Semiconductor Quantum Dots, why are they so quantum? Genesis, prospects & challenges

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S. Zhao (PhD), Télécom Paris

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From Paris….to Palaiseau

- Telecom Paris, funded 12 July 1878
- Thevenin (known for Thevenin's theorem), became President in 1896
- Estaunié father of the word "telecommunications", became President in 1901

1878-1934

1934-2019

2019-present

PARIS-SACLAY INNOVATION PLAYGROUND

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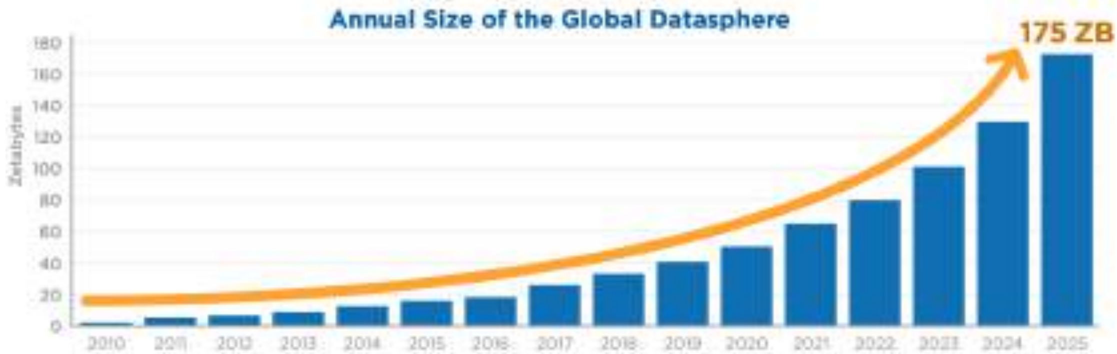
The world of data

- Data volumes keeps massively increasing
- 5G & future AI-driven 6G optical networks, datacenters, HPC, etc. Remember that one zettabyte is equivalent to a trillion gigabytes!



Nowadays quantum dot technology is a huge growth driver for achieving low cost and small footprint efficient transmitters

Source: IDC, The Digitization of the World, From Edge to Core (2018)

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Timeline of the quantum dot technology

Year	Milestones	From
1982	Reduced dimensionality	Univ. of Tokyo
1994	1st lasing (optical pumping)	Ioffe Institute
1994	1st lasing (current injection)	TU Berlin & Ioffe Institute
1996	Proposed QDs for light-emitting devices on silicon	CNET
1999	Near zero α_H-factor	Univ. of New-Mexico
2000	Record-breaking J_{th} = 13 A/cm^2	Univ. of New-Mexico
2002-2003	Superior temperature stability	Univ. Texas, Austin; Ioffe Institute; Univ. of Michigan
1999- present	Hybrid QD lasers on silicon & Epitaxial QD lasers on silicon	Univ. of Michigan; UCL; UCSB, University of Tokyo

Commercialization

2001 Zia Laser Inc., United States
2003 Innolumne – GmbH, Germany
2006 QD lasers Inc., Japan

Not an exhaustive list

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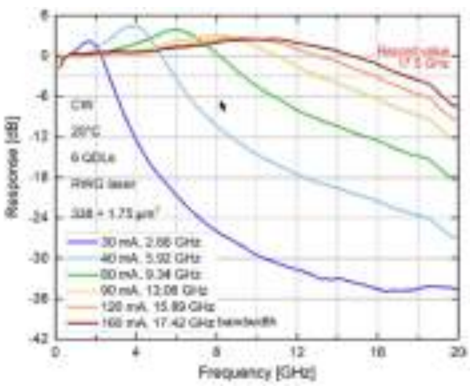
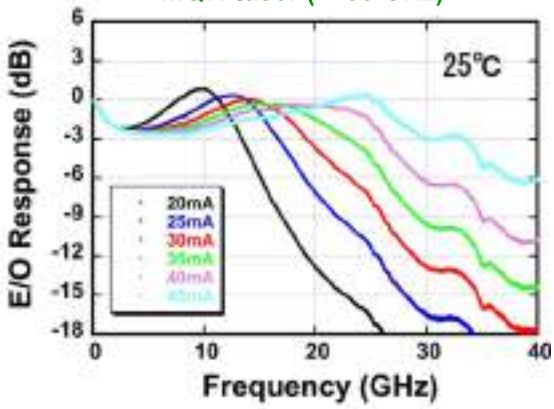
Limitations of QD lasers

- **Quantum dots do not offer superior performance for direct modulation applications…**

QD laser (17.5 GHz)



MQW laser (> 30 GHz)



A. Abdollahinia et al. Optics Express (2018), **Tadokoro, IEEE J. of Lightwave Technology (2012)**

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Limitations of QD lasers

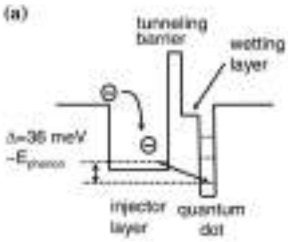
- Energy relaxation through fully-quantized dot levels can be very slow because nonradiative channels are efficient on electrons stored more than nanoseconds

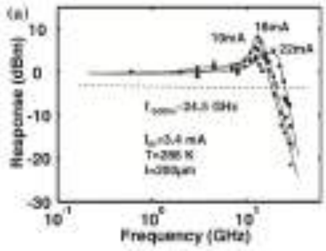
RAPID COMMUNICATIONS

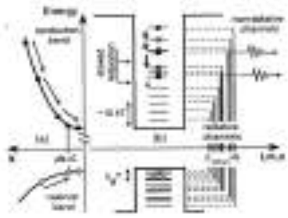
PHYSICAL REVIEW B VOLUME 44, NUMBER 19 15 NOVEMBER 1991-I

Intrinsic mechanism for the poor luminescence properties of quantum-box systems

- Bypassing the excited state could produce larger bandwidth but at the price of a more complicated technology…..**not better than multi-quantum well lasers**







T. S. Fathpour, J. of Physics D (2005); H. Benisty et al., Physical Review B(1991)

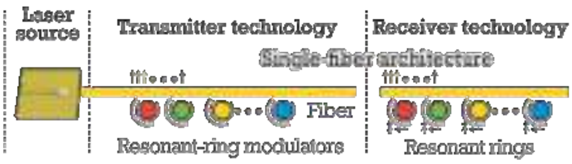
Quantum dot lasers: the resurrection?

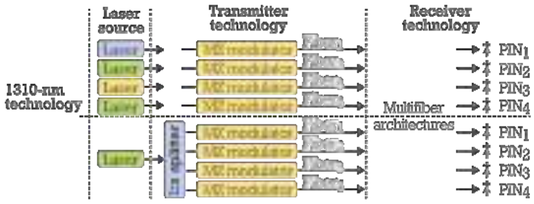
RANOVUS

Source: OFC, San Diego (2023), Alfalume (2023)

Quantum dot lasers: the resurrection?

- **Silicon photonics market revenue to cross USD 55 Billion by 2035**
- **The quantum dot technology must**:
  - Satisfy the increasing demand for bandwidth.
  - Deliver significant reduction in the power dissipation, size, and cost of optical interconnects.
  - Reduce network latency
- **QD lasers and silicon photonics devices is an ideal implementation for achieving these goals in inter/intra-data-center interconnects, HPC, etc.**





Sources: Research Nester August 2023; Ranovus

Quantum dot lasers: the resurrection?

"QD laser allow to operate with a substantially lower threshold, requiring only a tenth of the electrical power to get the same performance, making it ideal for high-performance computing. This provides ~1 pJ/bit energy efficiency; 15X to 20X better than products currently on the market" (2019)

Hewlett Packard Labs

"The QD laser market is projected to expand to around US$50 billion by 2025 with a compound annual growth rate of some 60%." (2020)"

"We are pleased to combine our QD gain functionality with Tower's proven silicon photonics process to enable a disruptive new capability…." (2022)

"There is no other technology today which can provide the power level of O-band DFB lasers above 200 mW with power efficiency of 20% at 105°C with the ability to operate efficiently up to 150°C. Our uncooled lasers are ideal for pluggable transceivers offering the highest efficiency at high temperatures." (March 2023)"

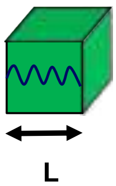
ALFALUME

Outline

- Fundamentals of quantum dots
- Where quantum dot lasers hold the promises?
  - Efficient light-emitting devices on silicon
  - Reduced power consumption & thermal efficiency
  - Isolator-free transmitters
  - Ultralow noise oscillators
  - Mode-locking & combs
- Conclusions & outlooks

Quantization, what for?

- Shape of density of states (gain spectral width)
- Number of states (transparency current)
- Carrier confinement
- Energy tuning

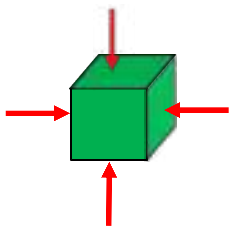


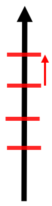
$$k_j L = n_j \pi \qquad j = x, y, z$$

$$E_n = \frac{h^2\pi^2}{8mL^2}\left(n_x^2 + n_y^2 + n_z^2\right)$$

Energy quantization

Wavefunction confinement within the heterostructure potential





$$\Delta E \propto \frac{1}{L^2}$$

$$\Delta E > kT \Leftrightarrow L < \lambda \approx \frac{h}{\sqrt{2m^* kT}} \approx 30\ \text{nm}$$

Electrons in GaAs at 300K

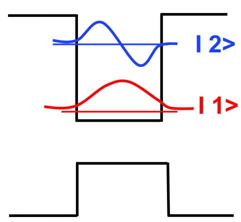
Quantization, what for?

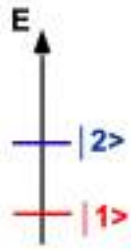
$[H, \boldsymbol{k}] \neq 0$

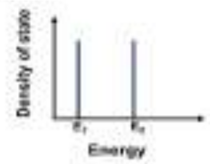
- Shape of density of states (gain spectral width)
- Number of states (transparency current)
- Carrier confinement
- Energy tuning

0D nanostructure: Quantum dot

Courtesy of K. Jacobi (FHI)







$$\rho(E) \propto \delta(E - E_n)$$

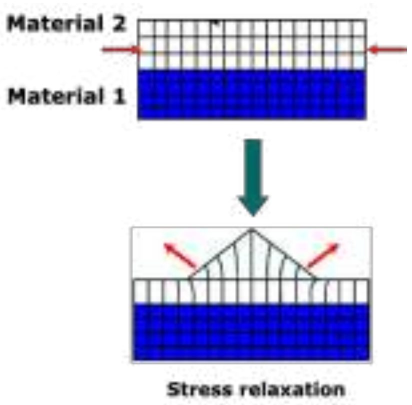
Only in 0D nanostructures, energy levels are completely discrete → semiconductor atoms

But making a QD laser require many many dots!

Self-assembled quantum dots

- MBE & MOCVD kinetically constrained growths

Year	QD Composition	QD T_{growth}	Epitaxy method	QD layers	J_{th}	T_{op}
1994 [59]	InAs	460-490 °C	MBE	1	1 kA/cm^2	300 K
1995 [91]	In$_{0.5}$Ga$_{0.5}$As	510 °C	MBE	1	0.8 kA/cm^2	85 K
1996 [69]	In$_{0.3}$Ga$_{0.7}$As	515 °C	MBE	1	1.2 kA/cm^2	300 K
1996 [92]	In$_{0.4}$Ga$_{0.6}$As	500-550 °C	MBE	1	650 A/cm^2	300 K
1996 [65]	In$_{0.5}$Ga$_{0.5}$As	485 °C	MBE	3	62 A/cm^2	300 K
1996 [74]	InAs	485-505 °C	MOCVD	3	220 A/cm^2	300 K
1998 [93]	InGaAs	512 °C	MBE	1	270 A/cm^2	300 K
1998 [94]	InAs	-	MBE	2	160 A/cm^2	296 K
1998 [95]	InAs	-	MBE	7	82 A/cm^2	295 K
1999 [12]	InAs	490 °C	MBE	1	83 A/cm^2	296 K
1999 [75]	InGaAs	500 °C	MOCVD	3	210 A/cm^2	295 K
2000 [96]	InAs	-	MBE	1	13 A/cm^2	300 K
2000 [97]	InGaAs	450 °C	MBE	3	98 A/cm^2	220 K
2000 [76]	InGaAs	490 °C	MOCVD	3	110 A/cm^2	300 K
2001 [98]	InAs	510 °C	MBE	6	375 A/cm^2	300 K
2002 [78]	In$_{0.47}$Ga$_{0.53}$As	485 °C	MOCVD	3	60 A/cm^2	293 K



InAs/InP: lattice mismatch ~3%

InAs/GaAs: lattice mismatch ~7%

F. Grillot et al., Quantum Photonics (2023)

Self-assembled quantum dots

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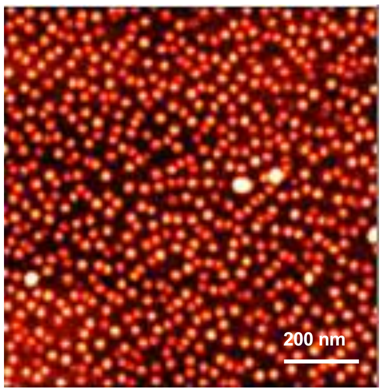
2002 [78]	$In_{0.87}Ga_{0.13}As$	485 °C	MOCVD	3	60 A/cm^2	293 K

InAs/GaAs (MBE)



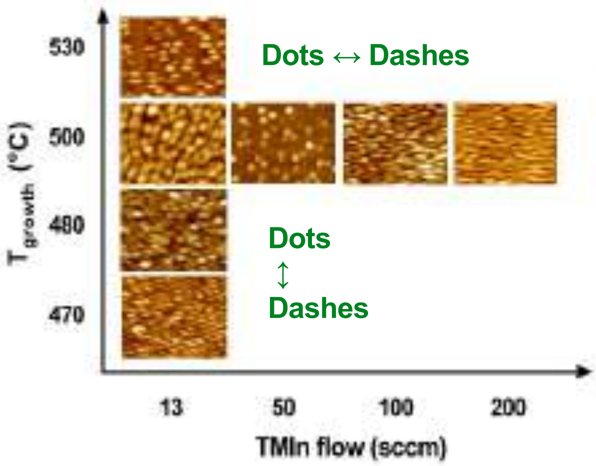
Courtesy of Prof. Bowers (UCSB)

F. Grillot et al., **Quantum Photonics (2023)**

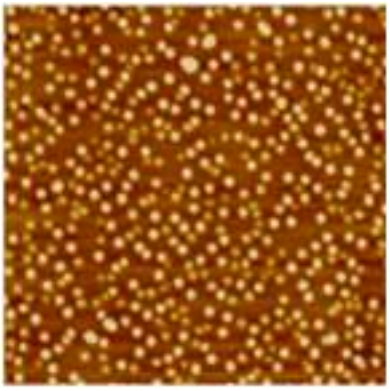
Self-assembled quantum dots

- Every parameter matters i.e. temperature, V/III, growth rate, pre-layer, capping, etc.

InAs/InP



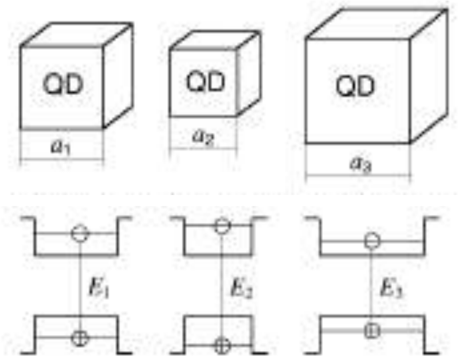
InAs/GaAs (MOCVD)



L. Wang et. al, Advanced Photonics Congress(2022)

Gain broadening mechanisms

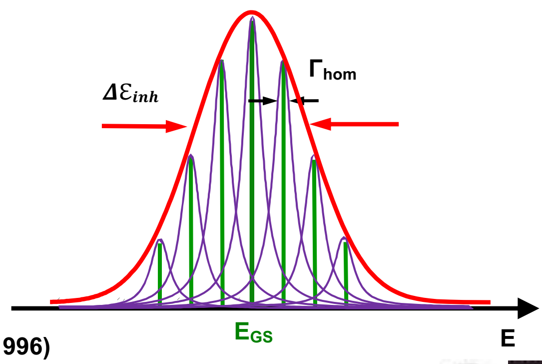
- Real system : fluctuation in QD Size
- Gain inhomogeneous broadening



Number of QD layer
QD density

$$G \propto \frac{ZN_s}{\Delta\epsilon_{inh}}$$

Inhomogeneous width



L. V. Asryan et. al, Semiconductor Science & Technology (1996)

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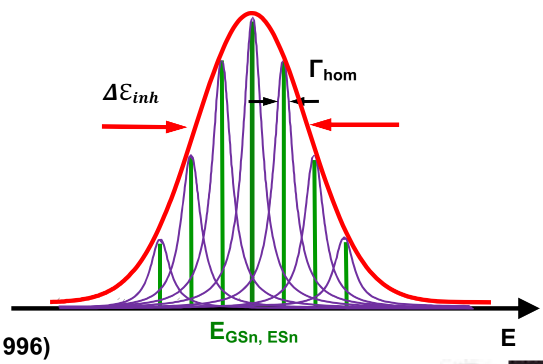
Non uniformity of quantum dots

- Adversely affected characteristics
  - Gain decreases
  - J_{th} increases & is more T-sensitive (T_0 decreases)
  - Output power decreases

Number of QD layer
QD density

$$G \propto \frac{ZN_s}{\Delta\epsilon_{inh}}$$

Inhomogeneous width



L. V. Asryan et. al, Semiconductor Science & Technology (1996)

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So, quantum dot lasers, why are they so quantum?

- All carriers strongly localized
- Energies of carriers are discrete delta like functions
- Carriers have no well-defined wavevector
- Large oscillator strength

D. Bimberg et al. Materialstoday (2011)

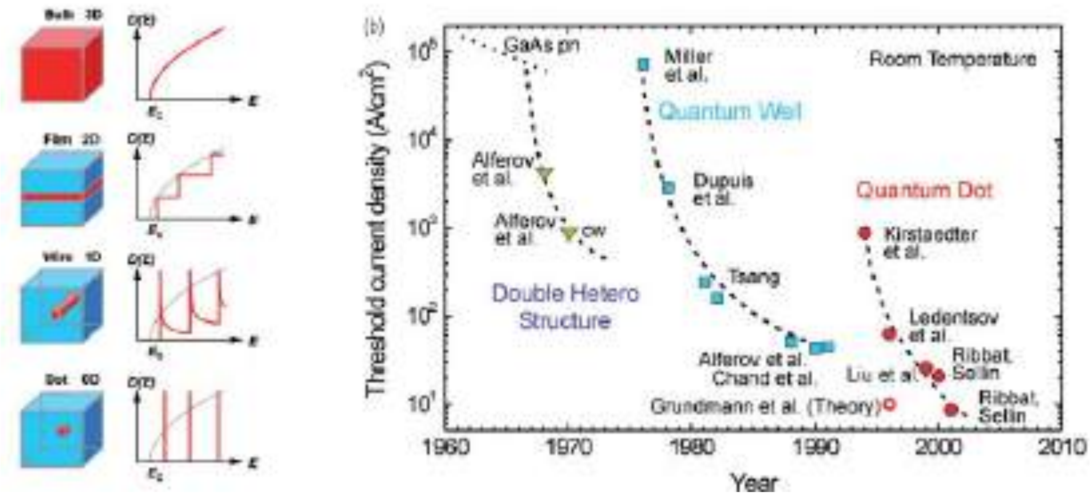
So, quantum dot lasers, why are they so quantum?

- All carriers strongly localized
- Energies of carriers are discrete delta like functions
- Carriers have no well-defined wavevector
- Large oscillator strength

Significantly lower threshold current
Significantly weaker temperature dependence
Optical reflection immunity
Superior for tuning gain spectrum width
Narrow emission line
Less intensity noise fluctuations
Efficient for light-emitting sources on silicon

D. Bimberg et al. Materialstoday (2011)

Threshold reduction & thermal stability



D. Bimberg et al. Materialstoday (2011)

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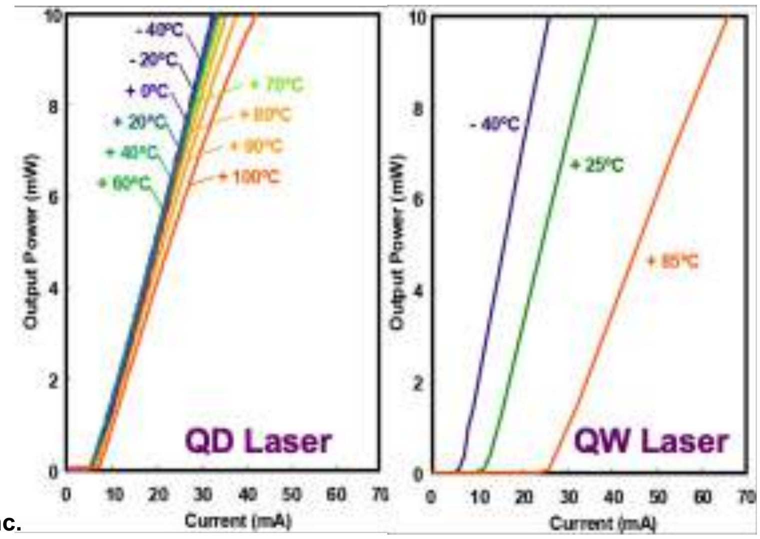
Threshold reduction & thermal stability

- Significantly lower threshold current, weaker temperature dependence. **TRUE on GaAs**



Source: QD Laser Inc.

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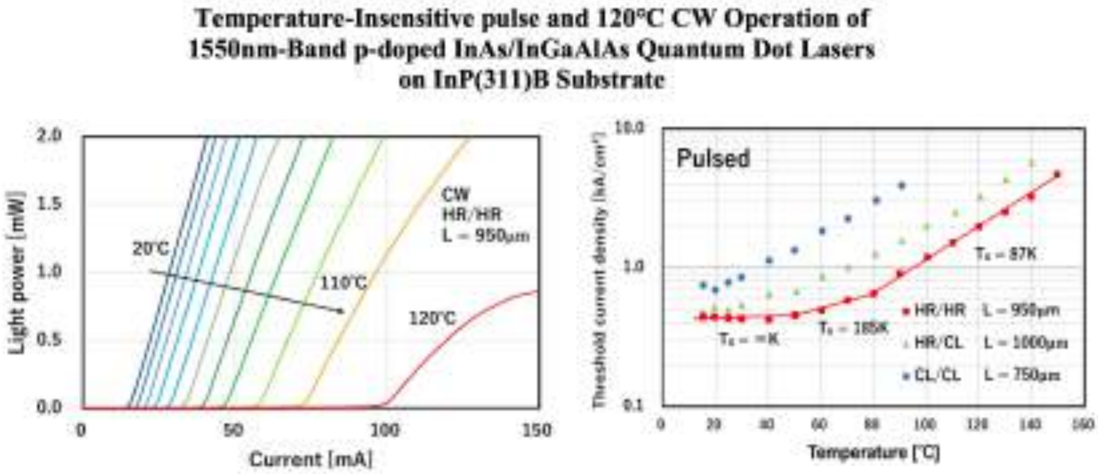
Threshold reduction & thermal stability

- Significantly lower threshold current, weaker temperature dependence. **NOT fully TRUE on InP.**



Source: R. Yakubi, Optical Fiber Conference (2023)

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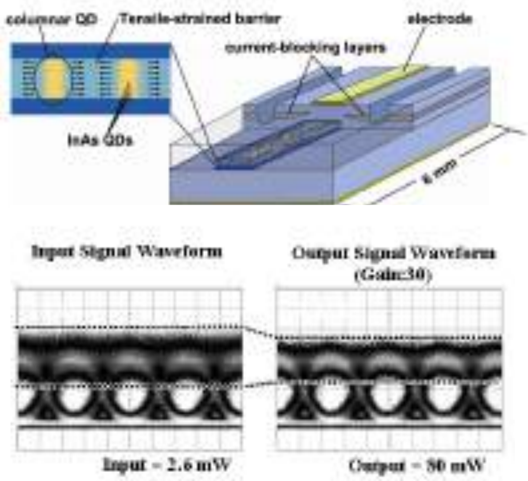
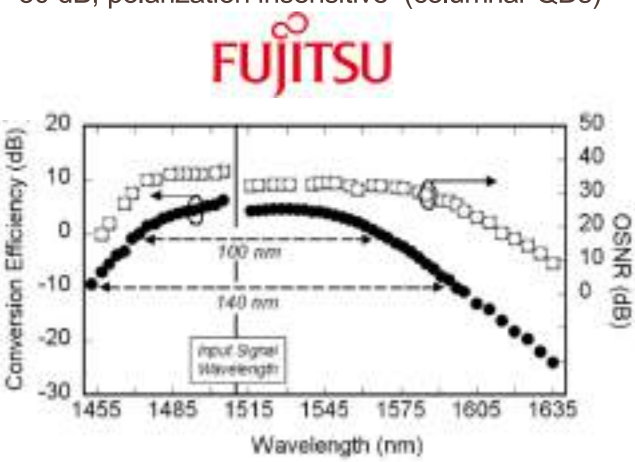
Semiconductor optical amplifiers

- Wide bandwidth > 100 nm with large OSNR > 30 dB, polarization insensitive (columnar QDs)





Source: Fujitsu

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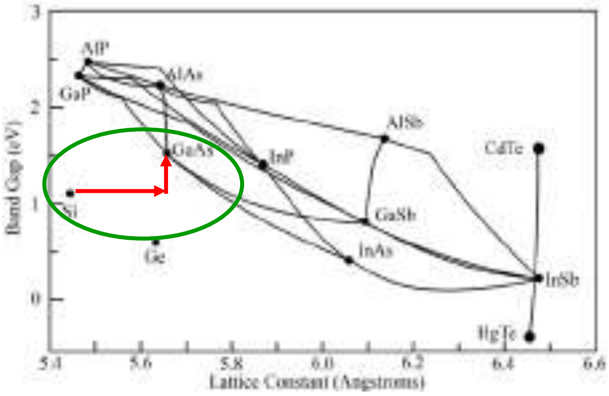
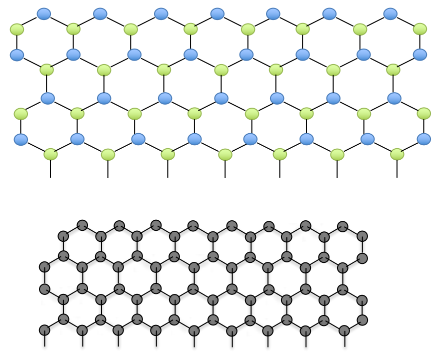
Challenges of epitaxial growth silicon

- **Crystal lattice mismatch**
  - High density of dislocations, antiphase domains
- **Thermal expansion mismatch**
  - Cracking, residual strain, dislocations



Bulk GaAs: $a = 0.565$ nm



Bulk Si: $a = 0.543$ nm

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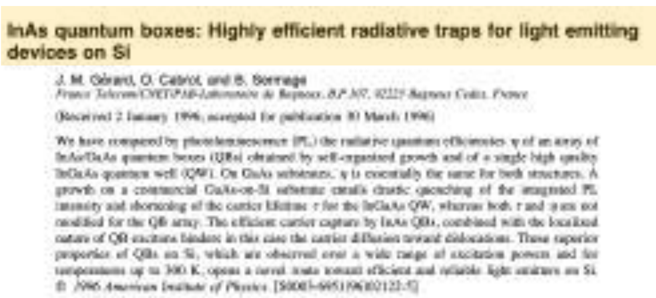
Eureka!

- The efficient carrier capture by InAs QDs, combined with the localized nature of excitons hinders the carrier diffusion toward dislocations
- **QDs for efficient light-emitting devices on silicon!**

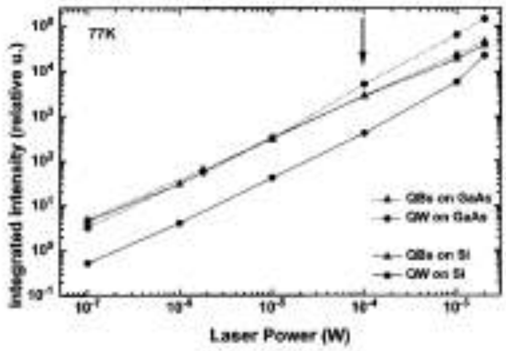


InAs quantum boxes: Highly efficient radiative traps for light emitting devices on Si

J. M. Gérard, O. Cabrol, and B. Sermage
France Telecom/CNET/PAB-Laboratoire de Bagneux, B.P. 107, 92225 Bagneux Cedex, France

(Received 2 January 1996; accepted for publication 30 March 1996)

We have compared by photoluminescence (PL) the radiative quantum efficiencies η of an array of InAs/GaAs quantum boxes (QBs) obtained by self-organized growth and of a single high quality InGaAs quantum well (QW). On GaAs substrates, η is essentially the same for both structures. A growth on a commercial GaAs-on-Si substrate entails drastic quenching of the integrated PL intensity and shortening of the carrier lifetime τ for the InGaAs QW, whereas both τ and η are not modified for the QB array. The efficient carrier capture by InAs QBs, combined with the localized nature of QB excitons hinders in this case the carrier diffusion toward dislocations. These superior properties of QBs on Si, which are observed over a wide range of excitation powers and for temperatures up to 300 K, opens a novel route toward efficient and reliable light emitters on Si. © 1996 American Institute of Physics.



Source: J. M. Gerard et al., Applied Physics Letters (1996), J. M. Gerard & C. Weisbuch, US Patent (1991)

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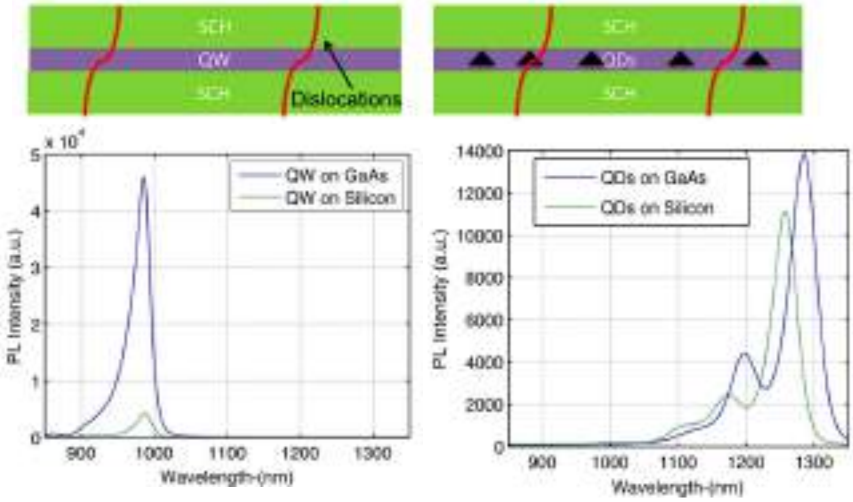
Eureka!

- 3D confinement provided by QDs prevents carriers from migrating to dislocations



A. Liu, Photonics Research (2015); C. Shang et al., ACS photonics (2021)

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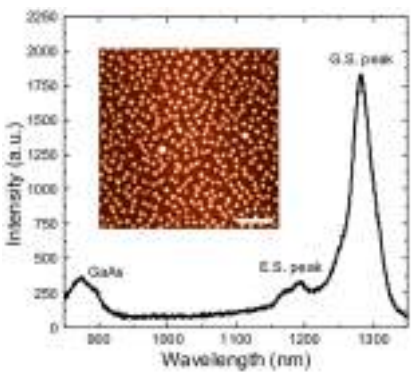
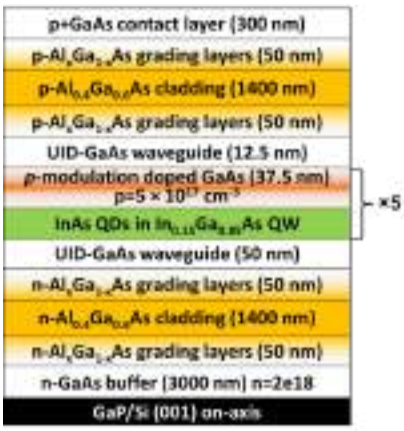
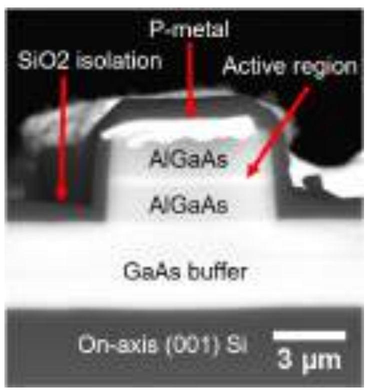
High performance QD lasers on Si

- MBE growth - 5 QD layers
- QD density: 4 x10^{10} cm^{-2}
- UID or p-doped
- $\Delta\mathcal{E}_{inh}$ ~ 20-30 meV







J. Duan et al., Appl. Phys. Lett. (2018)

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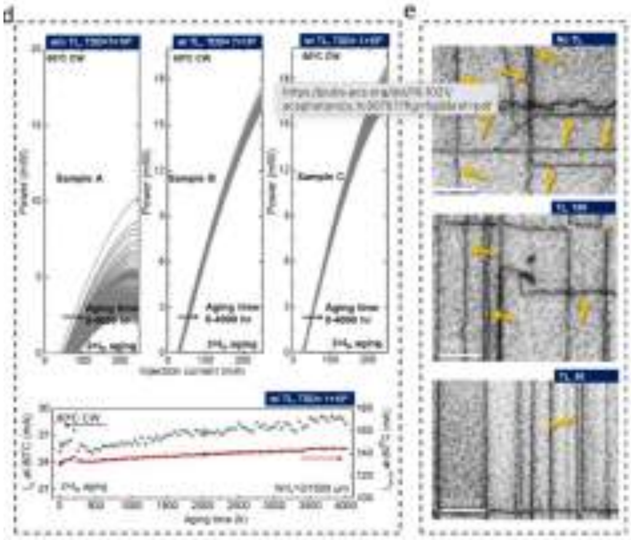
High performance QD lasers on Si

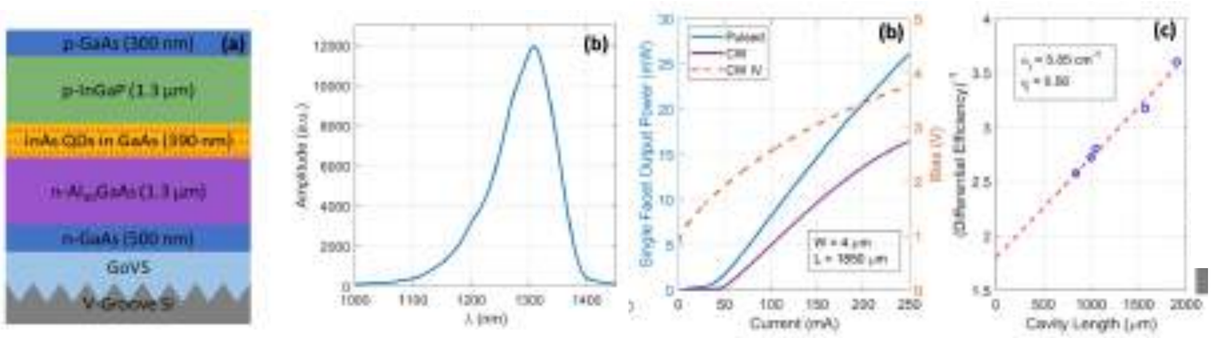
- **Outstanding output characteristics**
  - Low TDD of 7×10^6 cm^{-2}
  - CW threshold current of 4.8 mA
  - Wall plug efficiency of 38.4%
  - Single-facet output power 176 mW
  - Continuous wave operation to 107°C
- **QD essential for long lifetimes**
  - Extrapolated lifetime >100 years @35°C
  - Extrapolated lifetime > 8 years @60°C

J. Norman et al. APL Photonics (2018)
C. Shang et al., ACS Photonics (2021)



High performance QD lasers on Si

- **MOCVD growth - 5 QD layers**
- V-groove Si
- 16 mW single-facet CW output power & 354 A/cm^2 threshold current density
- Large scale monolithic integration



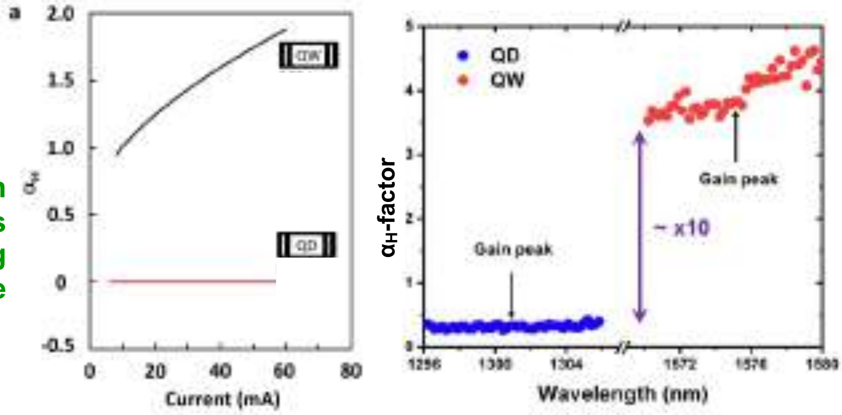
P. Verrinder et al., CLEO (2023)

Zero linewidth enhancement factor

- The α_H–factor is due to the coupling of the gain and refractive index (Kramers-Kronig)
- Invoked in the feedback immunity, the emission line, and optical nonlinearities

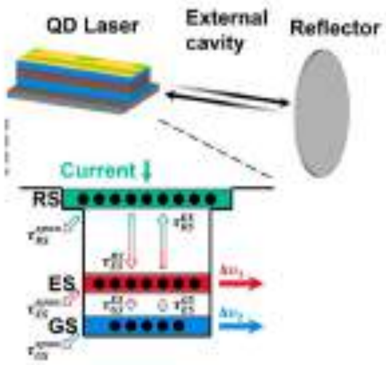
$$\alpha_H = \frac{2\,\delta\sigma_n/dN}{\delta g_n/dN}$$

The near zero α_H observed in epitaxial QD lasers results from the low threading dislocations & large QD size uniformity

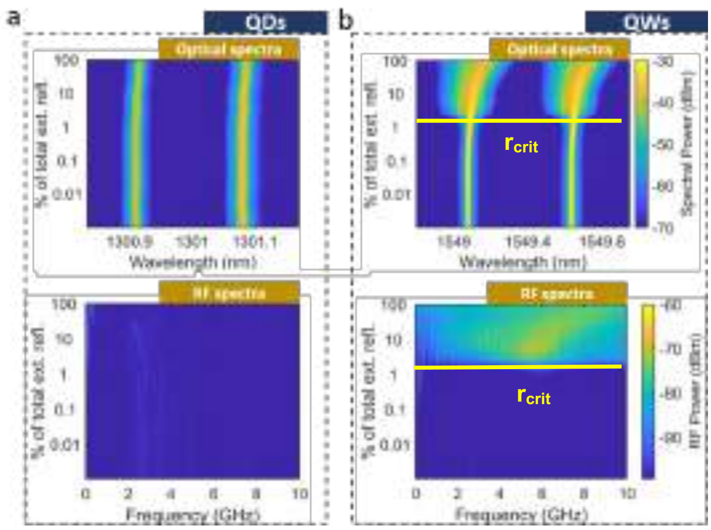


J. Duan et al., Appl. Phys. Lett. (2018); J. Duan et al., Photonics Research (2019)

Optical reflection immunity



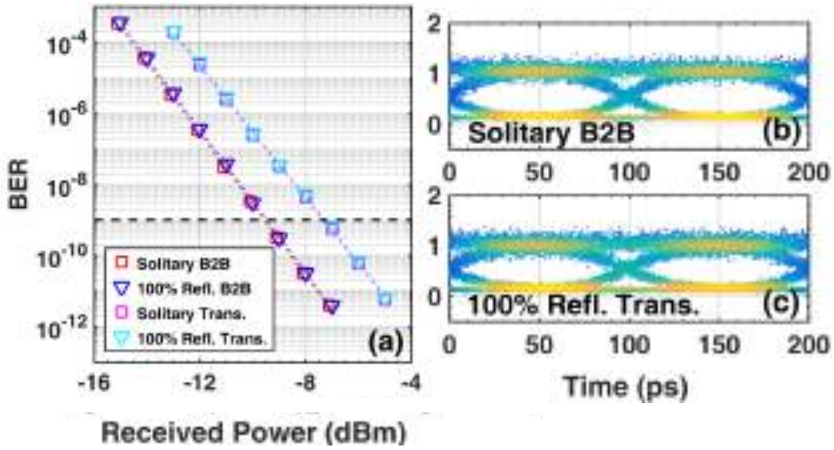
$$r_{crit} = C\left(\frac{1+\alpha_H^2}{\alpha_H^4}\right)$$



C. Shang et al. ACS Photonics (2021)

Optical reflection immunity

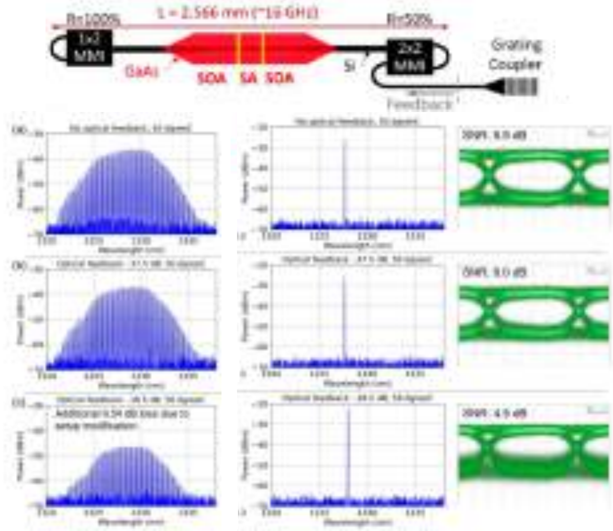
- Epitaxial QD lasers on silicon are fully insensitive to optical perturbations

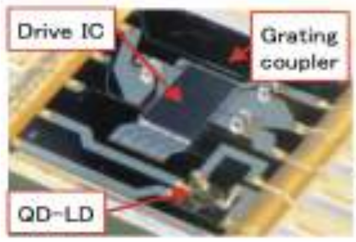


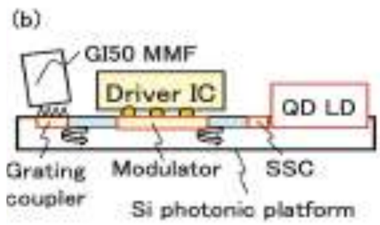
Isolation-free PIC: save cost and footprint

Y. Zhang, et al., Optica (2019); J. Duan et al., IEEE Photonics Technology Letter (2019)

Optical reflection immunity



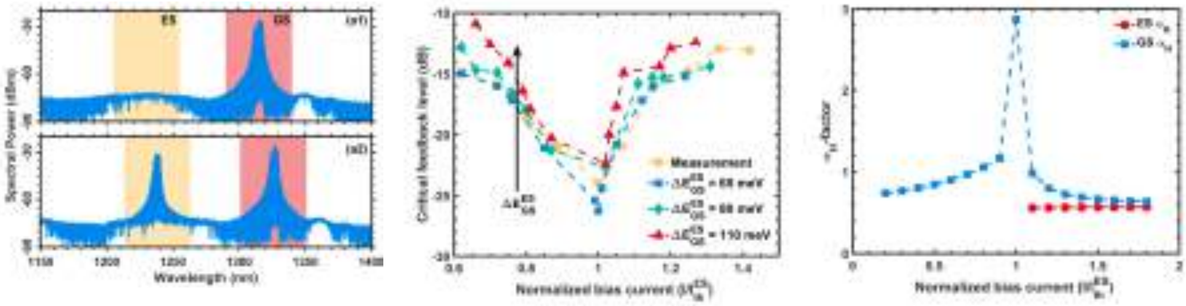




X. Xiao et al., IEEE Silicon Photonics Conference (2023); K. Mizutani et al., Group IV Photonics (2015)

Optical reflection immunity

- **QD lasers are optical feedback resistant as long as the ES does not pop-up**



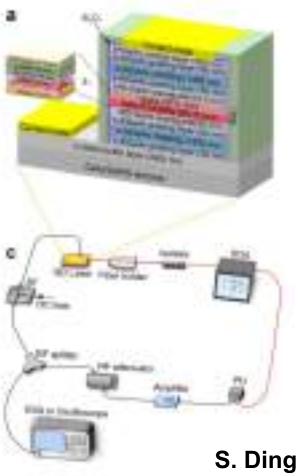
- The control of the ES emission can be minimized thru the increase of the GS-ES energy separation (lateral confinement)

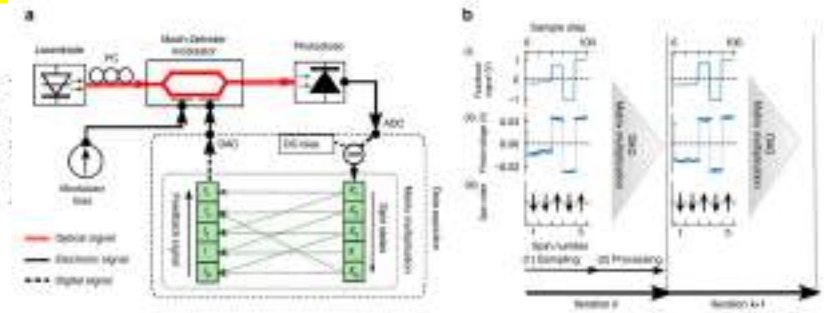
$$r_{crit} = C\left(\frac{1+\alpha_H^2}{\alpha_H^4}\right)$$

Z. Jin et al., Accepted in Photonics Research (2023)

Interlude: Optoelectronics feedback

- **As opposed to optical feedback, QD lasers exhibit a pronounced sensitivity of to optoelectronic feedback**



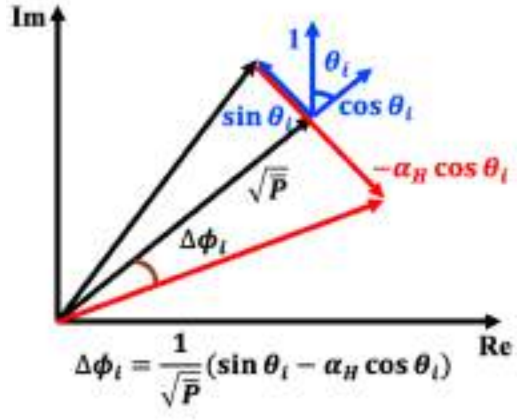


- P-I saturation & ES emission
- RF-port enables faster oscillation frequency
- Integrated OEF loop enables shaping the square waves

S. Ding et al. Submitted (2023); F Böhm et al., Nature communications (2019)

Narrow emission line

- Semiconductor lasers: phase diffusion is due to the joint action of both spontaneous emission events and phase-amplitude coupling



Extended S-T linewidth

$$\Delta\nu = \frac{F}{QP} n_{sp}(1+\alpha_H^2)$$

$$Q = \omega\tau_p = \frac{\omega}{v_g(\alpha_i+\alpha_m)}$$ Q-factor

$$n_{sp}(1+\alpha_H^2)$$ Figure of merit

F. Grillot et. Al., Light: Sciences & Applications (2021)

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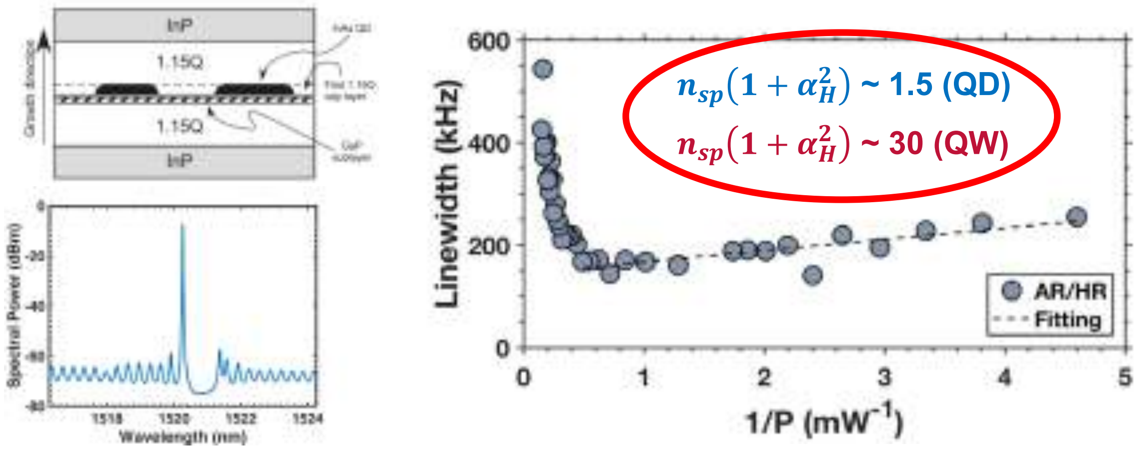
Narrow emission line

- Much smaller emission line than QW lasers (free-running)

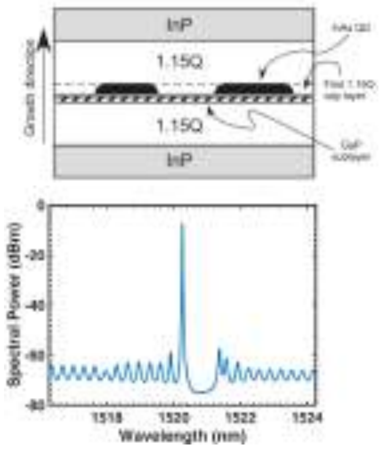


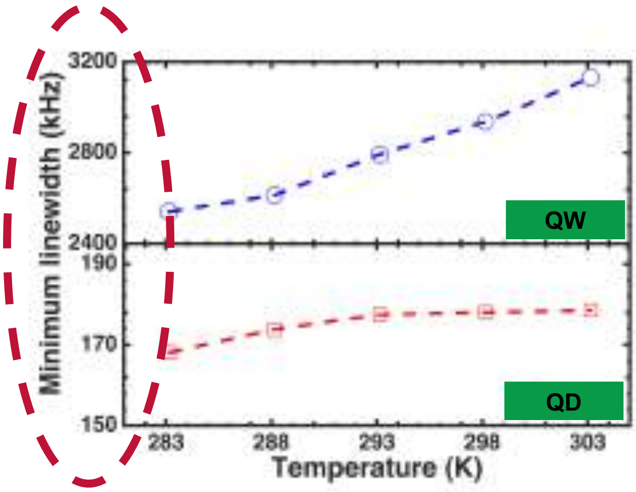
J. Duan et al., Applied Physics Letters (2018)

38

Narrow emission line

- Much smaller emission line than QW lasers (free-running)

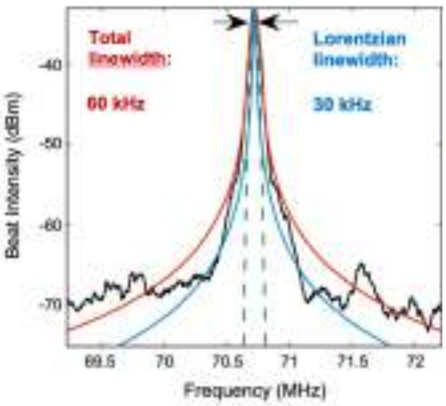




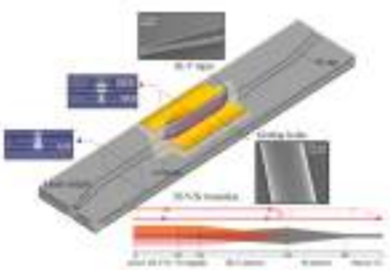
J. Duan et al., Applied Physics Letters (2018)

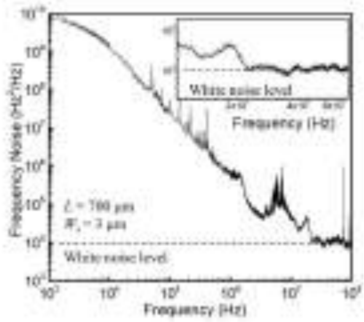
Narrow emission line

InAs/InP QD DFB laser
Spectral line: 30 kHz



Evanescent QD DFB laser on silicon
Spectral line: 26 kHz

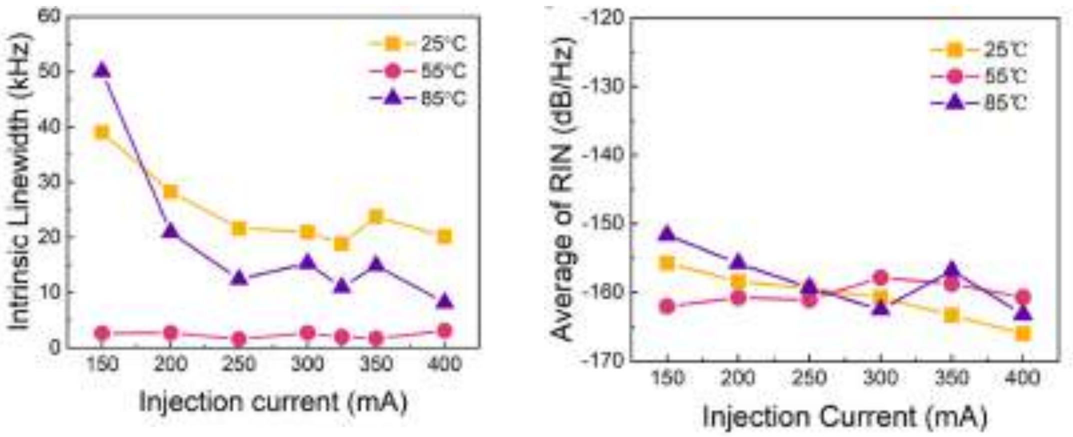




S. Bauer, OFC, paper #M4D.1 (2022); Y. Wan et al., Lasers & Photonics Reviews (2021)

Narrow emission line

InAs/GaAs QD DFB laser
Record spectral line of 1.6 kHz @55C, and low intensity noise < 150 dB/Hz



S. Bauer, Lasers & Photonics Reviews (2023)

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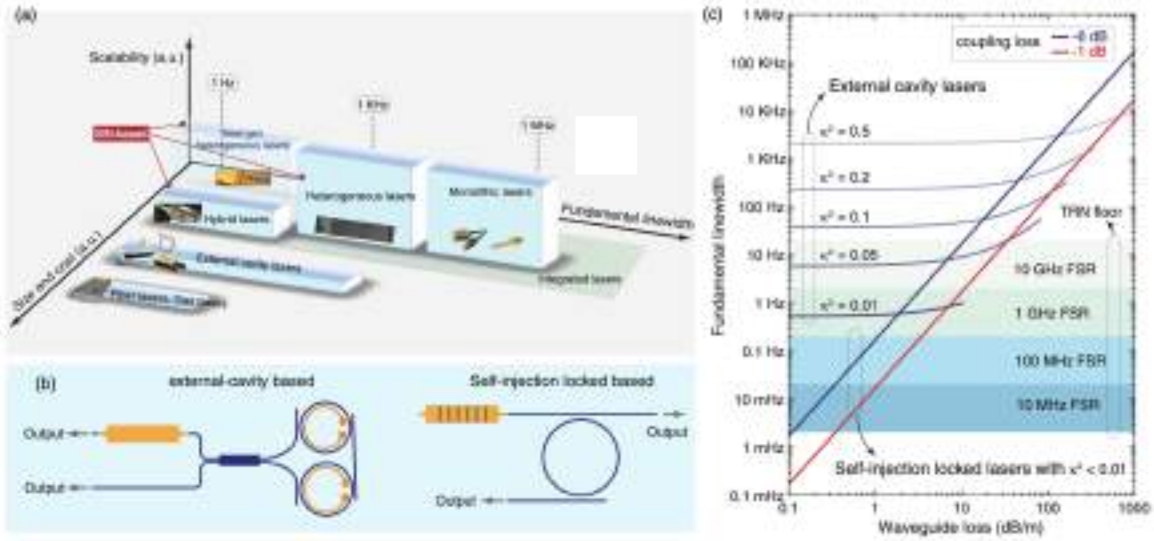
Towards ultra narrow emission line



C. Xiang et al., Photonics Research (2022)

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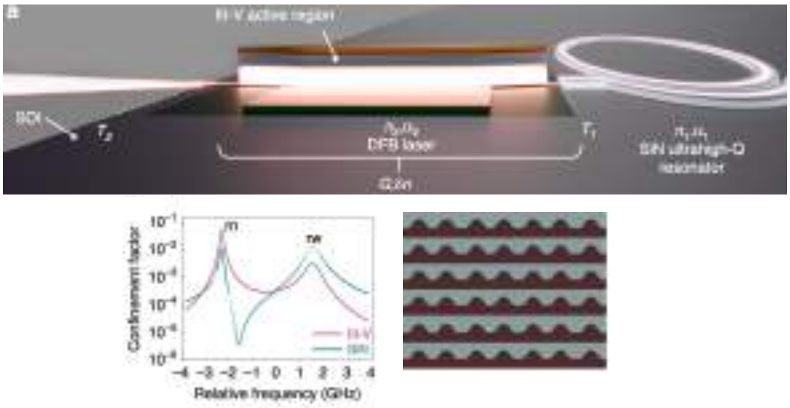
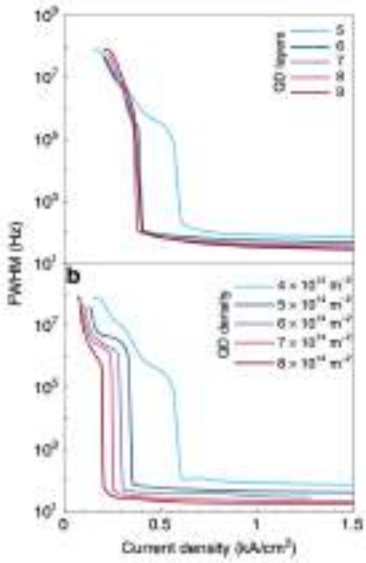
Towards ultra narrow emission line

- Self-injected integrated III-V - SiN lasers
- Optical coupling with a high-Q SiN resonator
- Several orders of magnitude linewidth reduction





E. Alkhazraji et al., Light Science & Applications (2023)

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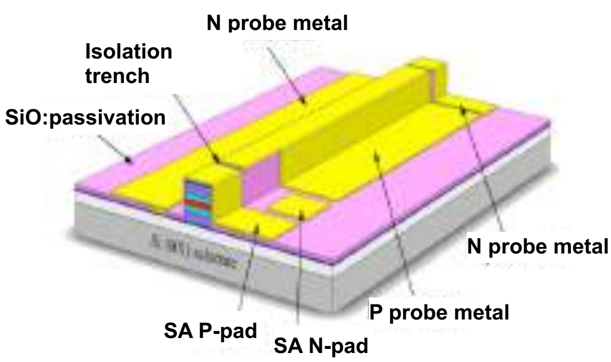
Passively mode-locked QD lasers

- Separate gain/absorber regions

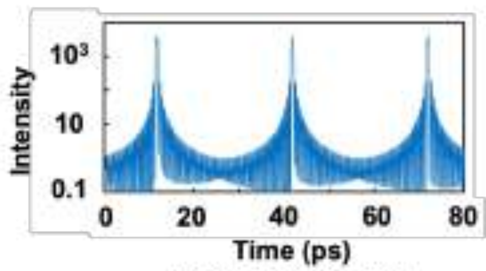


$$E(z,t) = \frac{1}{2}\sum_n E_n(t)\, e^{-i\psi_n(t)} u_n(z) + c.c$$

Pulse train

$$\psi_n(t) = (\nu_0 + n\Delta)t + \phi_n$$

$$\phi_0 = \phi_1 = \phi_2 = \dots$$



Locking of phases

Phase relation between modes
Pulse train widely emitted

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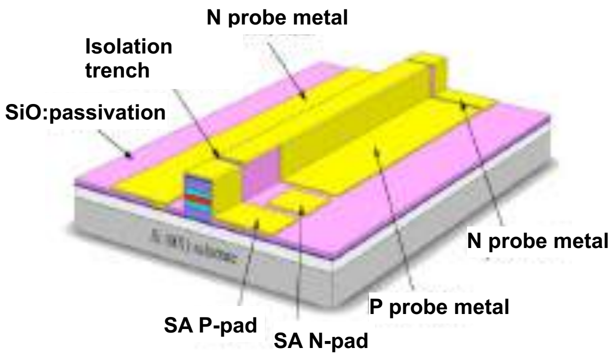
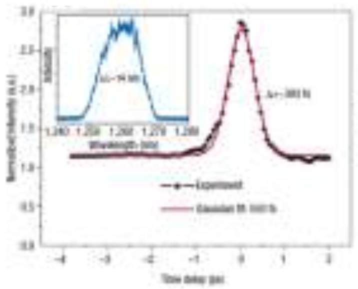
Passively mode-locked QD lasers

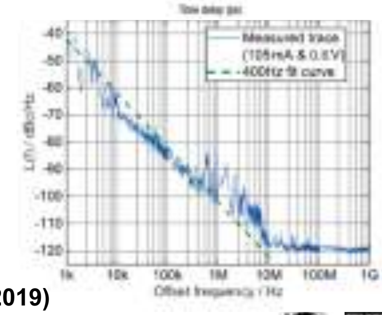
- Separate gain/absorber regions



Pulsewidth
393 fs
(InAs/GaAs)



RF beatnote
400 Hz
(InAs/GaAs/Si)



E. Rafailov et al., Nature Photonics (2007); D. Auth et al., Optics Express (2019)

Passively mode-locked QD lasers

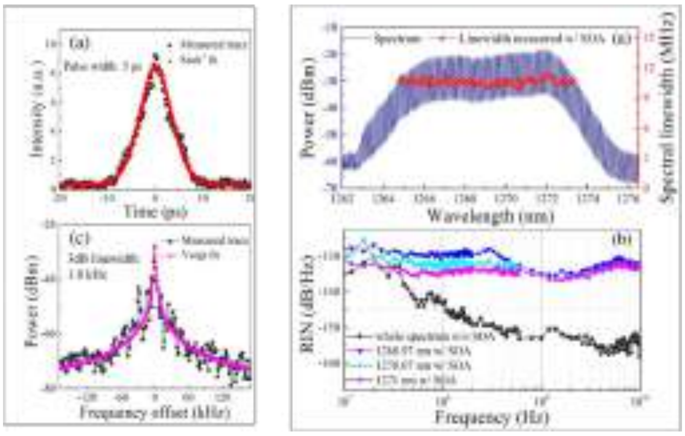
Substrate	Type	Repetition rate (GHz)	Pulse duration (ps)	TBP†	3-dB optical bandwidth (THz)	Year
InP	QDash	92	0.312	0.457	1.472	2008 [264]
InP	QDash	101	-	-	1.2	2009 [265]
InP	QDash	48-346	0.8	0.46	-	2011 [266]
InP	QD	50	0.43	-	1.65	2020 [267]
InP	QDash	34.2	-	-	1.6	2021 [268]
GaAs	QD	7.2-51	6.4	1.7	-	2007 [261]
GaAs	QD	39-237	0.36	0.5	-	2009 [262]
GaAs	QD	40	0.7	0.5	-	2010 [255]
GaAs	QD	60	-	-	2.46	2022 [269]
GaAs	QD	100	0.466	0.472	0.78	2022 [270]
GaAs	QD	100	0.81	0.45	1.9	2022 [189]
Si	QD	102	-	-	1.4	2018 [145]
Si	QD	20	5	-	1.14	2019 [257]
Si	QD	15.5	-	-	2.1	2022 [271]

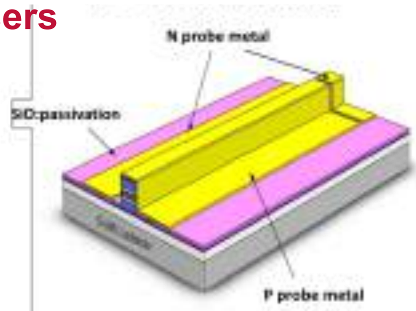
† Time-bandwidth product

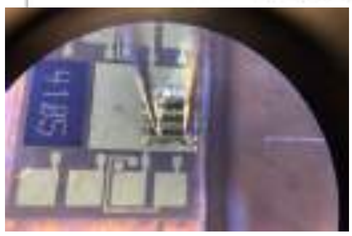
F. Grillot et al., Quantum Photonics (2023)

Self mode-locking with QD lasers

- Single QD gain section can also get mode-locked…..
- Large FWM involved





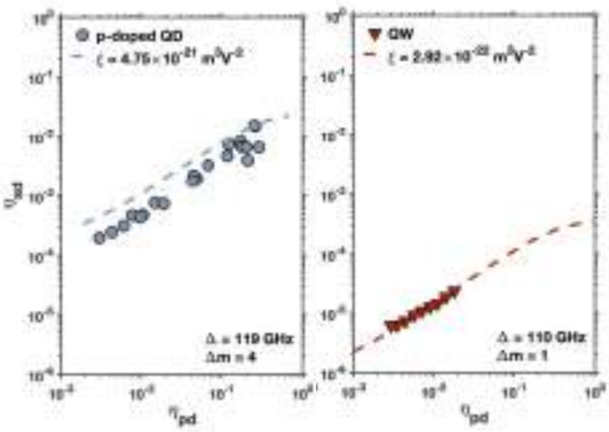


Courtesy of Prof J. E. Bowers

S. Liu, et al., Electron. Lett. (2018); S. Liu et al., Optica (2019)

Enhanced four wave-mixing in QDs

- Four wave mixing provides sufficient optical nonlinearities to overcome the dispersion
- QD lasers exhibit unique properties for realizing self mode-locking



Gain saturation, mode competition, and multiwave mixing connected through third-order optical nonlinearity

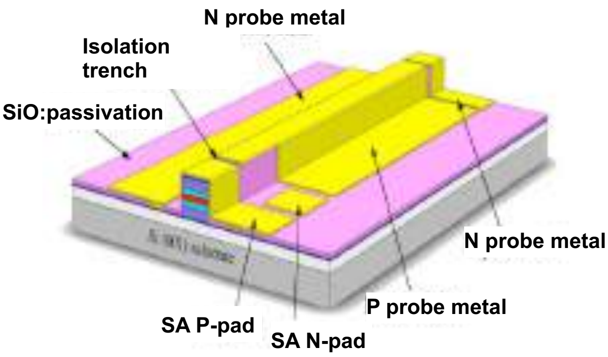
Third order coefficient

$$\chi^{(3)}_{sdpd} = \frac{\sqrt{2}n_b}{v_0\Gamma_{conf}}\left(\frac{\wp}{2\hbar\gamma}\right)^2 |\theta_{sdpd}|$$

J. Duan et al., Photonics Research (2022)

Mode-locking & combs

- Separate gain/absorber regions

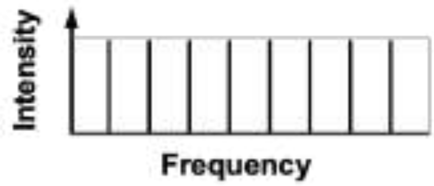


Phase relation between modes
Pulse train widely emitted

Frequency comb

$$\psi_n(t) = (\nu_0 + n\Delta)t + \phi_n$$

Locking of beatnotes



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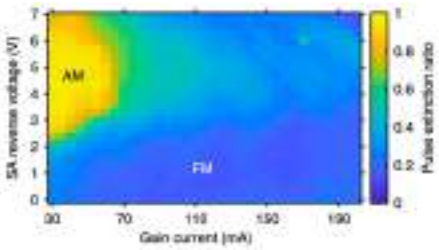
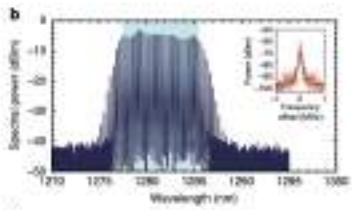
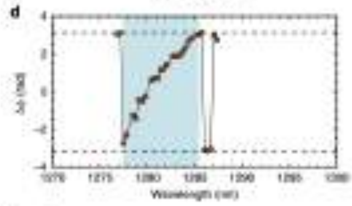
Mode-locking & combs

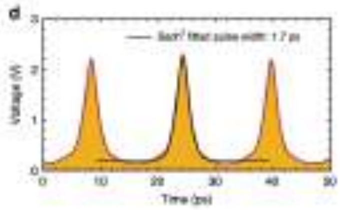
- **Broadband QD FM comb laser**
- FM combs: Kerr nonlinearity & FWM, GVD

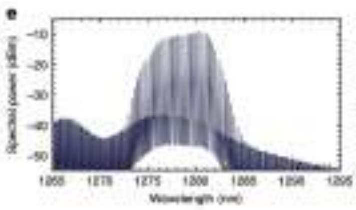
$$\eta_p = 1 - \frac{V_{CW}}{V_p} \begin{cases} \geq 0.5\ (AM\ dominant) \\ < 0.5\ (FM\ dominant) \end{cases}$$

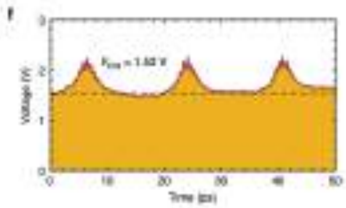












B. Dong et al., Light Science & Applications (2023)

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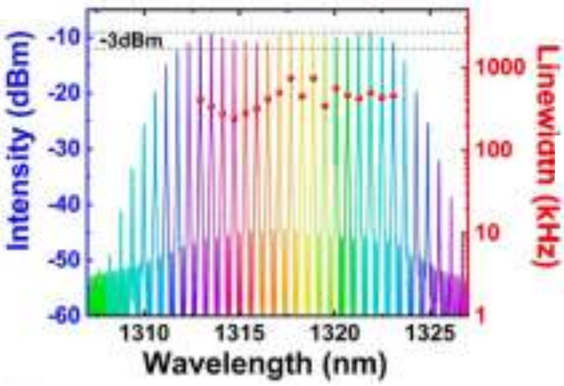
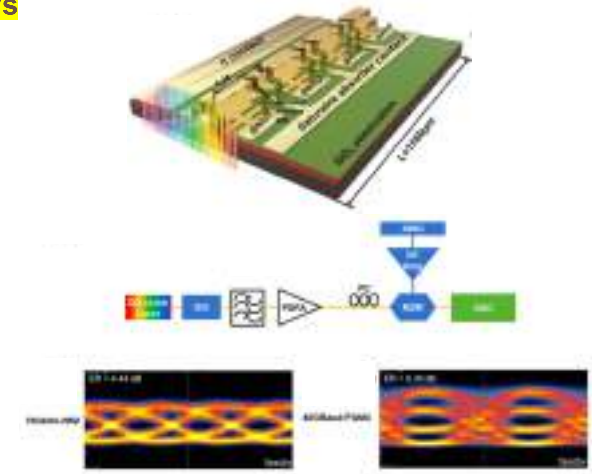
Mode-locking & combs

- 20 comb lines & 440 kHz linewidth. Extendable up to 60 comb lines with 100 GHz mode spacing, transmission capacity of 4.8 Tbit/s

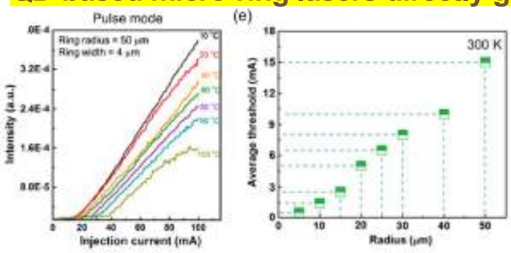


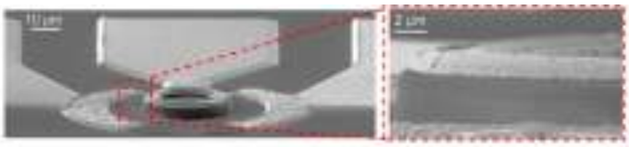


J.-Z. Huang et al., Photonics Research (2022)

Other related works

- QD-based micro-ring lasers directly grown on silicon (HPC)

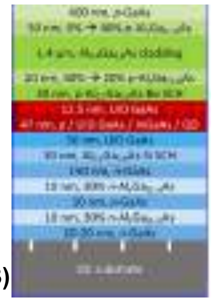


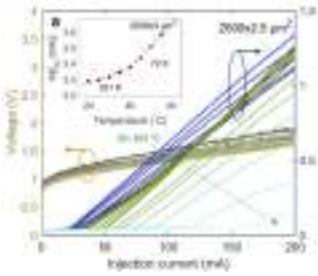


Electrical pumping, sub-milliamp threshold
Room temperature operation

- QD lasers heterogeneously integrated on SiC

Better thermal conductivity of SiC at 300K
Lowest threshold current density 233 A/cm^2 (CW)
Maximum output power 20mW.





Y. Wan et al., Optica (2017); Y. Wan et al., Optics Letters (2023)

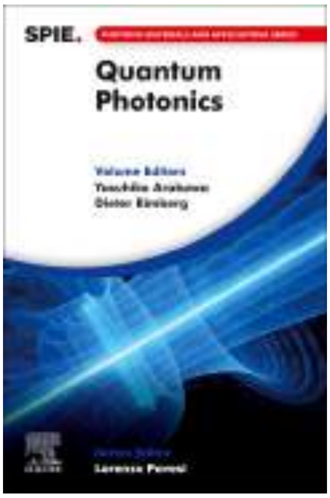
Conclusions

- **Self-organized nanostructures are one of the best practical examples of nanotechnologies which have revolutionized information communications through quantum mechanics**
- **QD lasers hold the promises**
  - Reduced power consumption, great thermal efficiency
  - Isolator-free transmitters
  - Mode-locking & frequency combs
  - Ultralow noise oscillators
- **Putting QD lasers to practical use**
  - Silicon photonics QD devices very useful for photo-electronizing servers, addressing optical connectivity in artificial intelligence / machine learning and datacenter markets.
  - On-chip atomic clock, sensing (optical radars)
  - Mid infrared & THz optical wavelengths using quantum cascade heterostructures
  - Quantum technologies (polarized & entangled photons, squeezed light)

Takeaway message

About 40 years later after their discovery, QDs are now implemented into industrial products in order to sustain the growing needs of the communication and information.

Their deployment onto the market is a direct consequence of the strong development of nanotechnology over the last twenty years and therefore provides a solid foundation for the delivery of efficient photonic solutions



Let's do it with dots!

Quantum Photonics, Edited by Professors Yasuhiko Arakawa and Dieter Bimberg, SPIE & Elsevier (2024)