasers.

M. Sugwara et al., **Nature Photonics 3,** 30 (2009)

Advantages of QDs- less sensitive to defects

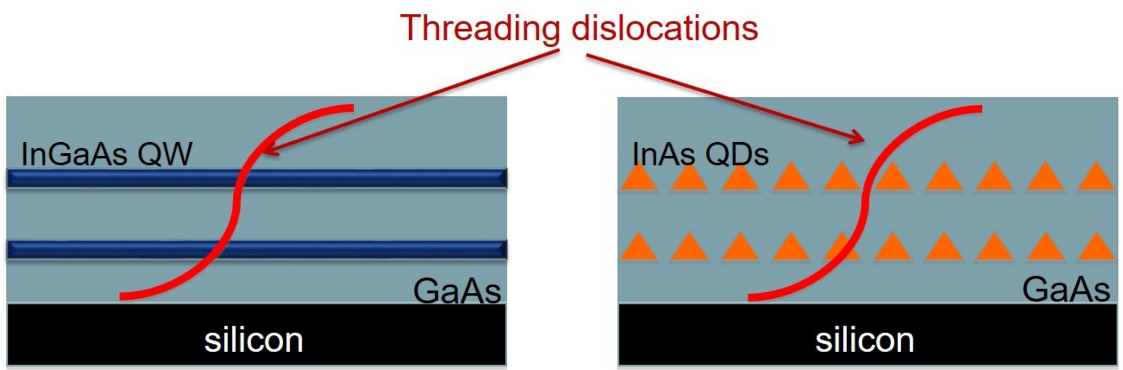


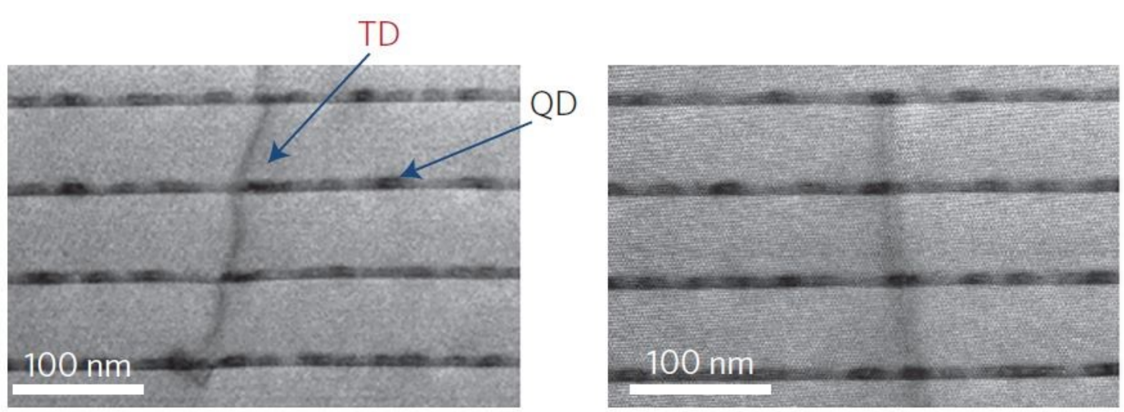


Liu et al., **Photonics Research 3**, B1-B9 (2015)

Advantages of QDs

1. Any threading dislocations through the QW will become non-radiative recombination centre; one TD can only one or a very limited number of dots.
2. TDs can be either pinned or propelled away from QDs- the strong strain field of a QD array prevents the in-plane motion of dislocations.



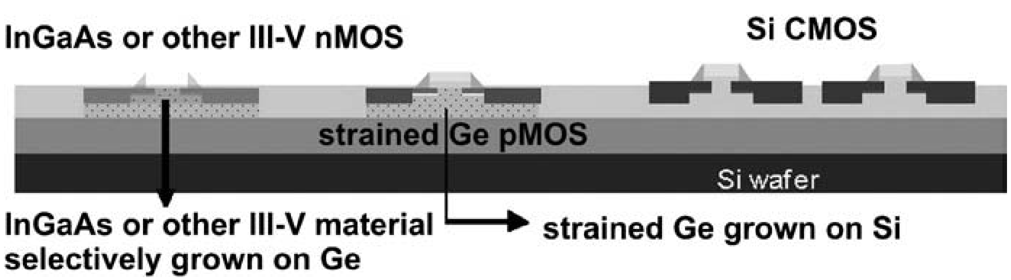


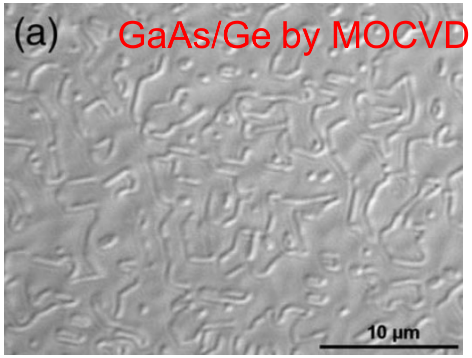
Outline

1. Why III-V QD laser on silicon
2. **III-V QD FP lasers monolithically grown on Ge and Ge-on-Si substrates**
3. III-V QD FP lasers monolithically grown on silicon
4. III-V QD DFB laser array monolithically grown on silicon
5. Future plan and summary

Why QD laser on Ge substrate and what is the challenge?

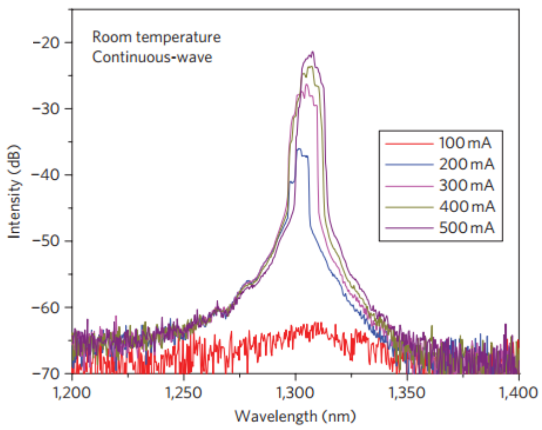
- Very small mismatch between GaAs and Ge (0.08%);
- The fabrication of low-defect (~$10^6/cm^2$) Ge/Si "virtual substrates" are well studied and available commercially;
- Ge epilayer will replace Si as p-channel in future CMOS, because Ge has a four times larger hole mobility compared to Si
- The problem is "self-terminating one-monolayer As" surface does not work for Ge epi-surface.

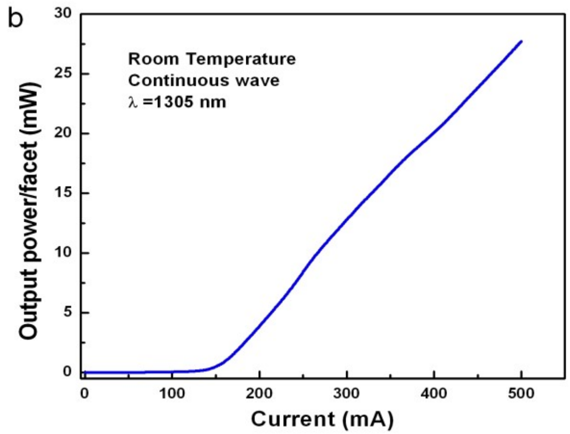


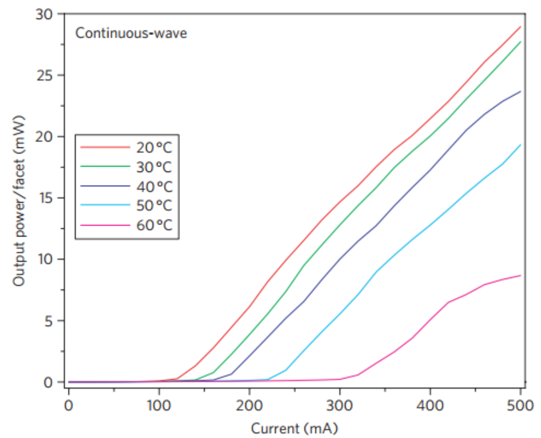


G. Brammertz et al., **Thin Solid Film 517**, 148 (2008)

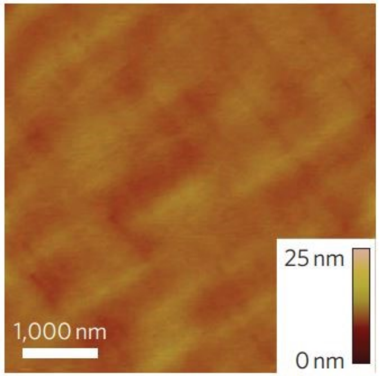
The first 1.3 μm InAs QD laser on Ge







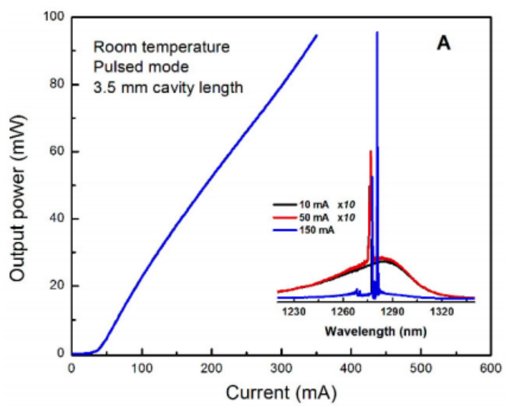
Ga prelayer technique

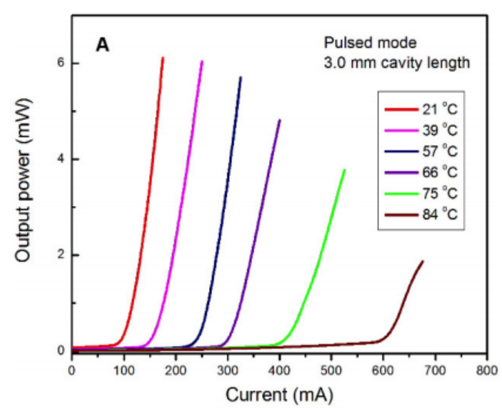


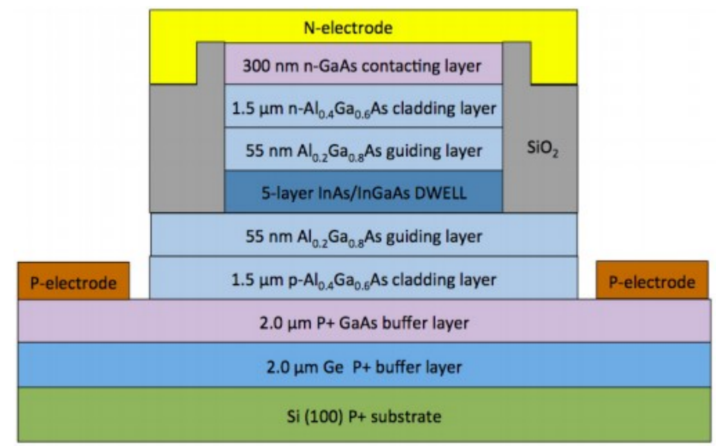
- CW mode
- J_{th} = 55.2 A/cm^2 (RT)
- P_{out} =28 mW/facet at (RT)
- λ_{peak} = 1305 nm
- T_{max} = 60 ^{o}C

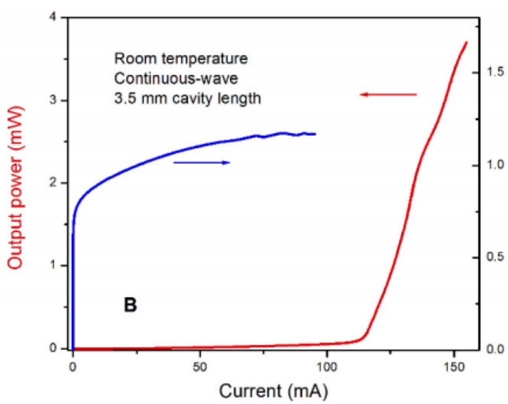
H. Liu et al., **Nature Photonics 5**, 416 (2011)

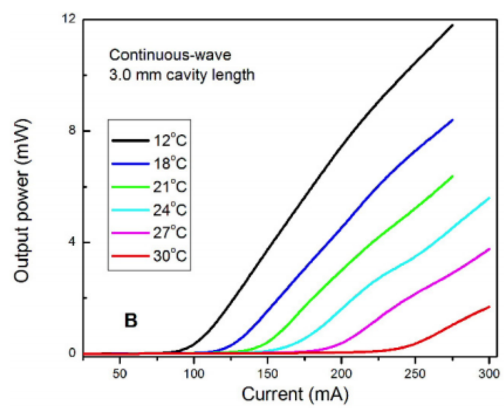
The first 1.3 μm InAs QD laser on Ge/Si







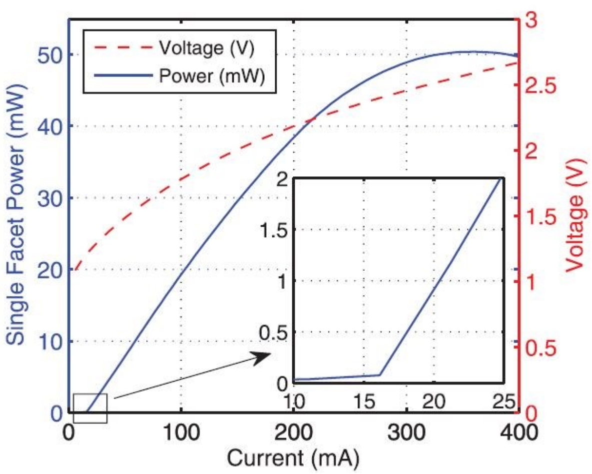


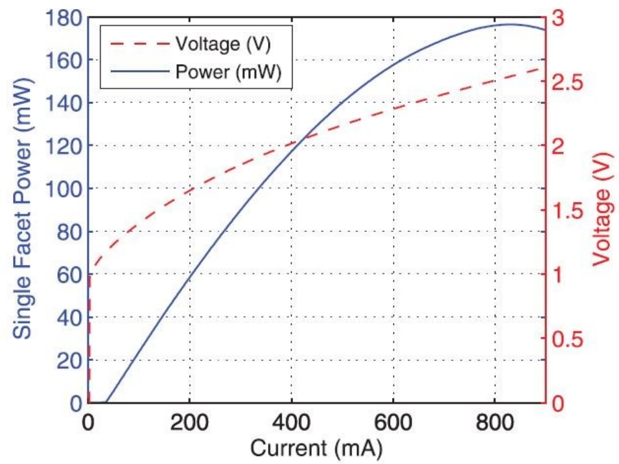


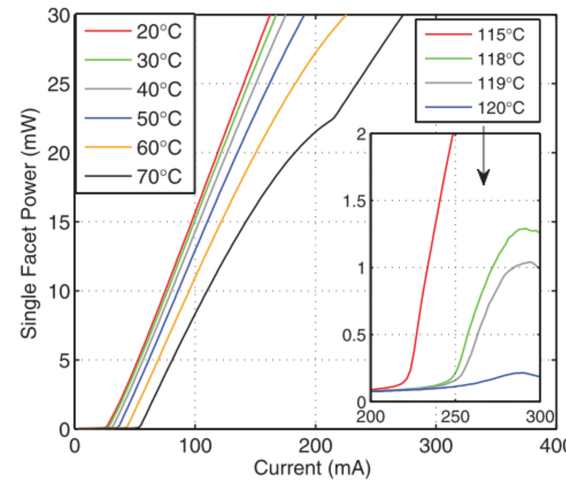
	c.w.	pulse
Rs (Ω)	~5	
J_{th} (A/cm^2)	163	64.3
P_{out} (mW)	3.7	93
T_{max} (°C)	30	84
T0 (K)	~23	~37

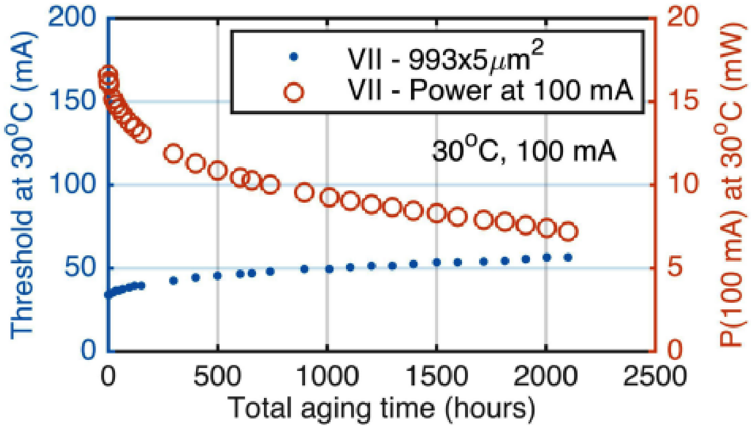
A. Lee et al., **Opt. Express 20**, 22181 (2012)

InAs QD laser on Ge/Si - Results from Bowers's Group









- Low CW threshold (16 mA)
- ~180 mW maximum CW output power
- CW lasing up to 119°C
- Over 2700 h of constant current stress at 30 °C

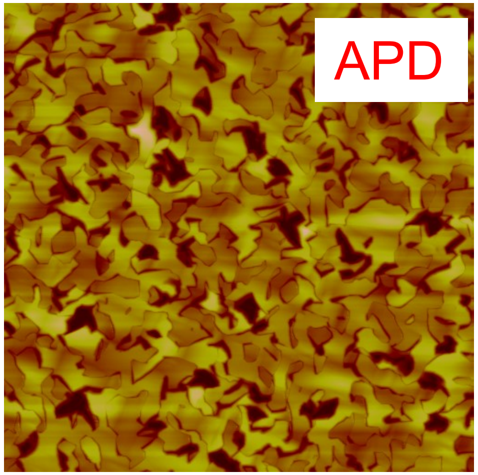
A. Liu et al, **IEEE J. Sel. Topics Quantum Electron. 21**, 1900708 (2015)

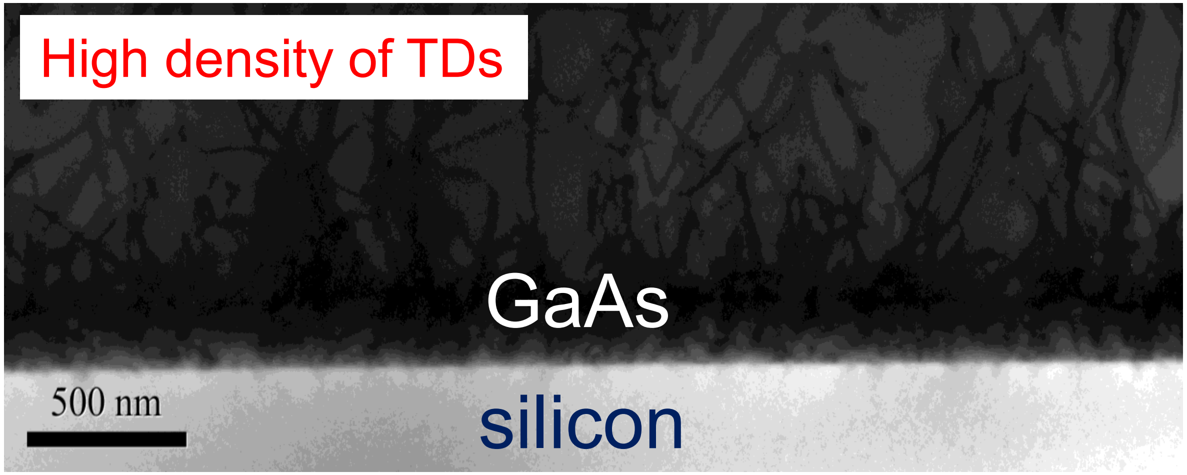
Alan Liu et al., **Appl. Phys. Lett. 104**, 041104 (2014)

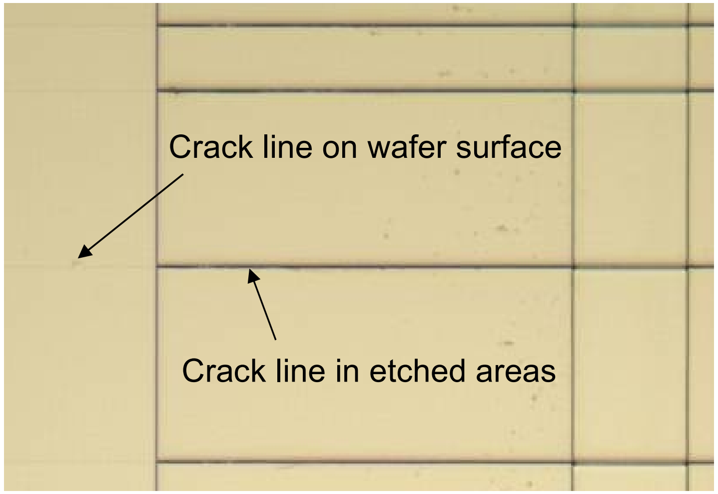
Outline

1. Why III-V QD laser on silicon
2. III-V QD FP lasers monolithically grown on Ge and Ge-on-Si substrates
3. **III-V QD FP lasers monolithically grown on silicon**
4. III-V QD DFB laser array monolithically grown on silicon
5. Summary

Challenges for direct GaAs growth on Si

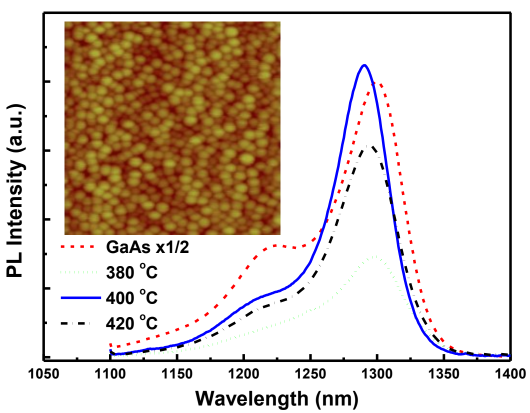


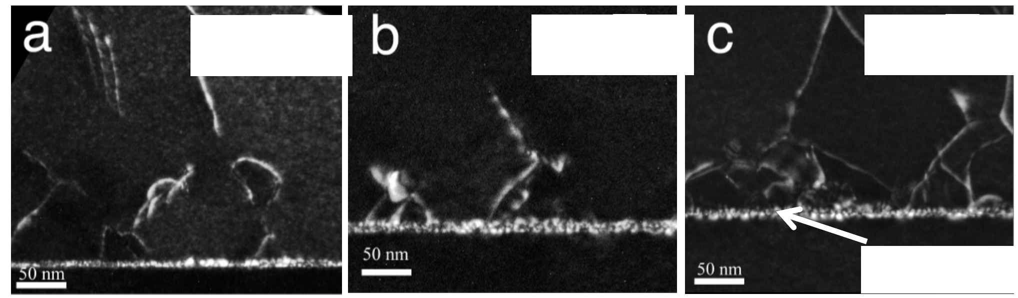


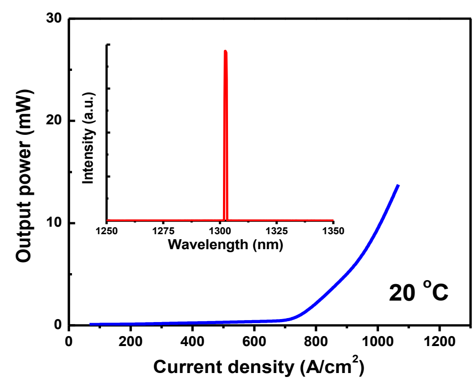


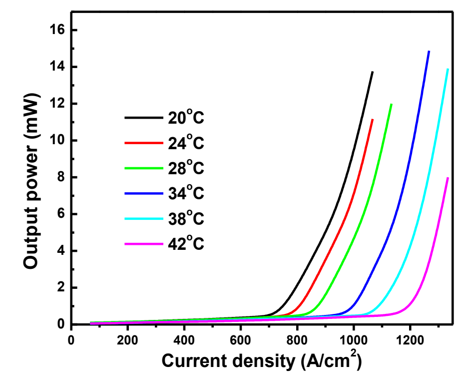
- Native SiO_x removal within III-V MBE
  - HF etch, difficult to control;
- Polar/non-polar growth => Anti-phase domains;
- Large lattice mismatch (4.1%) => Threading dislocations (TDs);
- Large thermal expansion coefficient mismatch(120%) => Micro-cracks and TDs.

The first 1.3 µm QD laser on Si





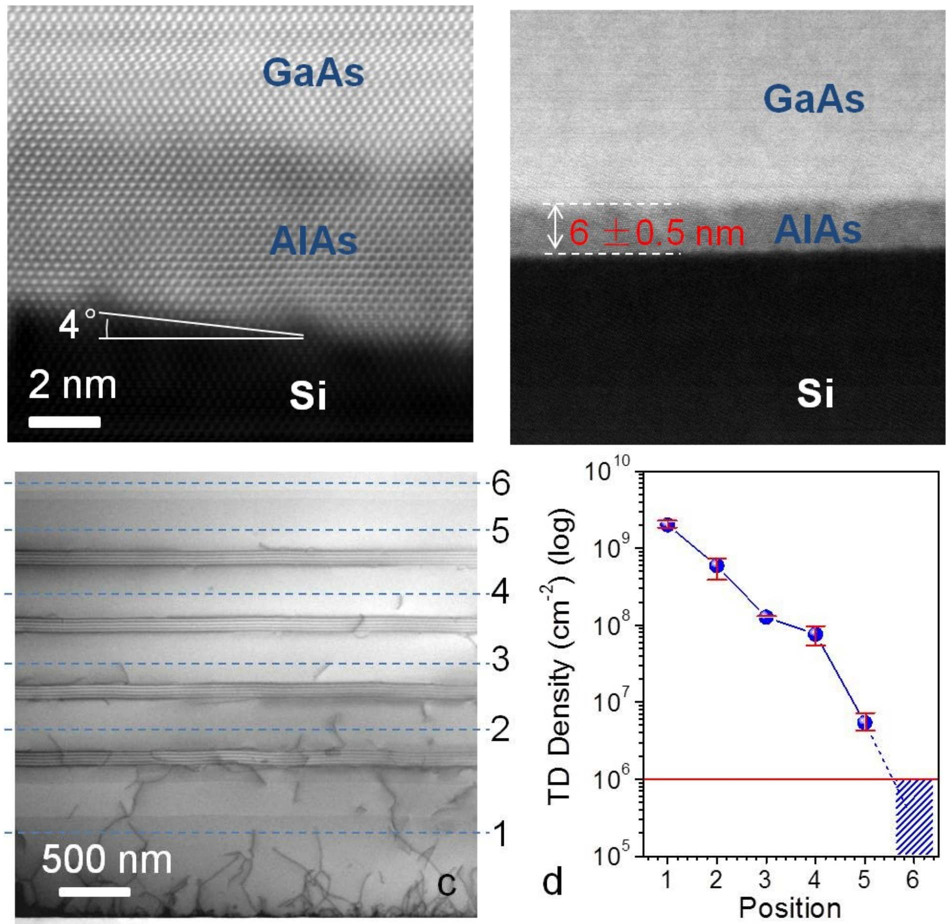




- Off-cut substrate
- Pulse mode
- J_{th} = 725 A/cm^2 (RT); P_{out} =26 mW/facet at (RT)
- λ_{peak} = 1300 nm
- T_{max} = 42 °C ; T_0 = 44 K (20-42 °C)

T. Wang et al., **Opt. Express 19**, 11381-11386 (2011)

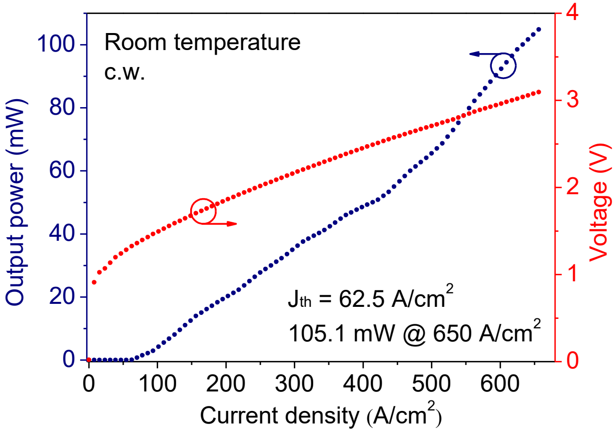
Optimization of III-V buffer layer

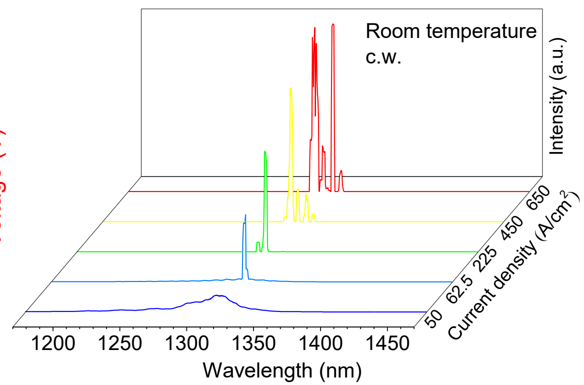


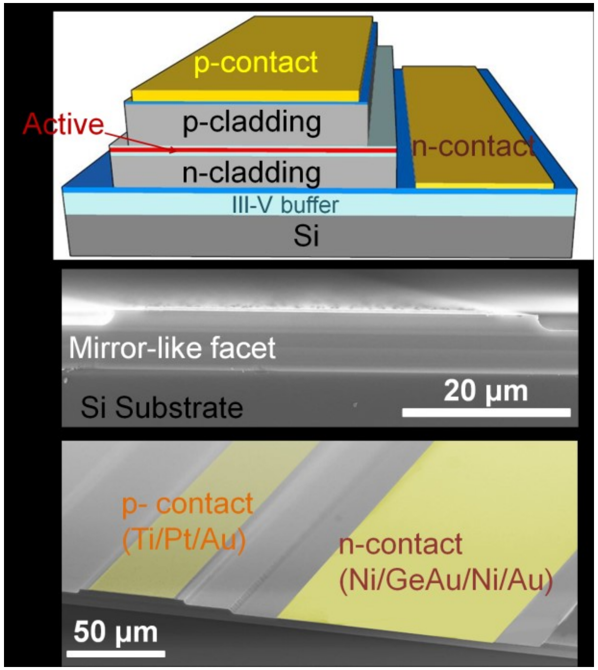
- Phosphorus-doped Si(100) wafers with 4º ***offcut*** to the [011] plane- prevent the formation of APBs
- A thin ***AlAs nucleation layer*** was deposited by MEE at a low growth temperature of 350 ºC- suppress three-dimensional growth and provides a good interface for succeeding III-V material growth.
- ***InGaAs/GaAs DFLs*** were grown to effectively suppress the propagation of the TDs
- **in situ thermal annealing** of SLS was also carried out to further improve the efficacy of filtering defects.
- After the last set of SLS, the density of TD has been reduced to the order of ***~10^5 cm^{-2}***.

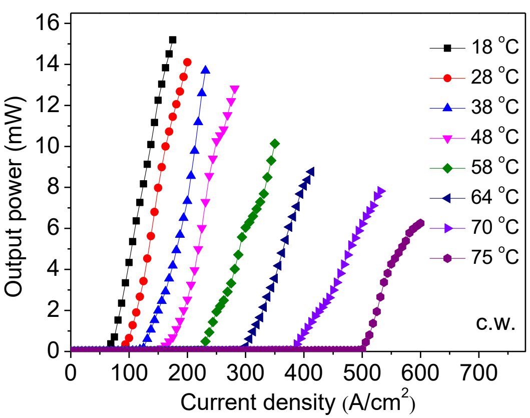
S. Chen et al., **Nature Photon. 10**, 307-311 (2016)

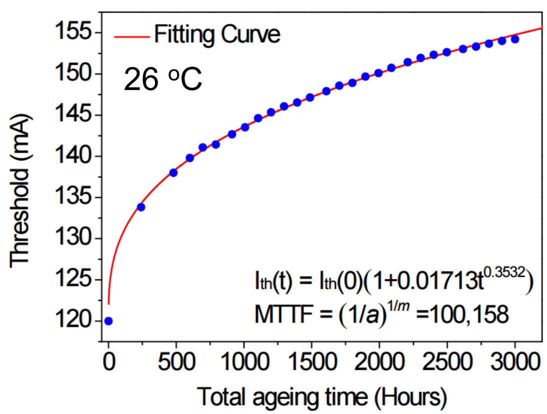
High-performance 1.3µm QD laser on Si







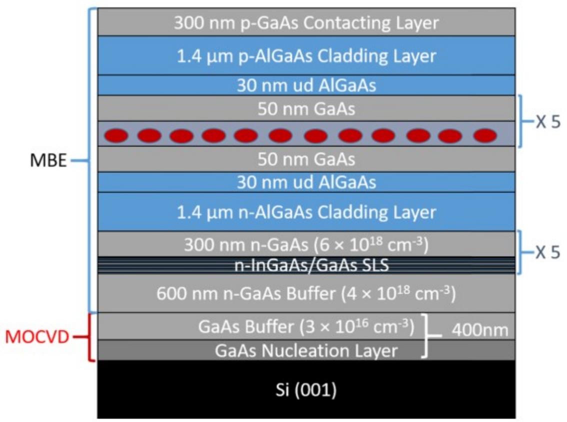


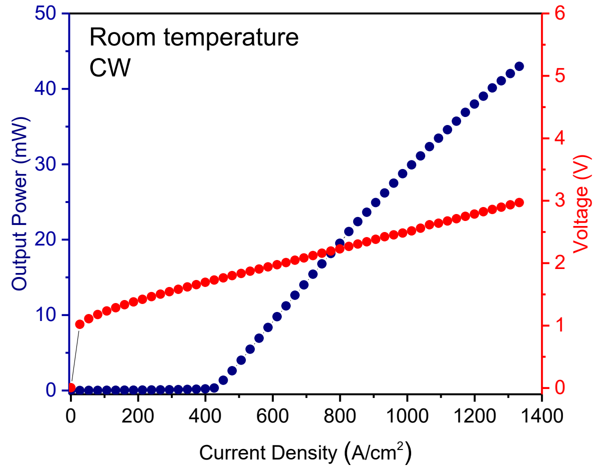


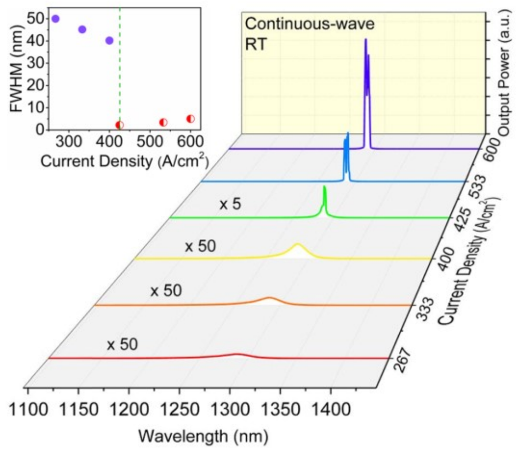
- Off-cut substrate
- CW
- J_{th} = 62.5 A/cm^2 (RT)
- P_{out} =105 mW/facet at (RT)
- λ_{peak} = 1315 nm
- T_{max} = 75 °C (c.w.) 120 °C (pulsed)
- Extrapolated lifetime > 100,000 hours

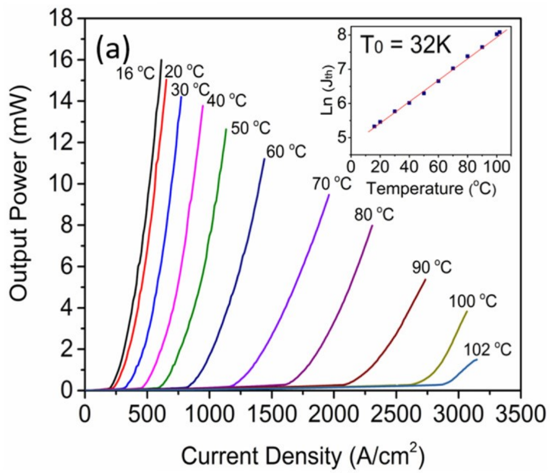
S. Chen et al., **Nature Photon. 10**, 307-311 (2016)

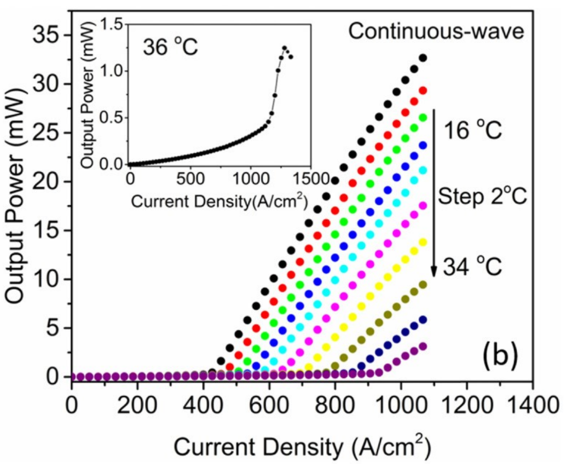
1.3 μm InAs QD laser on on-axis Si (001)











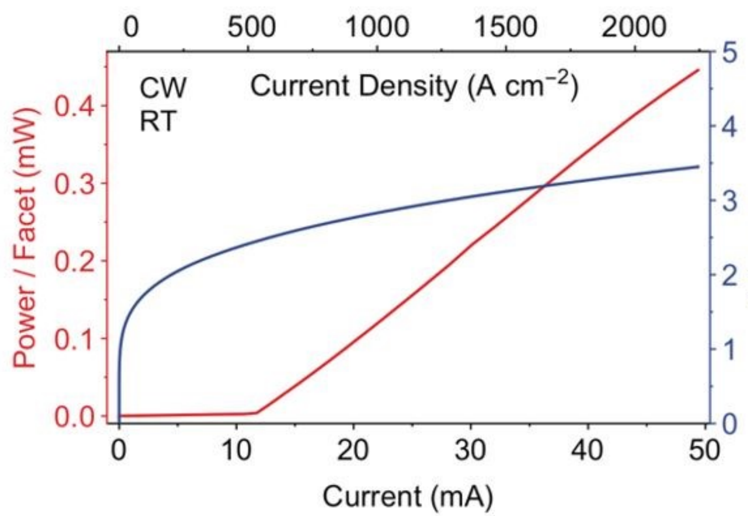
- On-axis Si (001) substrate
- CW
- J_{th} = 425 A/cm^2 (RT)
- P_{out} =40 mW/facet at (RT)
- λ_{peak} = 1292 nm
- T_{max} = 36 °C (c.w.) 102 °C (pulsed)

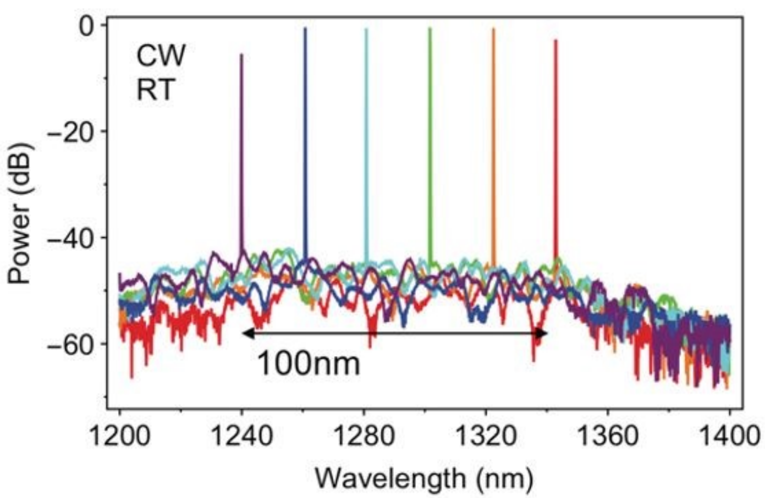
S. Chen et al., **Optics Express** 25, 4632 (2017)

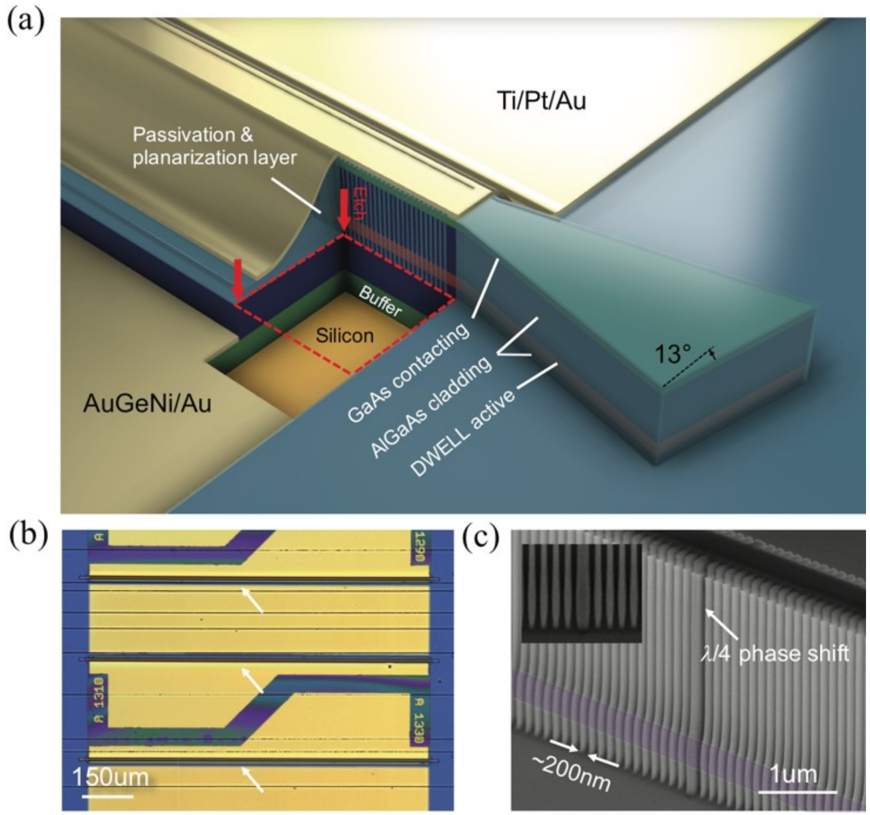
Outline

1. Why III-V QD laser on silicon
2. III-V QD FP lasers monolithically grown on Ge and Ge-on-Si substrates
3. III-V QD FP lasers monolithically grown on silicon
4. **III-V QD DFB laser array monolithically grown on silicon**
5. Summary

The first QD DFB array on Si







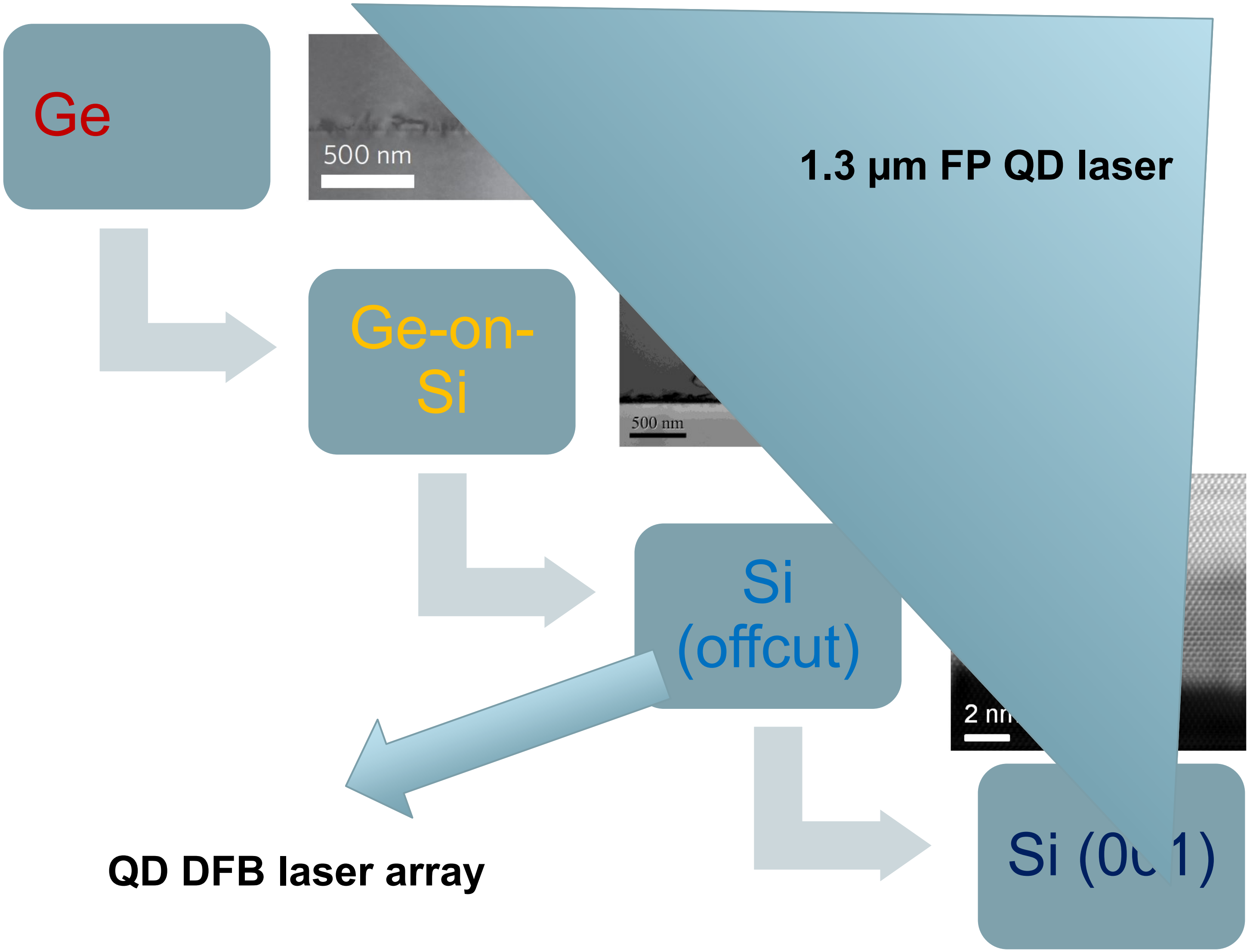
- Thresholds as low as 12mA.
- SMSRs as high as 50 dB
- Well-aligned channel spacing of 20±0.2 nm for CWDM
- A record wavelength coverage range of 100 nm

arXiv preprint arXiv:1801.01052

Outline

1. Why III-V QD laser on silicon
2. III-V QD FP lasers monolithically grown on Ge and Ge-on-Si substrates
3. III-V QD FP lasers monolithically grown on silicon
4. III-V QD DFB laser array monolithically grown on silicon
5. **Summary**

Summary


Ge
500 nm
1.3 µm FP QD laser
Ge-on-Si
500 nm
Si (offcut)
2 nm
Si (0 1)
QD DFB laser array

Team:

Mengya Liao, Mingchu Tang, Jiang Wu, Alwyn Seeds, Huiyun Liu

Collaboration:

Acknowledgement:

Thanks