Quantum dot light sources
-Past, present, and future-

Yasuhiko Arakawa

The University of Tokyo

Outline

- Historical overview of QD laser research
- QD lasers for silicon photonics
- QDs for single photon sources
- Outlook

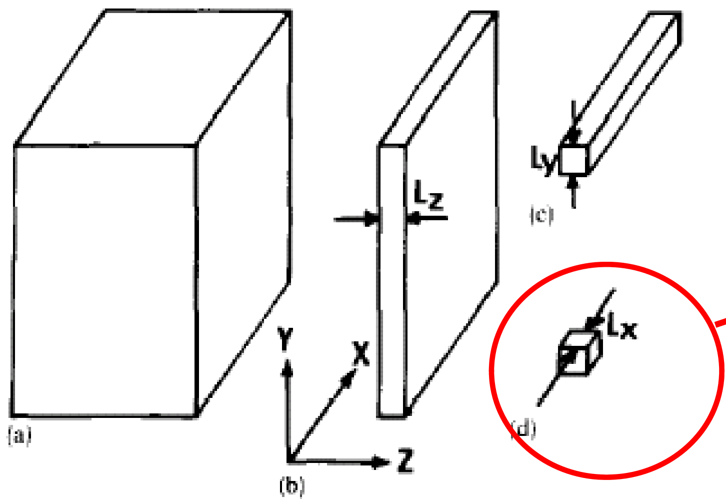
Quantum dot (1982)

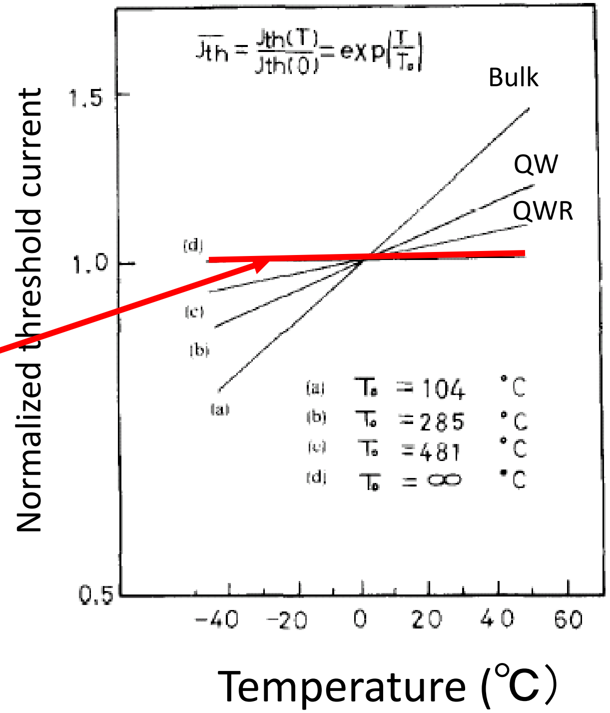
939 Appl. Phys. Lett. 40(11), 1 June 1982 0003-6951/82/110939-03$01.00

Multidimensional quantum well laser and temperature dependence of its threshold current

Y. Arakawa and H. Sakaki
Institute of Industrial Science, University of Tokyo, Minato-ku, Tokyo 106, Japan

(Received 19 January 1982; accepted for publication 23 March 1982)





Citation: 3 ,484 times

Quantum dot (1982)

939 Appl. Phys. Lett. 40(11), 1 June 1982 0003-6951/82/110939-03$01.00

Multidimensional quantum well laser and temperature dependence of its threshold current

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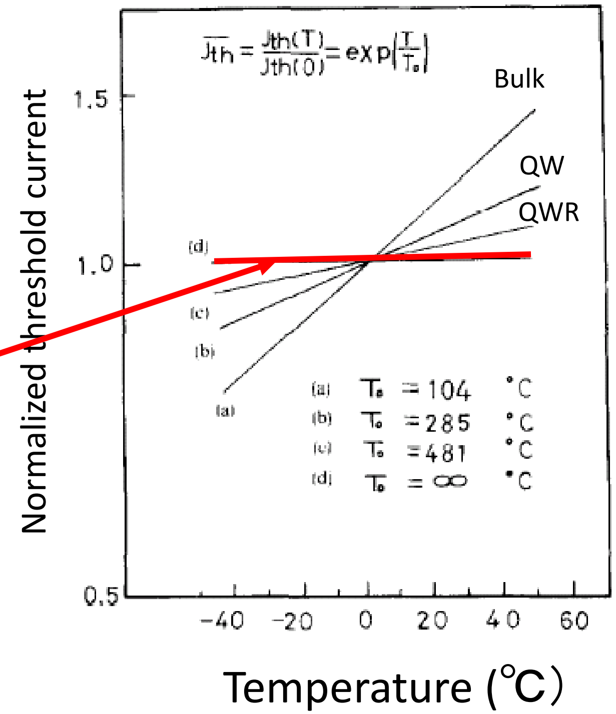
(Received 19 January 1982; accepted for publication 23 March 1982)

Theoretical work:

- High temperature stability — Arakawa (1982)
- Low threshold current — Asada, Suematsu (1986), Yariv (1987)
- High modulation frequency — Arakawa, Yariv (1986)
- Zero α-parameter — Arakawa, Yariv (1986)
- P-doping — Arakawa (1982
- Tunneling injection — Arakawa (1991)



Citation: 3 ,484 times

Quantum-size effect on laser dynamics

Appl. Phys. Lett. **45**, 950 (1984)

Quantum noise and dynamics in quantum well and quantum wire lasers

Yasuhiko Arakawa,[a] Kerry Vahala, and Amnon Yariv
California Institute of Technology, Pasadena, California 91125

(Received 2 April 1984; accepted for publication 8 August 1984)

$$f_r = \frac{1}{2\pi}\left(\frac{P\omega}{2\tau\mu_0}\frac{d\chi_I(n)}{dn}\right)^{1/2}$$

$$\alpha = \frac{d\chi_R(n)/dn}{d\chi_I(n)/dn},$$

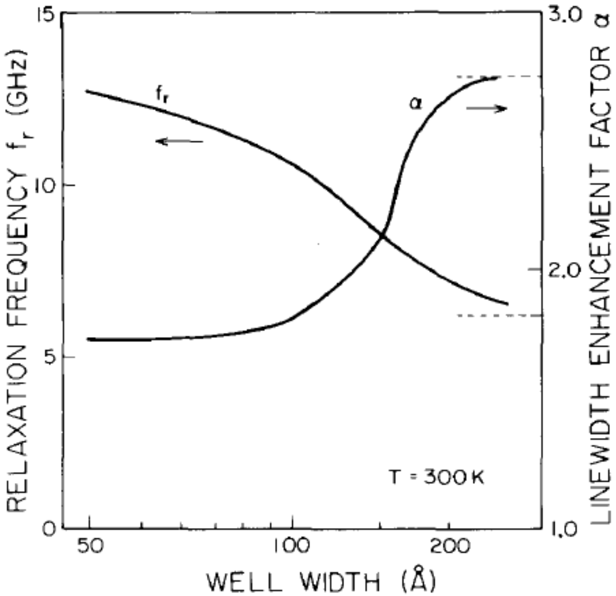


FIG. 2. α and f_R of a quantum well laser as a function of well width L_z.

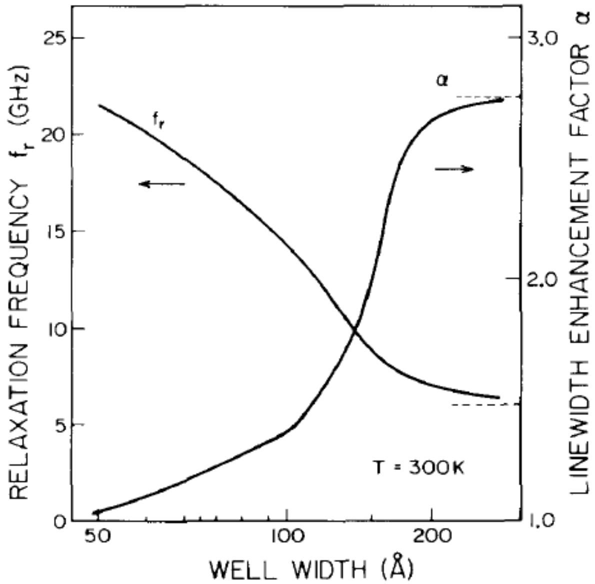


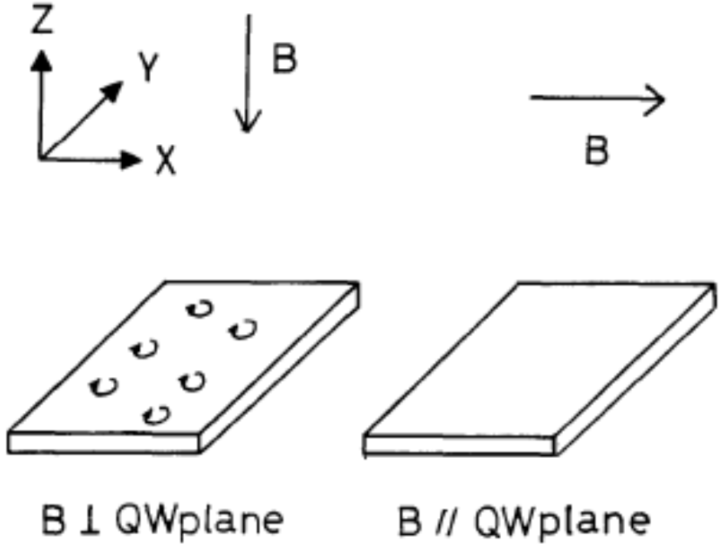
FIG. 3. α and f_R of a quantum wire laser as a function of well width L_z.

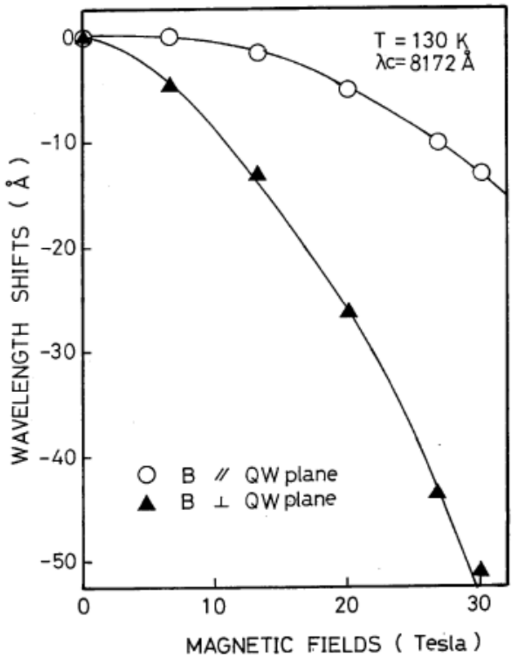
Experimental simulation of quantum dot effect

Japan J. of Applied Phys. 22 L804 (983)

Spontaneous Emission Characteristics of Quantum Well Lasers in Strong Magnetic Fields —An Approach to Quantum-Well-Box Light Source—

Yasuhiko ARAKAWA,* Hiroyuki SAKAKI,* Masao NISHIOKA,*
Hiroshi OKAMOTO** and Noboru MIURA***





Stranski-Krastnanov(S-K) growth of quantum dots

Growth by molecular beam epitaxy and characterization of InAs/GaAs strained-layer superlattices

L. Goldstein, F. Glas, J. Y. Marzin, M. N. Charasse, and G. Le Roux
Centre National d'Etudes des Telecommunications, 196 rue de Paris, 92220 France

(Received 26 July 1985; accepted for publication 4 September 1985)

Appl. Phys. Lett. 47 (1985) 1099.

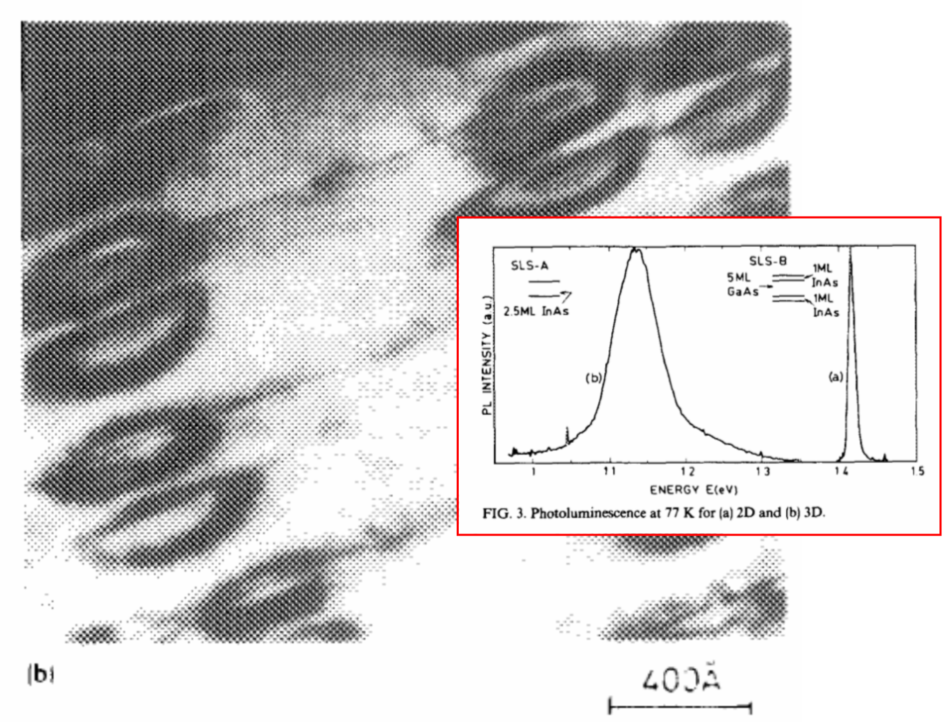
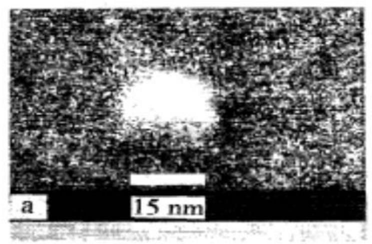
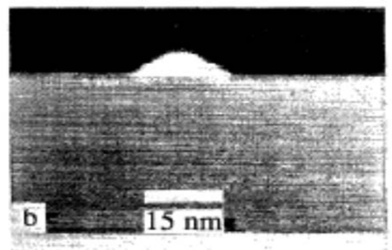


FIG. 3. Photoluminescence at 77 K for (a) 2D and (b) 3D.

- •Glas *et al* 1987
- •Sasaki *et al* 1992
- •Moison *et al* 1993
- •Petroff *et al* 1993
- •Ledentsov *et al* 1994

The first InGaAs/GaAs grown by MOCVD



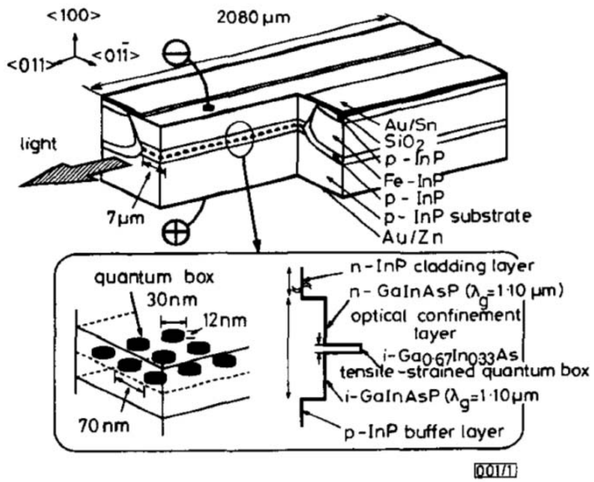


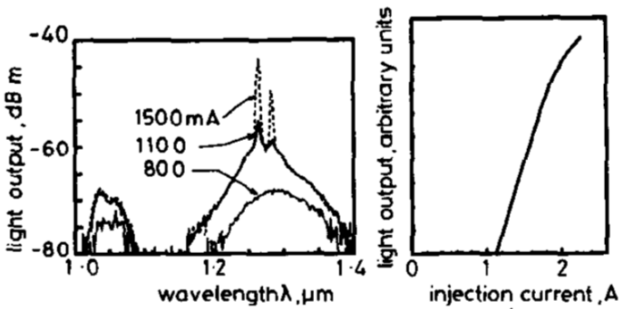
Oshinowo, YA, *et al.*, Appl. Phys. Lett. **65**, 1421 (1994)

Trials of fabrication of quantum dot lasers in 1994

Lasing action of $Ga_{0.67}In_{0.33}As$/GaInAsP/InP tensile-strained quantum-box laser

H. Hirayama, K. Matsunaga, M. Asada and Y. Suematsu

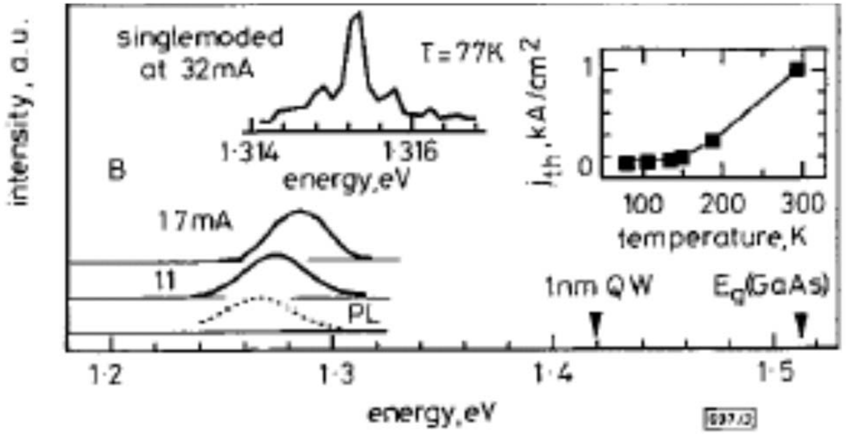


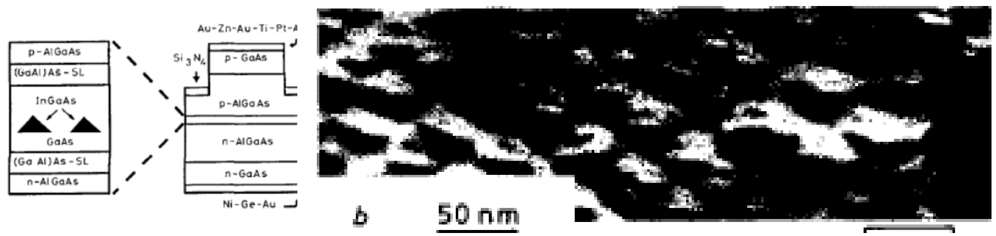


ELECTONICS LETTERS 30 142 (1994)

Low threshold, large T_o injection laser emission from (InGa)As quantum dots

N. Kirstaedter, N.N. Ledentsov, M. Grundmann, D. Bimberg, V.M. Ustinov, S.S. Ruvimov, M.V. Maximov, P.S. Kop'ev, Zh.I. Alferov, U. Richter, P. Werner, U. Gösele and J. Heydenreich





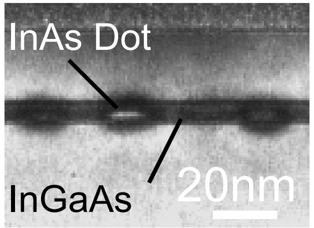
ELECTONICS LETTERS 30 281 (1994)

1.3μm quantum dot lasers

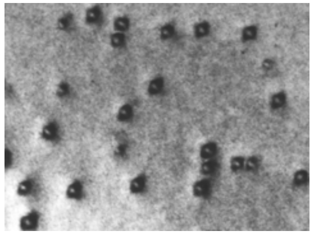
■ 1.3-μm self-assembled InAs quantum dots

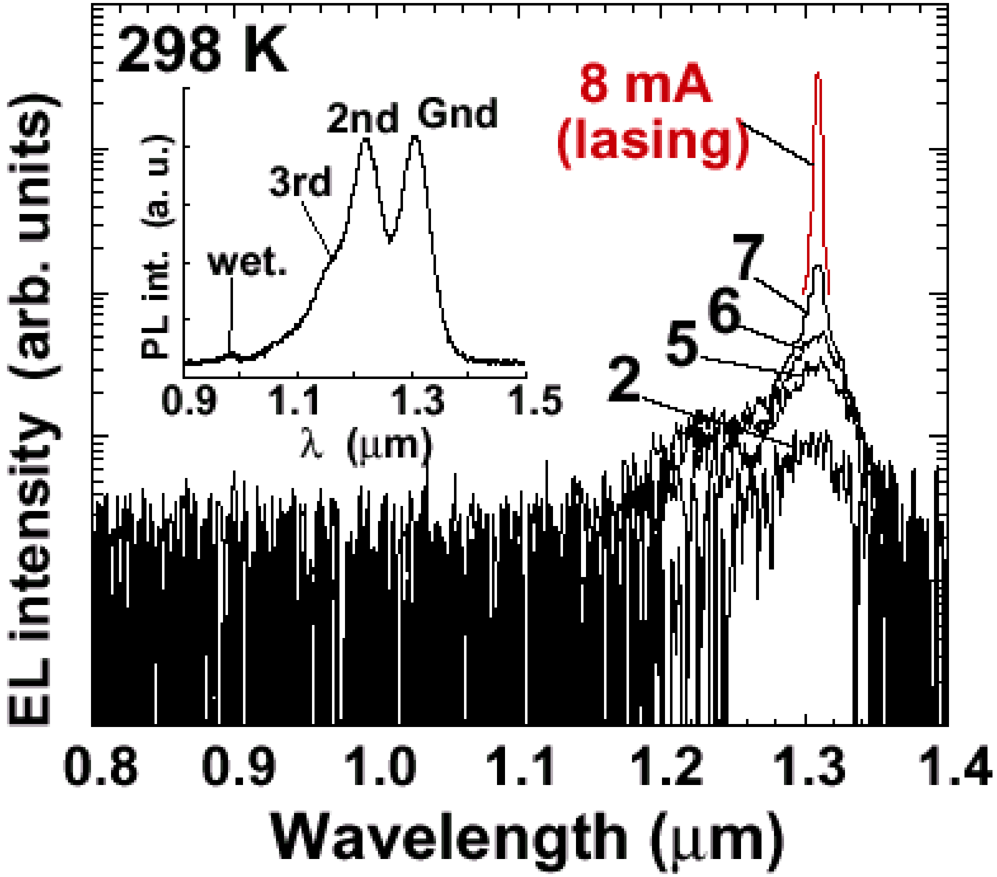
K. Mukai, et al., Fujitsu, Jpn. J. Appl. Phys. 33, L1710-1712 (1995).
US patent 5608229 (97.03.04), Japan patent 3,468,866 (2003. 09.05)

Cross section



Surface





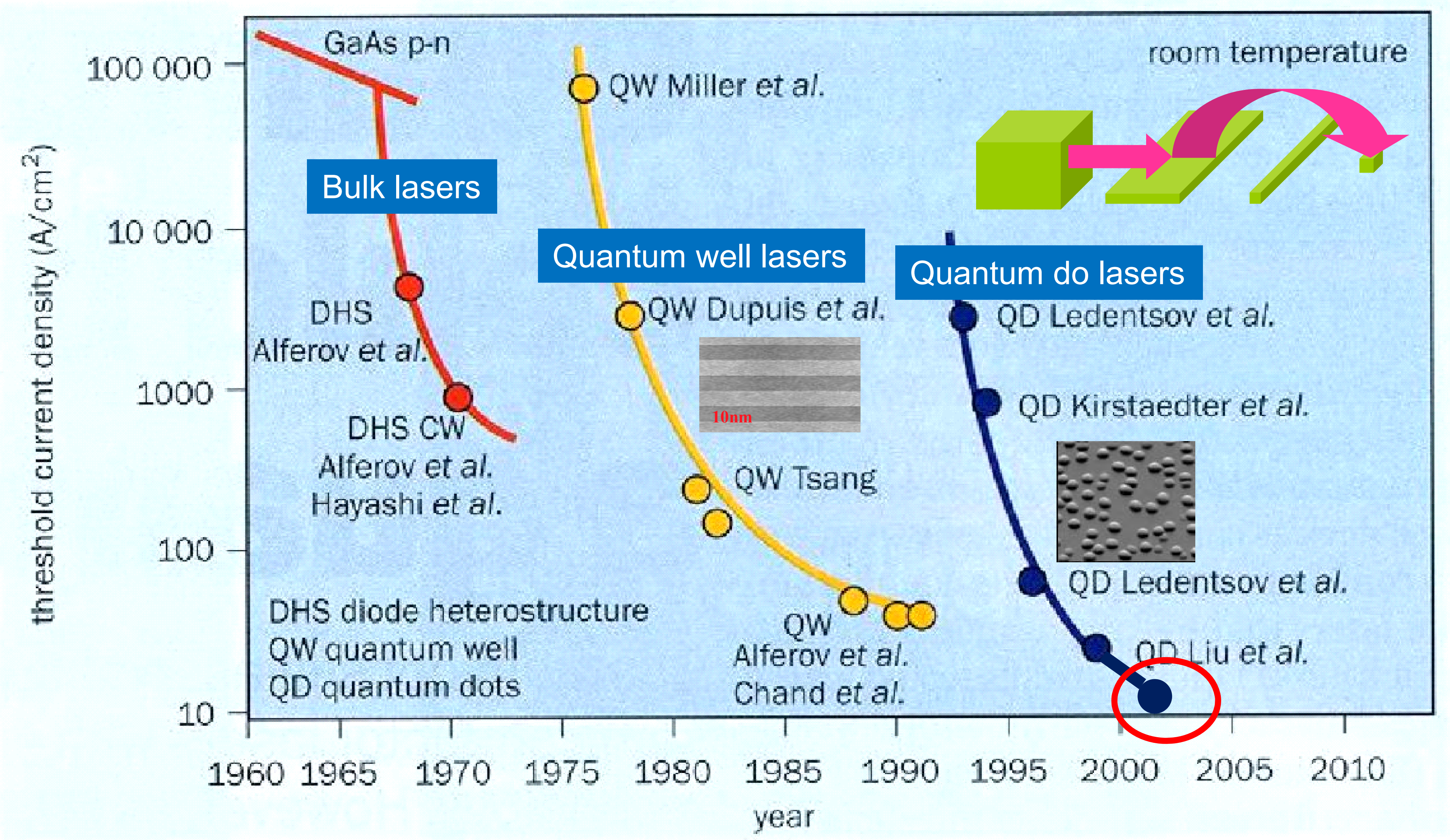
■ Pulsed operation at R.T.

D.L. Huffaker et al., Univ. Texas
APL 73, 2564 (1998).

■ CW operation at R.T.

K. Mukai, et al., Fujitsu
IEEE Phot. Tech. Lett. 11, 1205-1207 (1999).

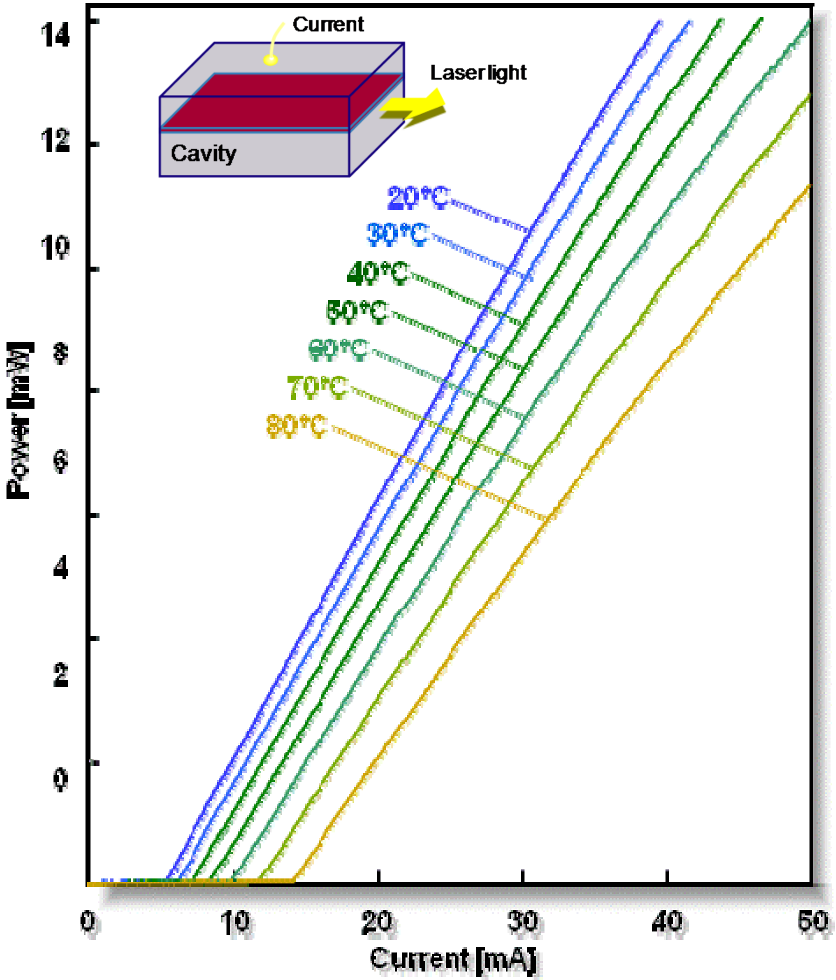
Evolution of threshold current



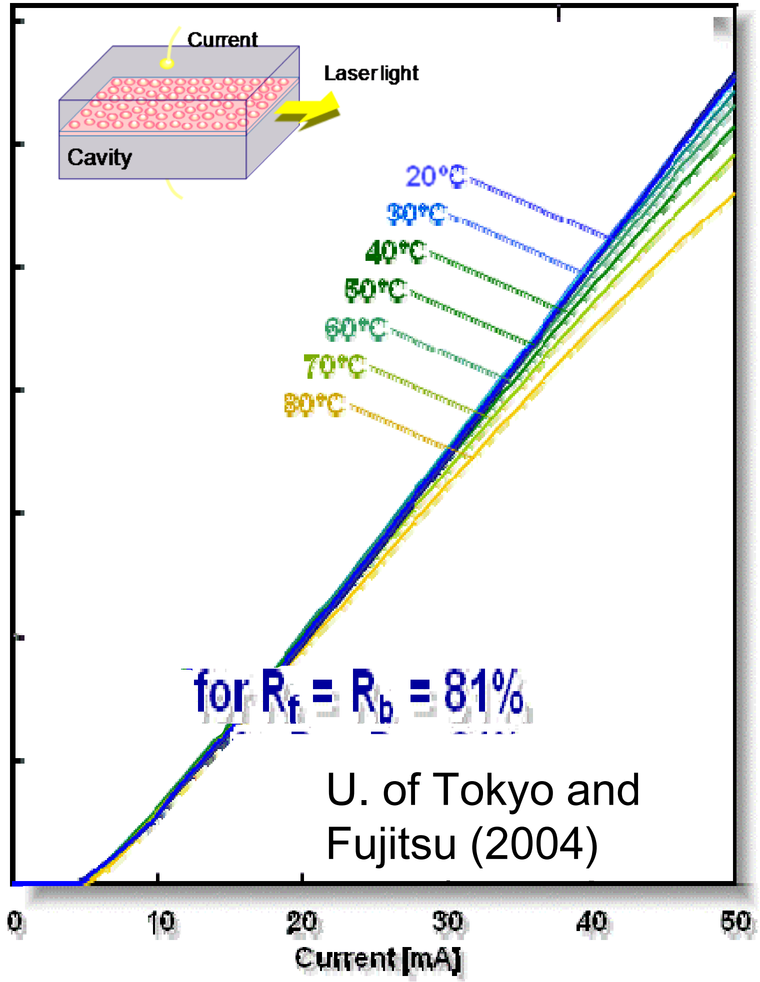
Ref. Opto & Laser Europe

Technical innovation for quantum dot lasers

Quantum well laser



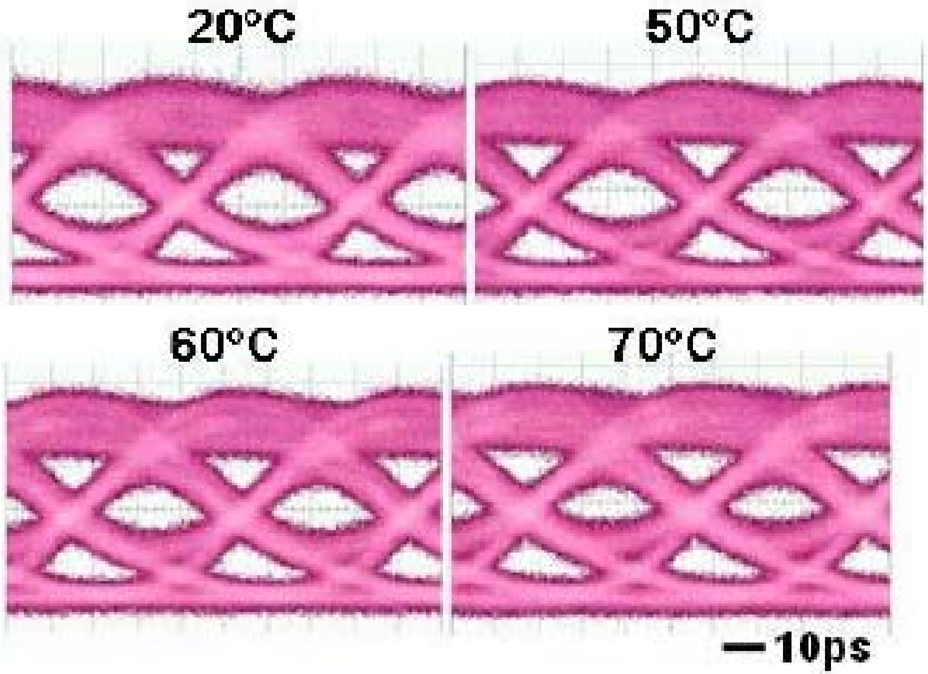
Quantum dot laser (p-doping)



No current adjustment is needed for a constant laser output power !

Temperature stability

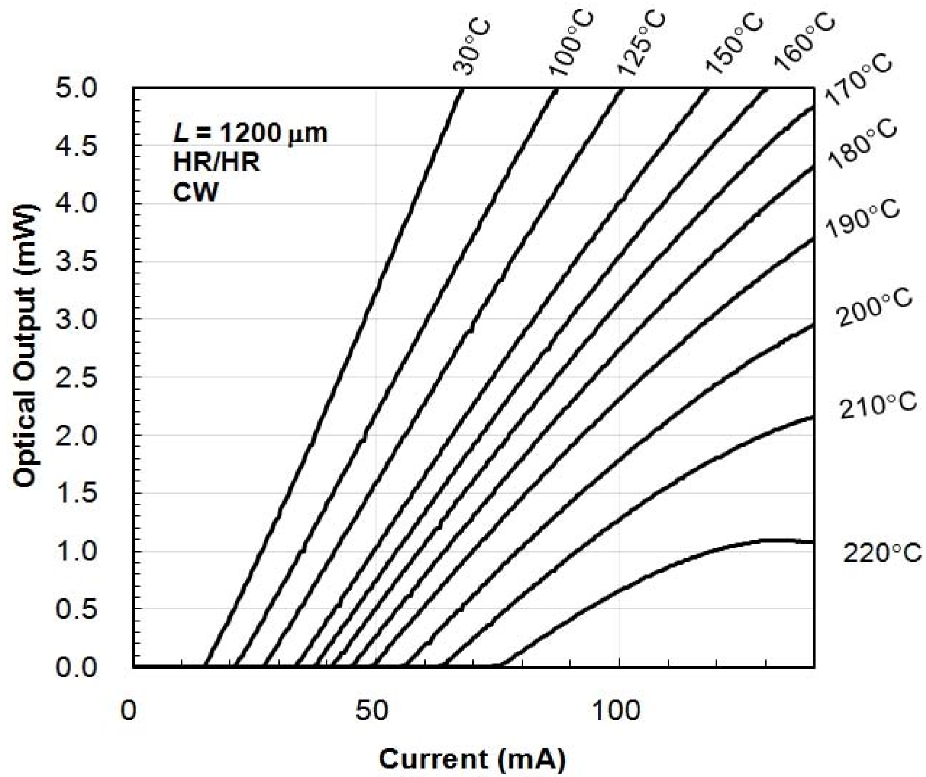
25Gbps modulation



Bias current : 130 mA
Drive voltage : 120mA $P_{p\text{-}p}$
Extinction ratio : 4.3 dB @20^{o}C
3.3 dB @70^{o}C

M. Ishida *et al.*, 2011

High temperature operation

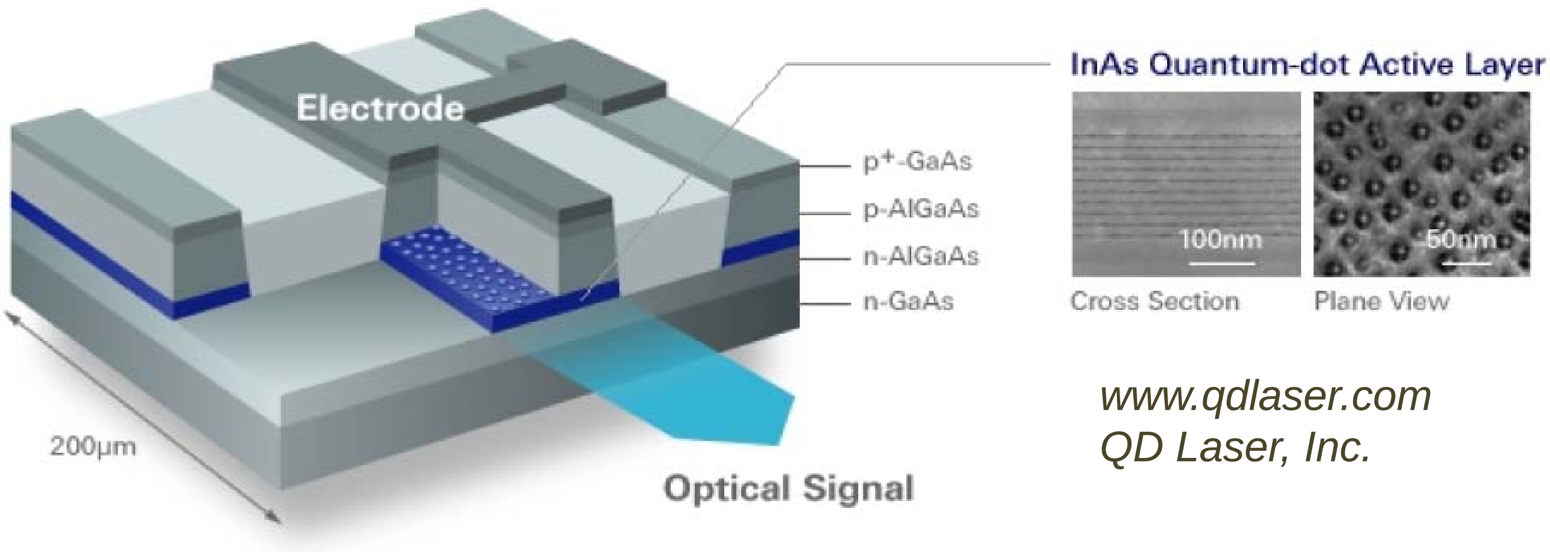


T. Kageyama *et al., 2011*

Quantum dot lasers

- Hold promise of temperature insensitive, low threshold current
- Extreme temperature operation up to 220°C
- Direct modulation > 20Gb/s with low chirping
- GaAs substrate → cheaper mass production than InP based devices

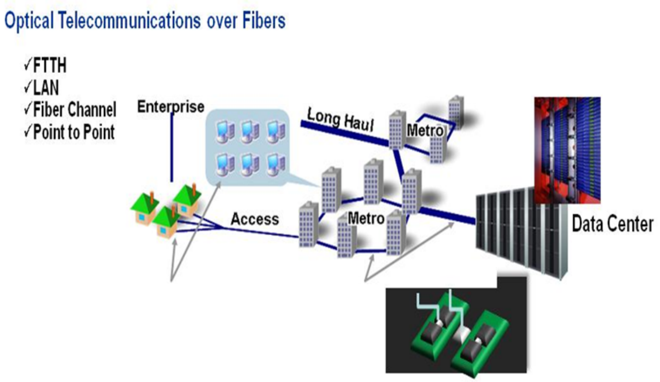
■ QD LASER Inc. was launched in 2006
■ More than 3 Million chips have been delivered to commercial market.



www.qdlaser.com
QD Laser, Inc.

Various applications of QD lasers

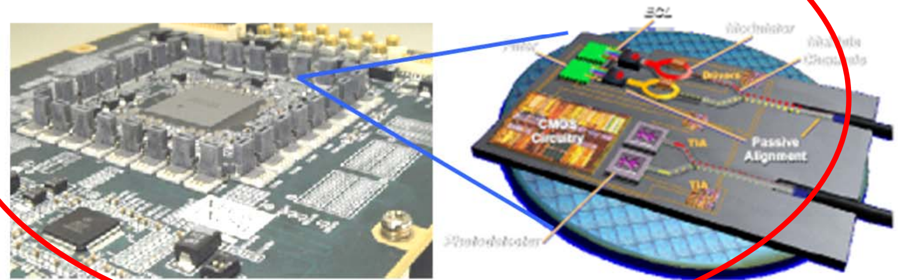
Telecom application



Medical & high power application

Sensing & data com at high temp.

Silicon photonics



Outline

- Historical overview of quantum dot laser research
- Quantum dot lasers for silicon photonics
- Quantum dots for single photon sources

QD lasers for hybrid silicon III-V lasers

- ✓ Low threshold current
  - ✓ Low-power consumption
- ✓ High temperature operation
  - ✓ High tolerance to heat generated by LSI chips
- ✓ Low noise properties (small α-parameter)
  - ✓ High tolerance to optical feed back noise

- ◆ Direct epitaxial growth
- ◆ Flip-chip bonding
- ◆ Wafer bonding

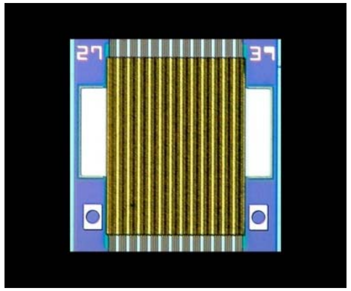
Flip-chip binding

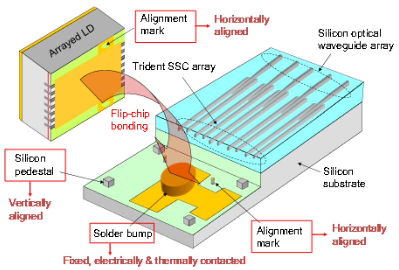
Integration of a QD laser array on silicon optical interposer

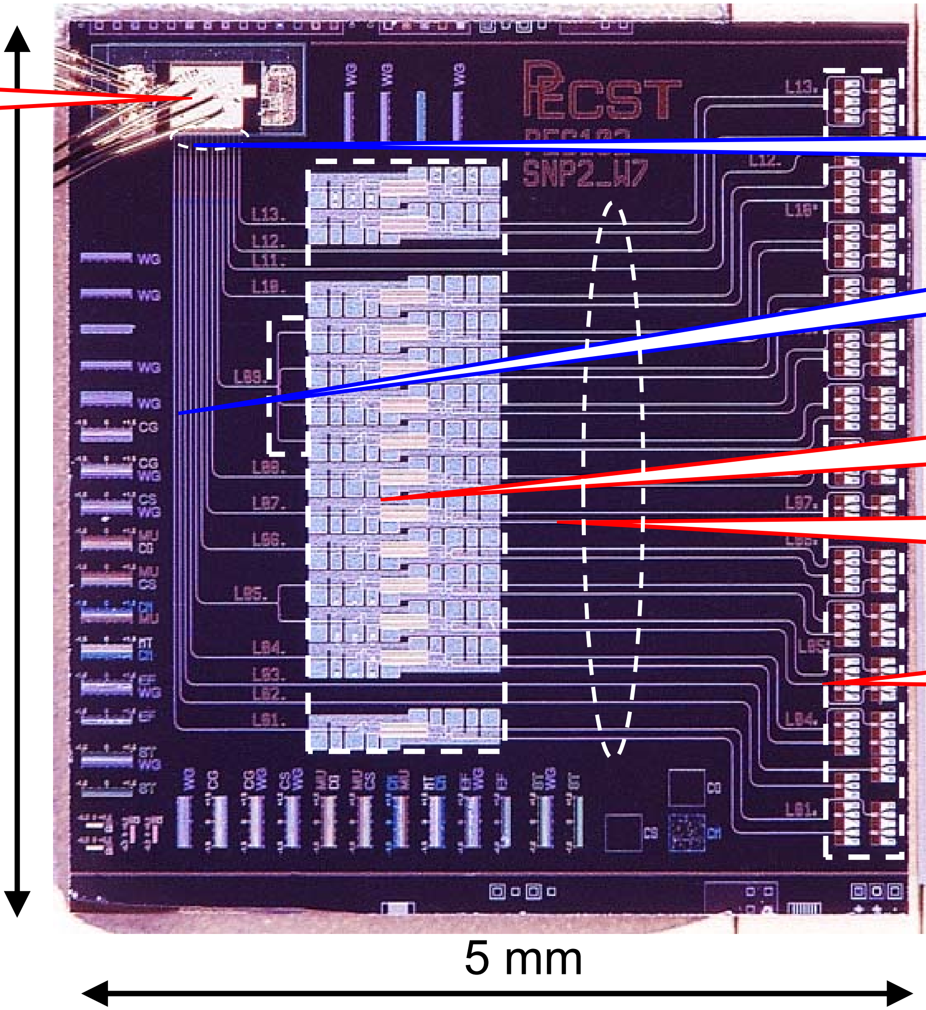
Hybrid integration

Monolithic integration

LD Array







Spot-size Converter

Optical Splitter Array

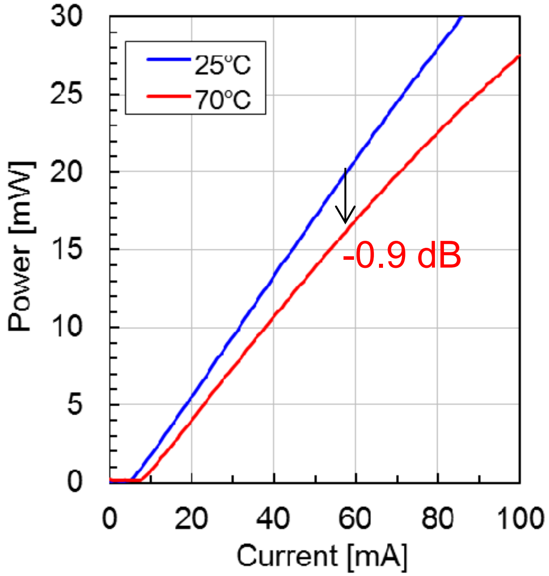
Optical Modulator Array

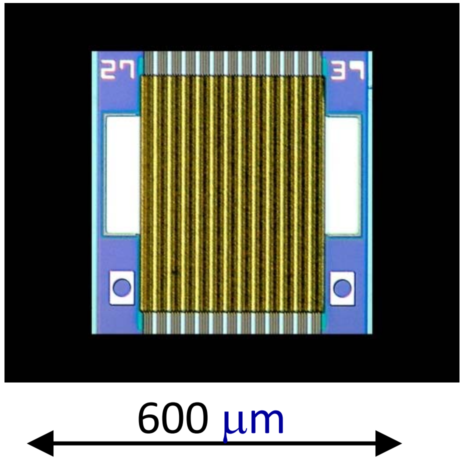
Optical Waveguide Array

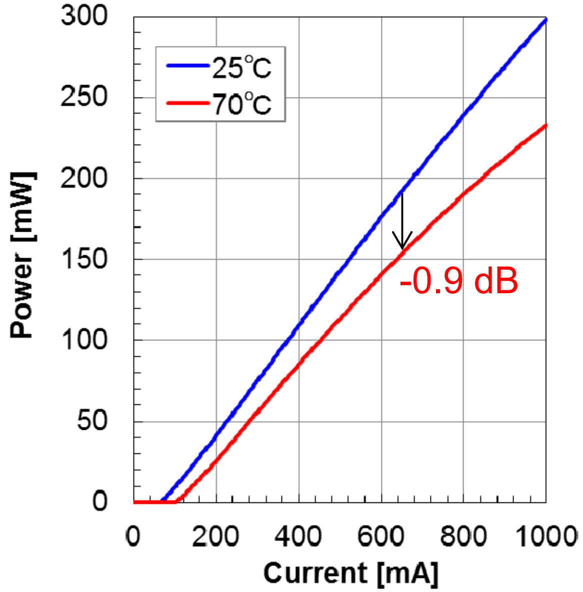
PD Array

PECST/U.Tokyo

13-channel arrayed quantum dot lasers







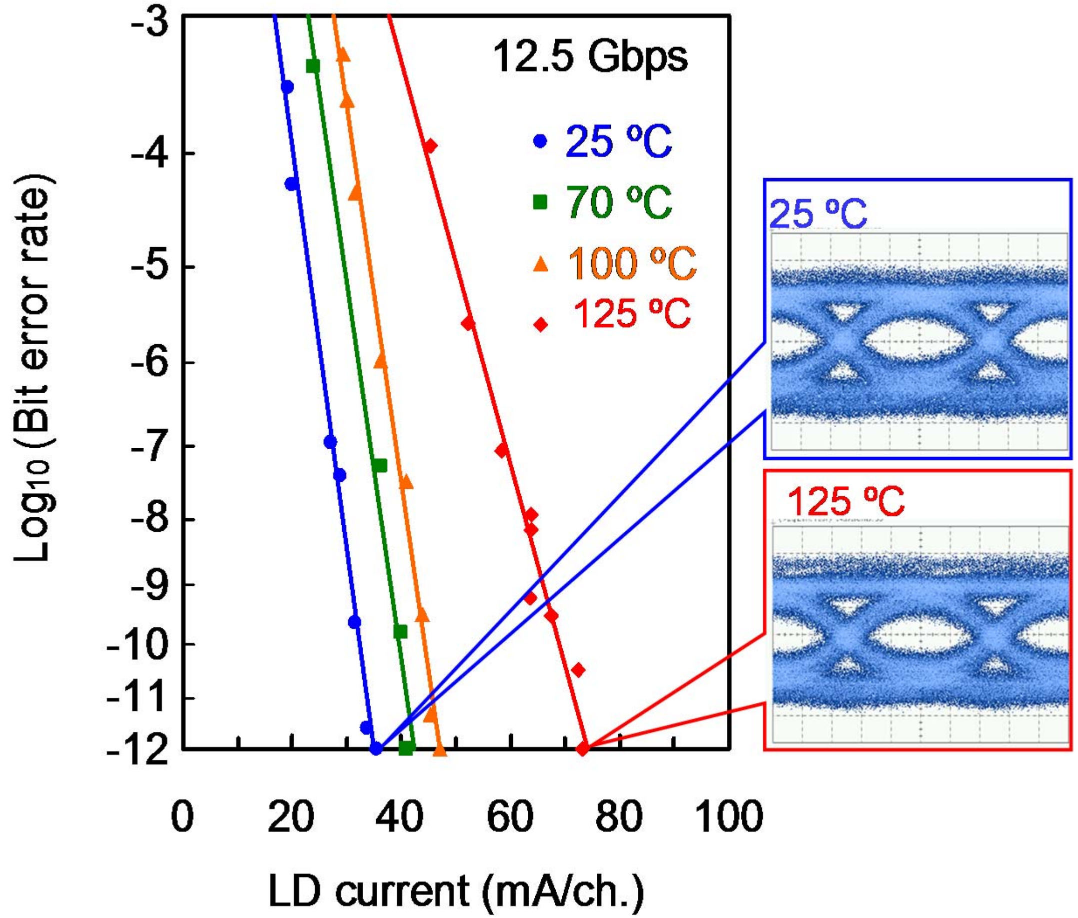
Single-ch. QD-LD

13-ch. arrayed QD-LD

I-L characteristics

- Fabricated by QD Laser, Inc.
- Multiple quantum dot layers
- Wavelength : 1.27 μm at room temperature
- Output power : > 130 mW up to 100 ºC

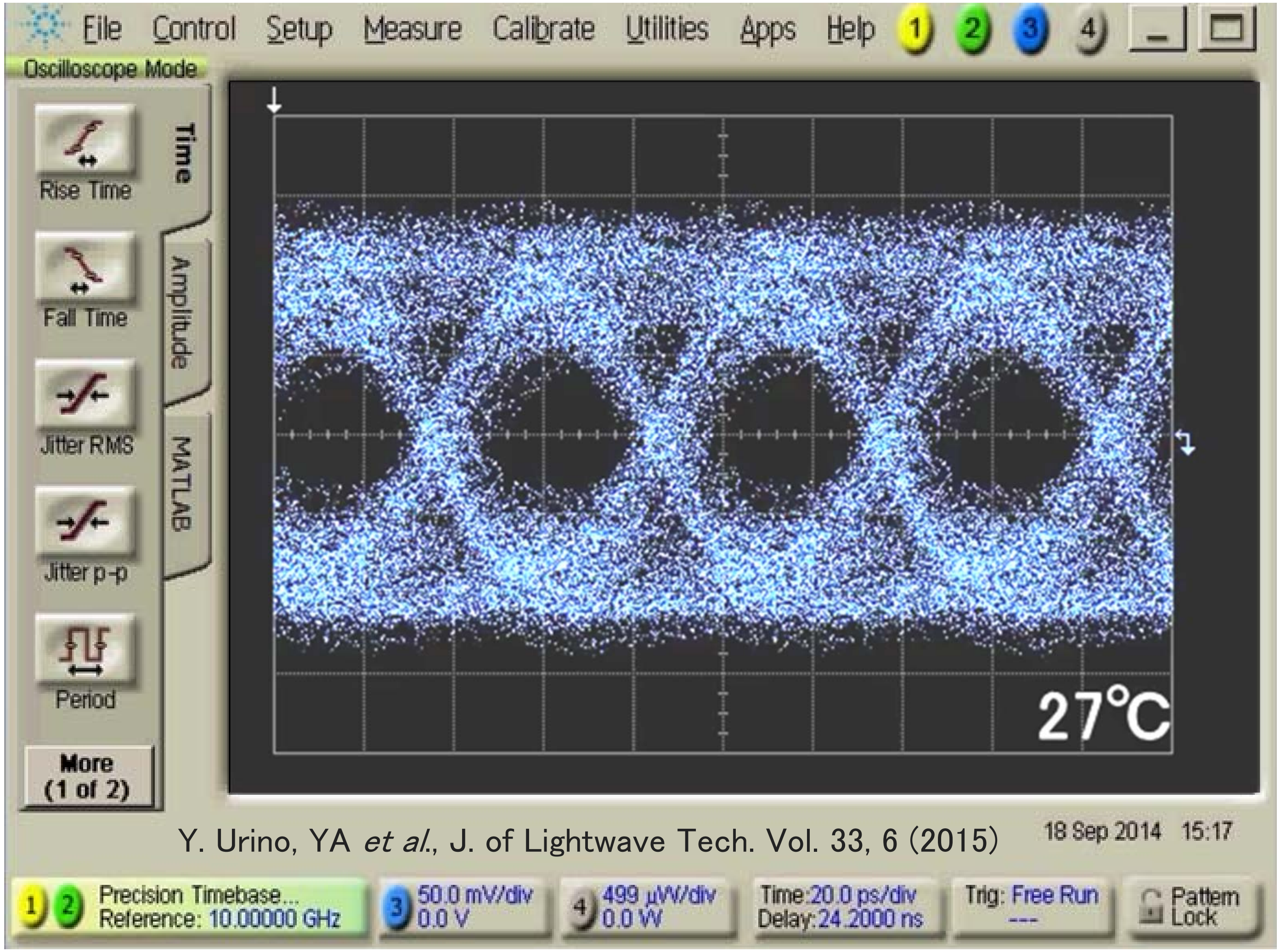
High temperature operation of Si optical interposer



- Error-free data links up to 125 ºC without any bias adjustments.
- Bandwidth density of 15Tbps/cm^2.

Y. Urino, *et al.*, IEEE J. of Lightwave Tech. **3** , 1223 (2015)

25Gbps without any adjustments

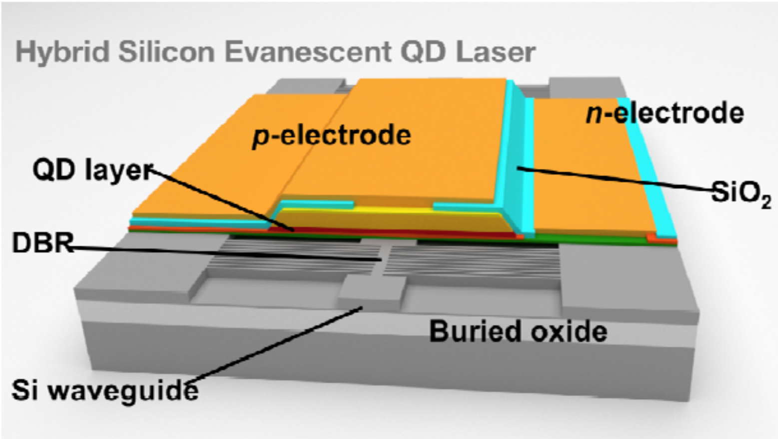


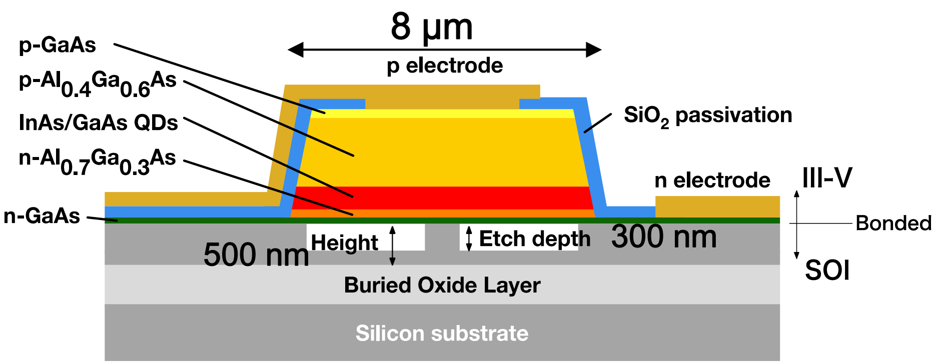
Y. Urino, YA *et al.*, J. of Lightwave Tech. Vol. 33, 6 (2015)

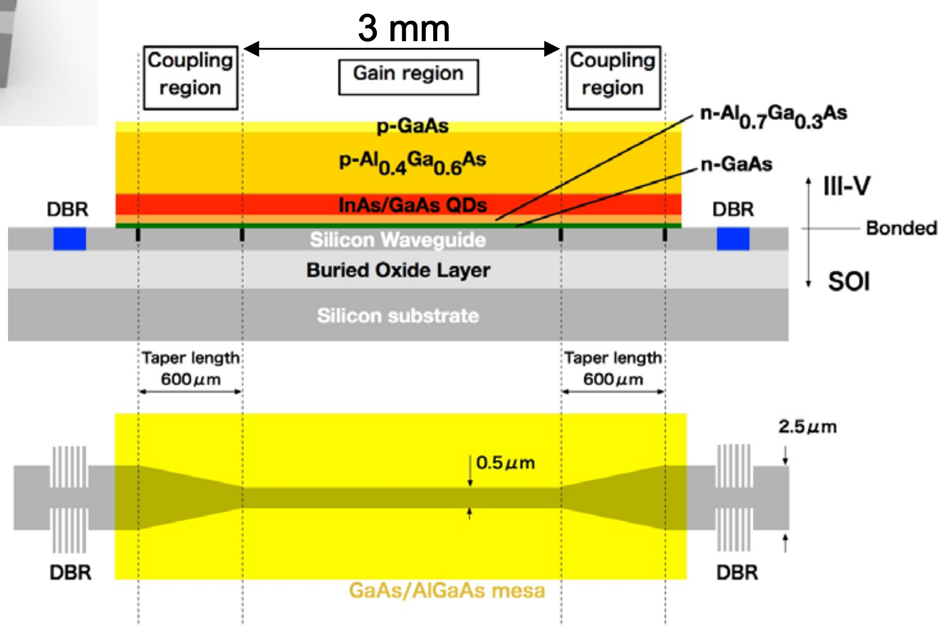
- Error-free data links up to 125 ºC without any bias adjustments.

Wafer bonding

Hybrid silicon/III-V quantum dot evanescent lasers

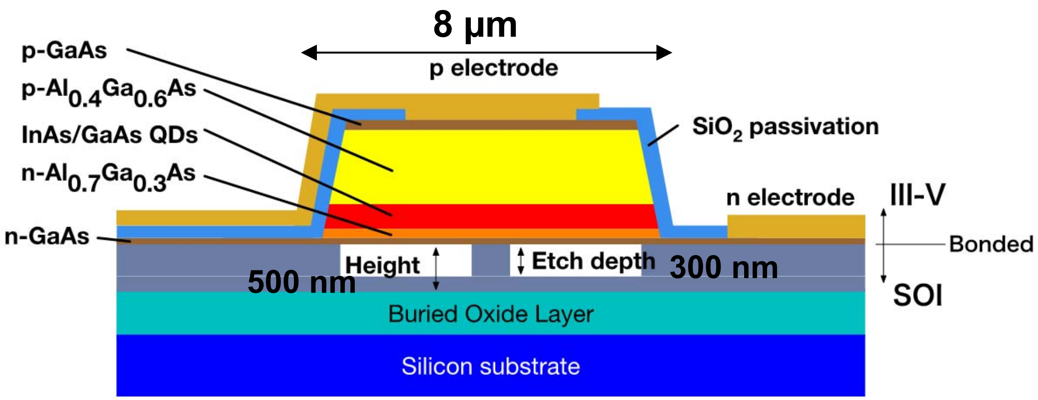


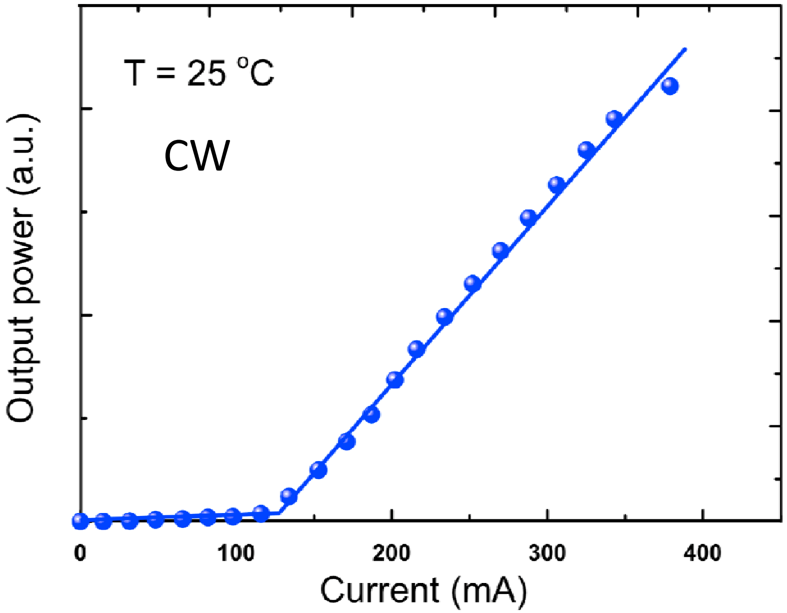




B. Jang, YA *et al.* Appl. Phys. Express **9** 092102 (2016)

I-L characteristics





- Fabricated a hybrid QD laser with 8 μm-wide mesa width
- I_{th} = 120 mA (CW) at room temperature

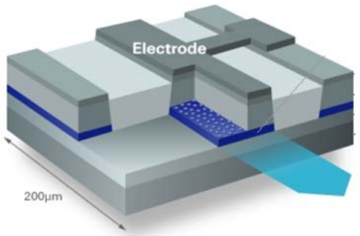
Temperature characteristics

- T_0 = 303 K near RT and operated up to 115 °C (pulsed operation)

B. Jang, YA *et al.* Appl. Phys. Express **9** 092102 (2016)

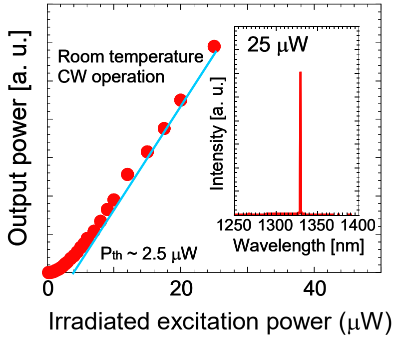
Advanced quantum dot light sources

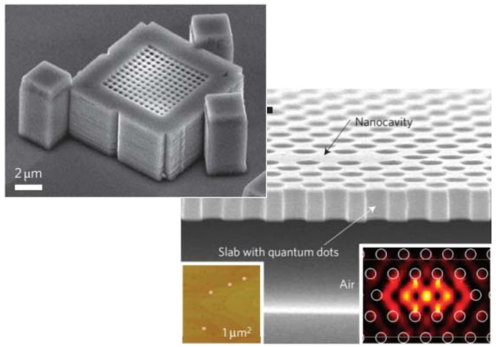
QD lasers



Y. Arakawa and H. Sakaki, APL **40**, 939(1982

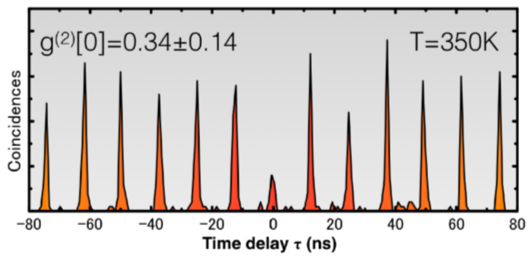
QD-based cavity QED lasers

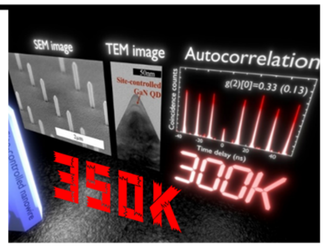




M. Nomura *et al*. Nat. Phys. **6**, 279 (2010).
K. Aoki *et al*. , Nat. Photon **2**, 243 (2007).
A. Tandaechanurat *et al*. , Nat. Photon **5**, 91 (2010)…etc

QD single photon sources

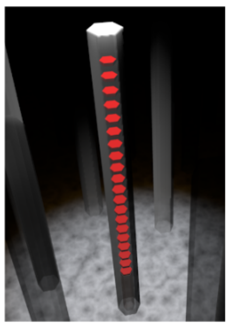


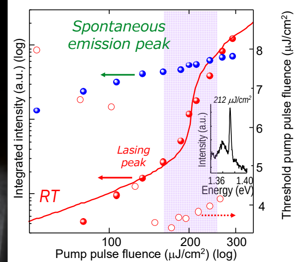


S. Kako et al., Nat. Mater. **5**, 887 (2006).
M. Holmes et al., Nano Lett. **14**, 982 (2014).
M. Holmes et al., ACS Photonics. **3** 543 (2016).. etc

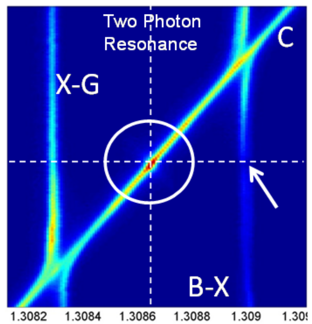
Novel QD light sources

Nanowire lasers





Two photon emitters



Y. Ota *et al*. PRL **107**, 233602 (2011).
J. Tatebayashi *et al*., Nat. Photon.**10**.1038 (2015)…etc

Outline

- Historical overview of quantum dot laser research
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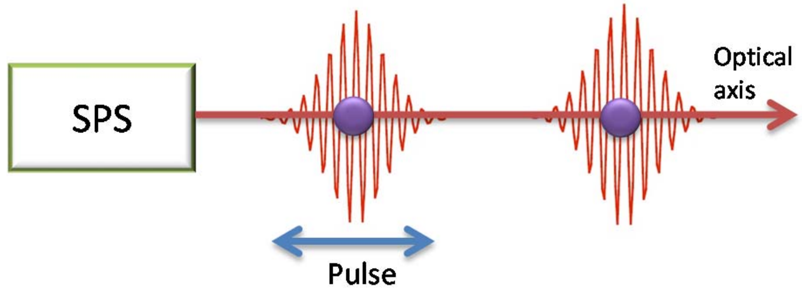
Single photon emission from QDs

Single photon emission using QD

- InAs/GaAs QD wavelength 855 nm [USA (2002)]
- GaAs/AlGaAs QD wavelength 738 nm [France (2003)]
- InP/GaInP QD wavelength 677 nm [Germany (2003)]



Challenging Issues

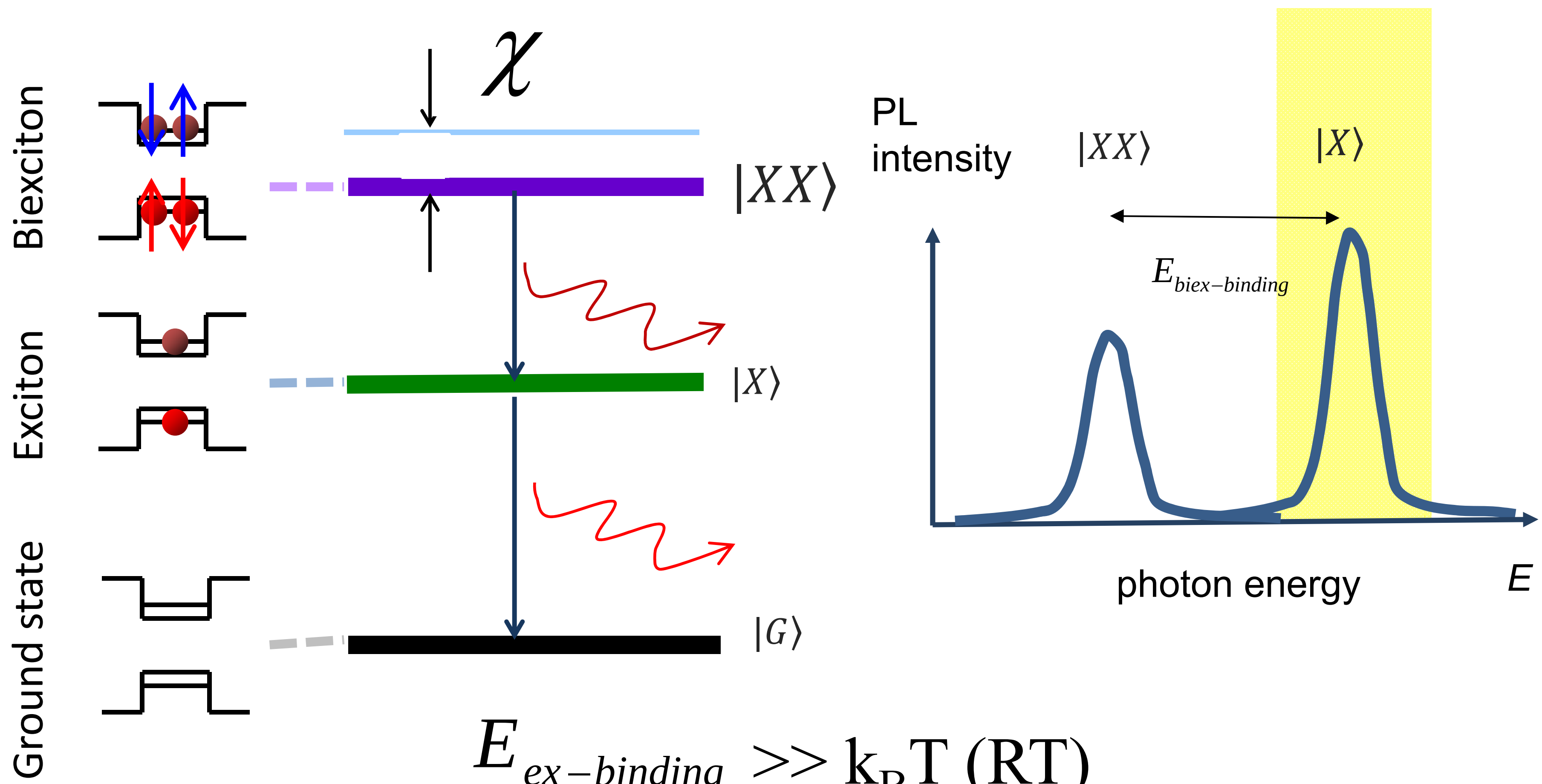
Telecom wavelength

➡ 2006 Fujitsu and U. of Tokyo

Higher temperature operation

➡ GaN QDs with a large exciton binding energy

Single photon emission from QDs

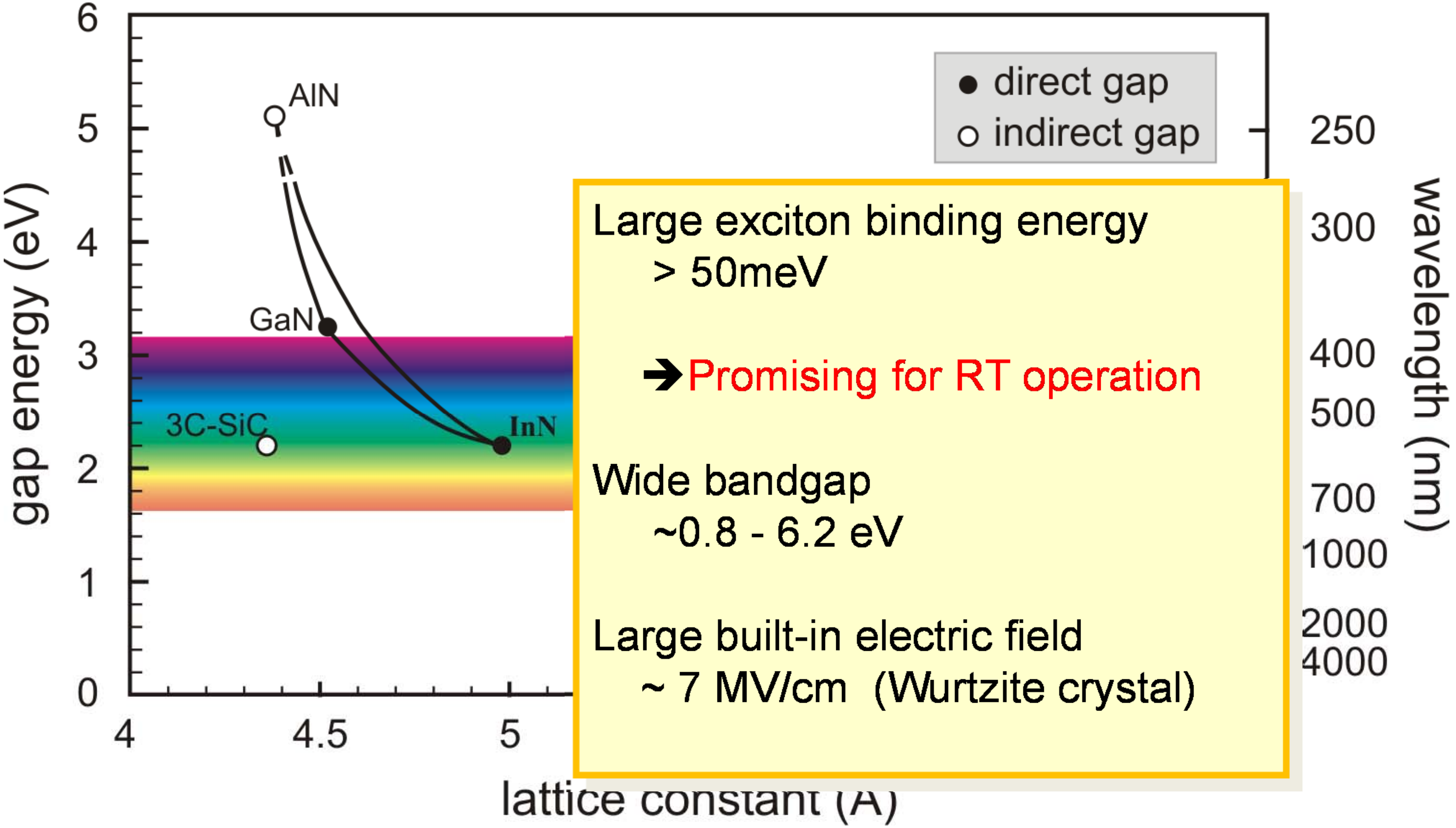


$$E_{ex-binding} >> \mathrm{k_BT\ (RT)}$$

$$E_{biex-binding}\ \mathrm{(InAs\ QD)} \sim 2\text{-}3\ \mathrm{meV} << \mathrm{k_BT\ (RT)}$$

Room temperature operation is impossible.

III-Nitride semiconductor



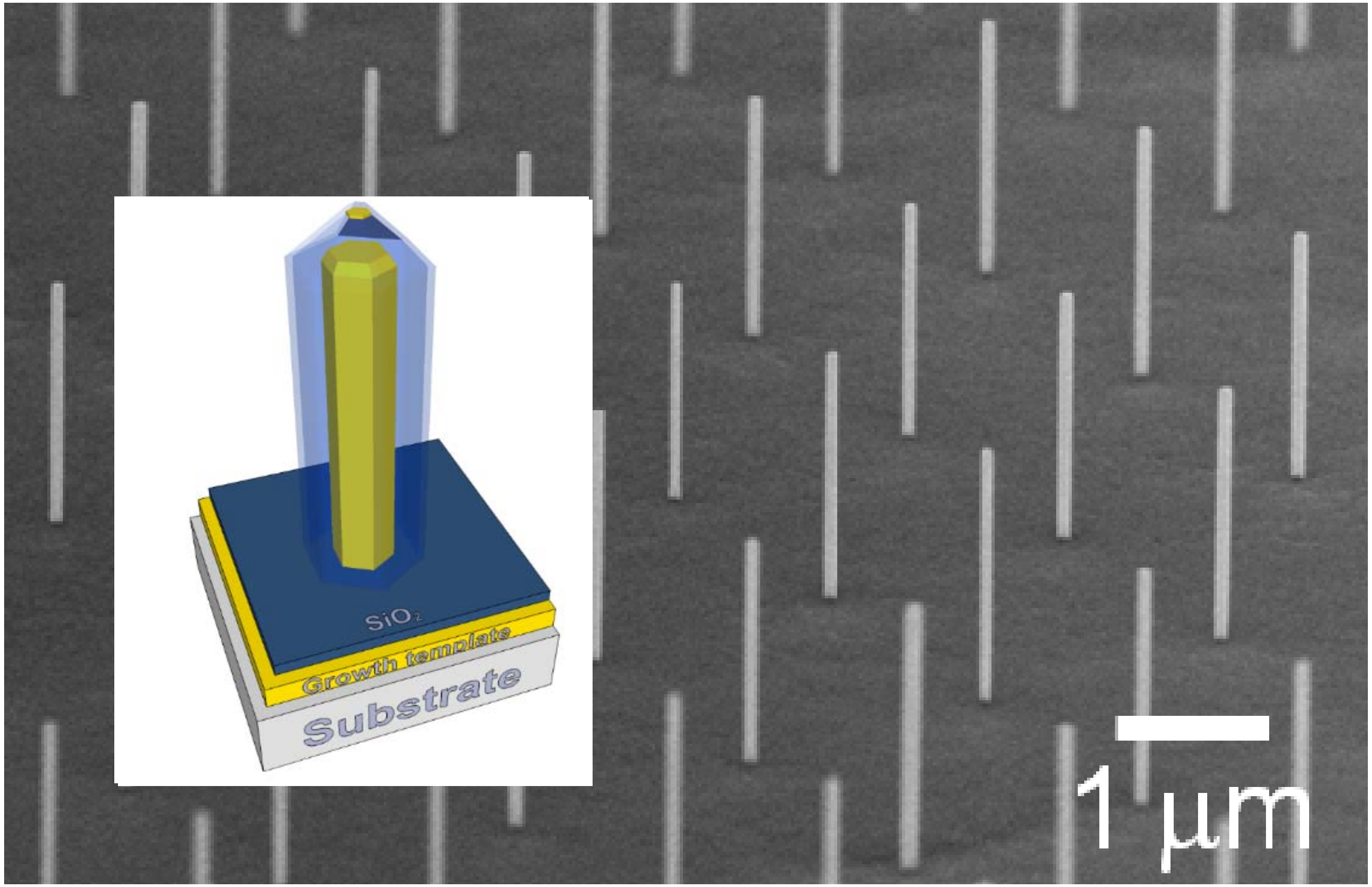
Large exciton binding energy
> 50meV

➔ Promising for RT operation

Wide bandgap
~0.8 - 6.2 eV

Large built-in electric field
~ 7 MV/cm (Wurtzite crystal)

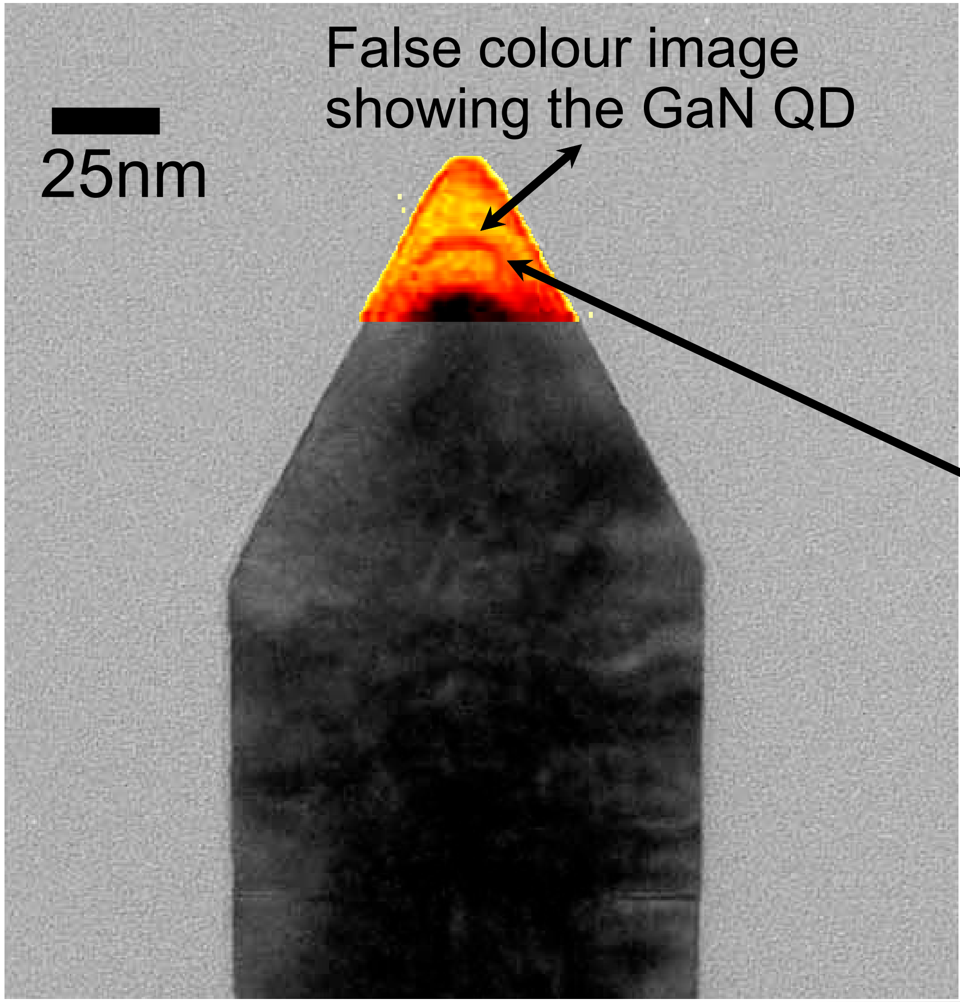
GaN nanowires

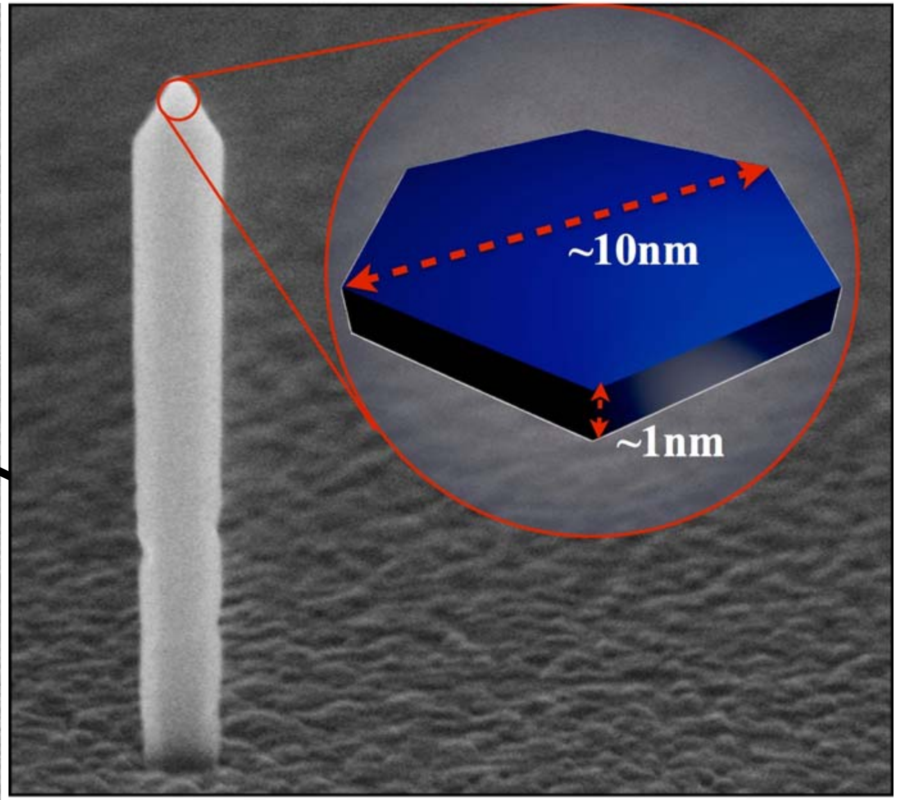


Diameter ~ 50nm

Site-controlled GaN nanowire quantum dot

TEM micrograph

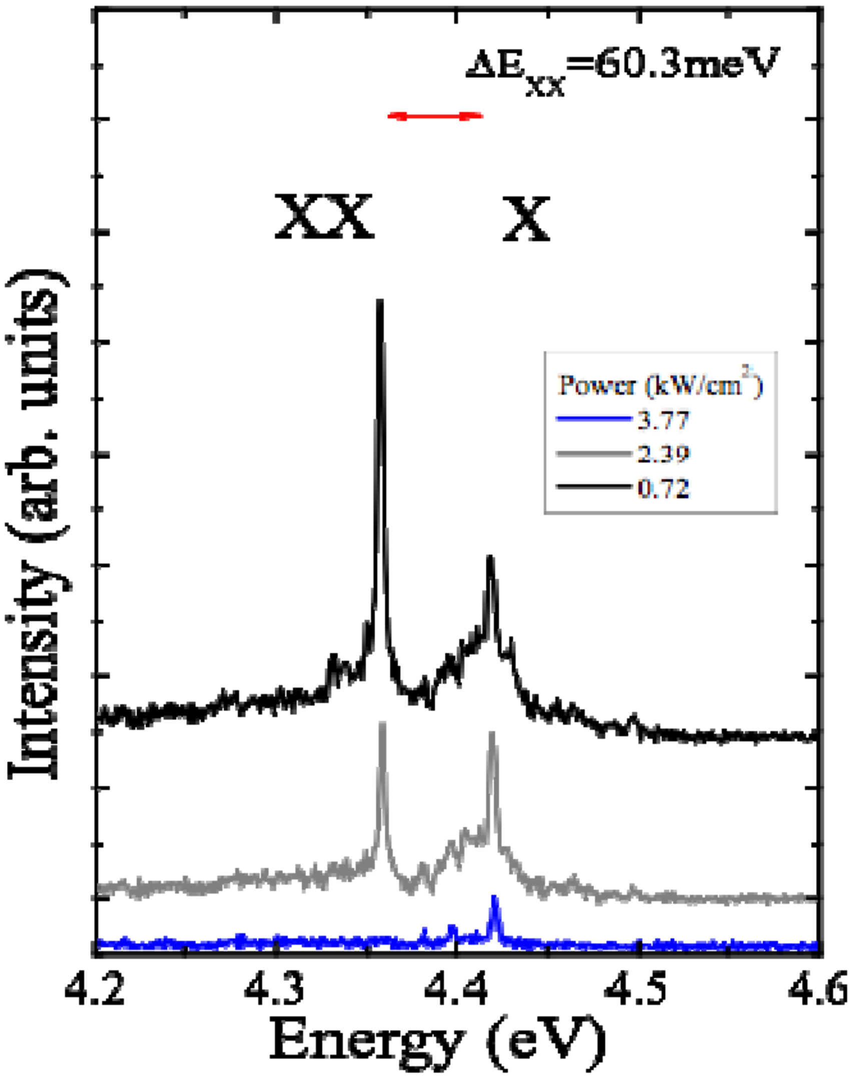


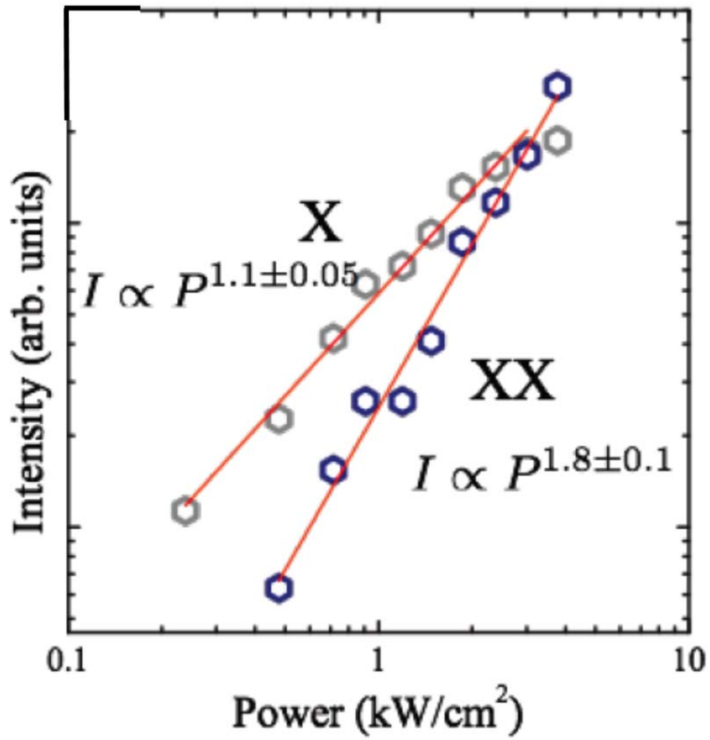


SEM image scale: 500nm

hexagonal disk shape

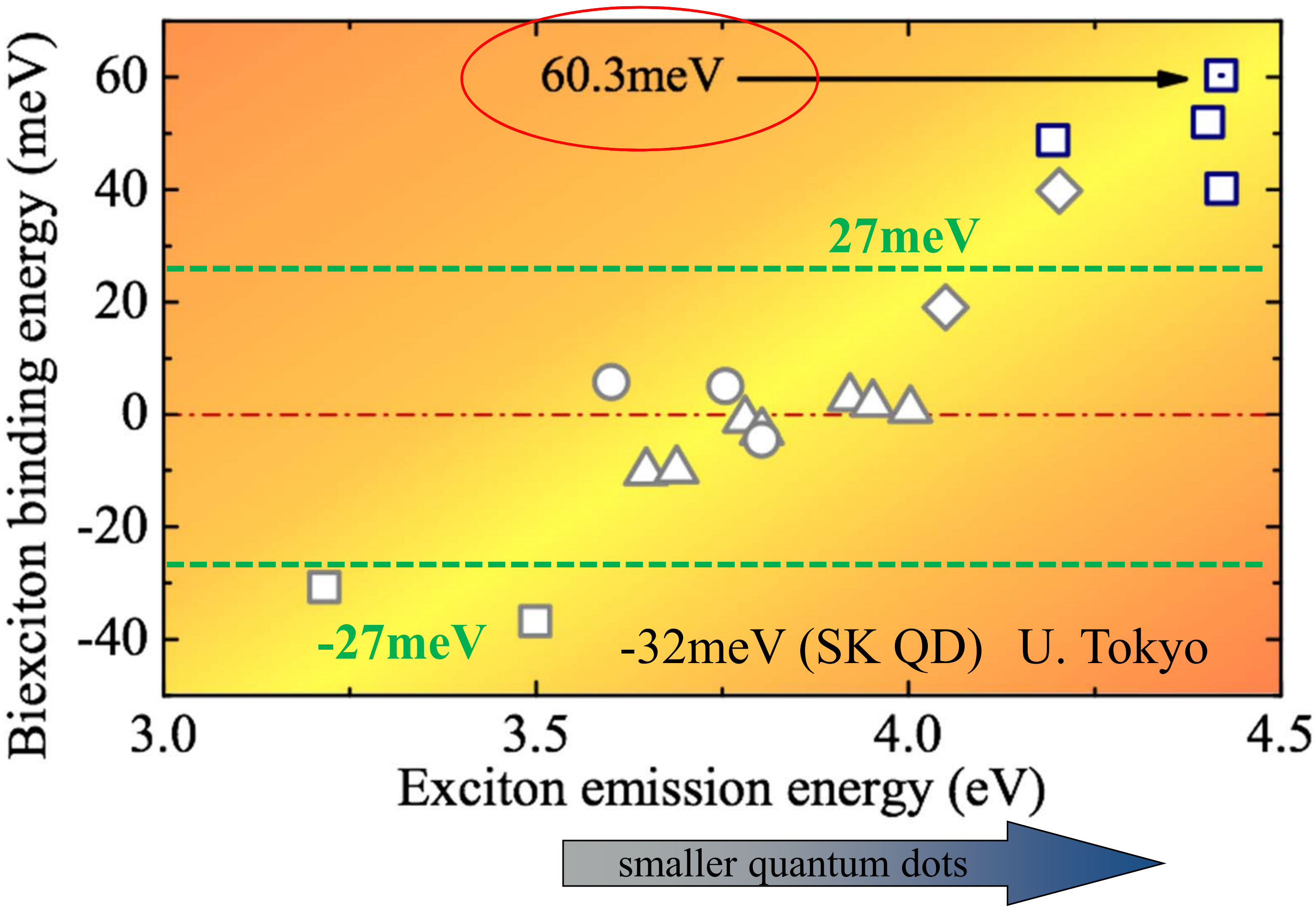
Giant biexciton binding energy





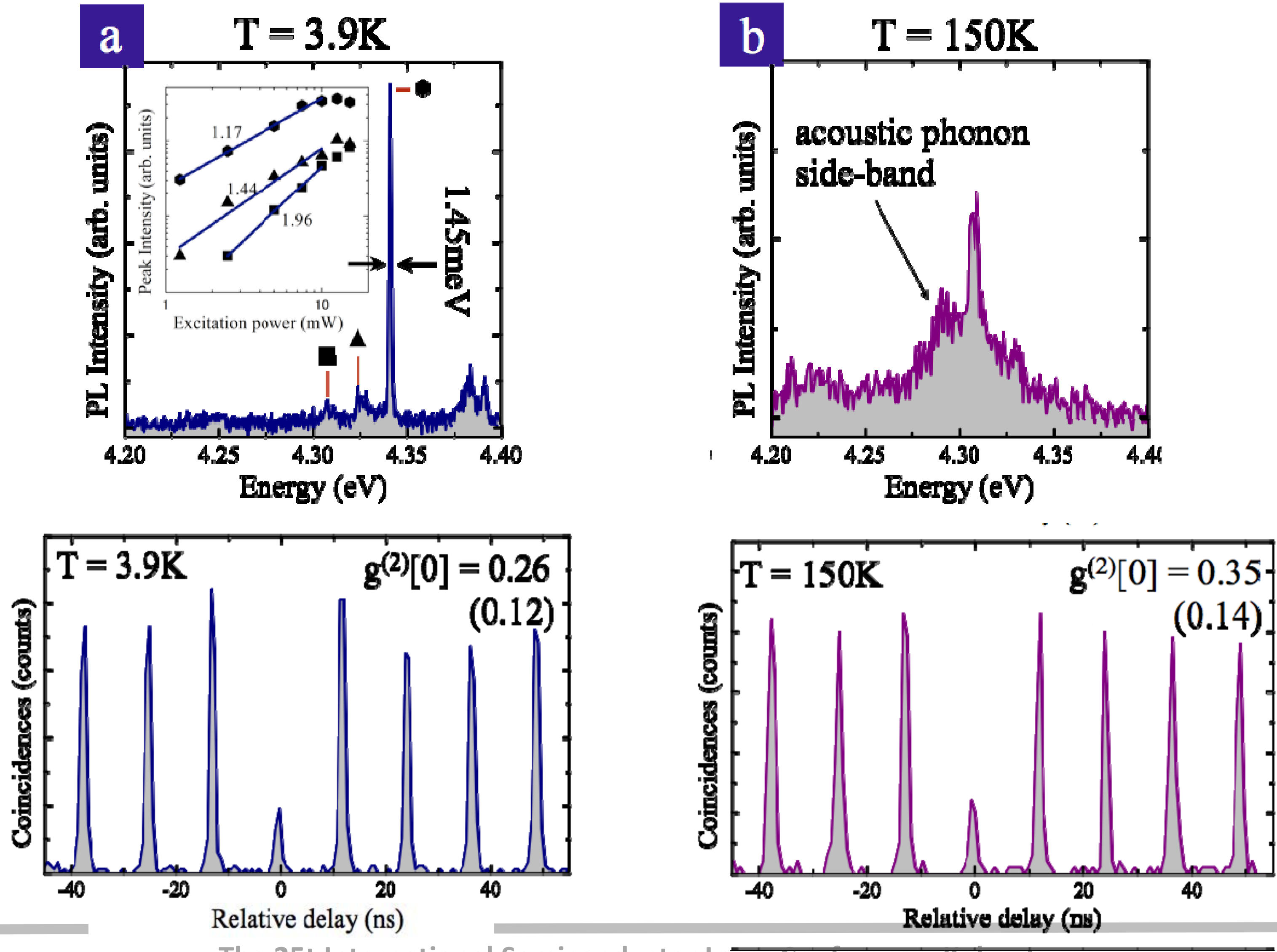
- **60.3meV** is the largest binding energy for a single semiconductor QD.
- We can expect that X and XX emission peaks remain separated, even at high temperatures.

Biexciton biding energy of quantum dots

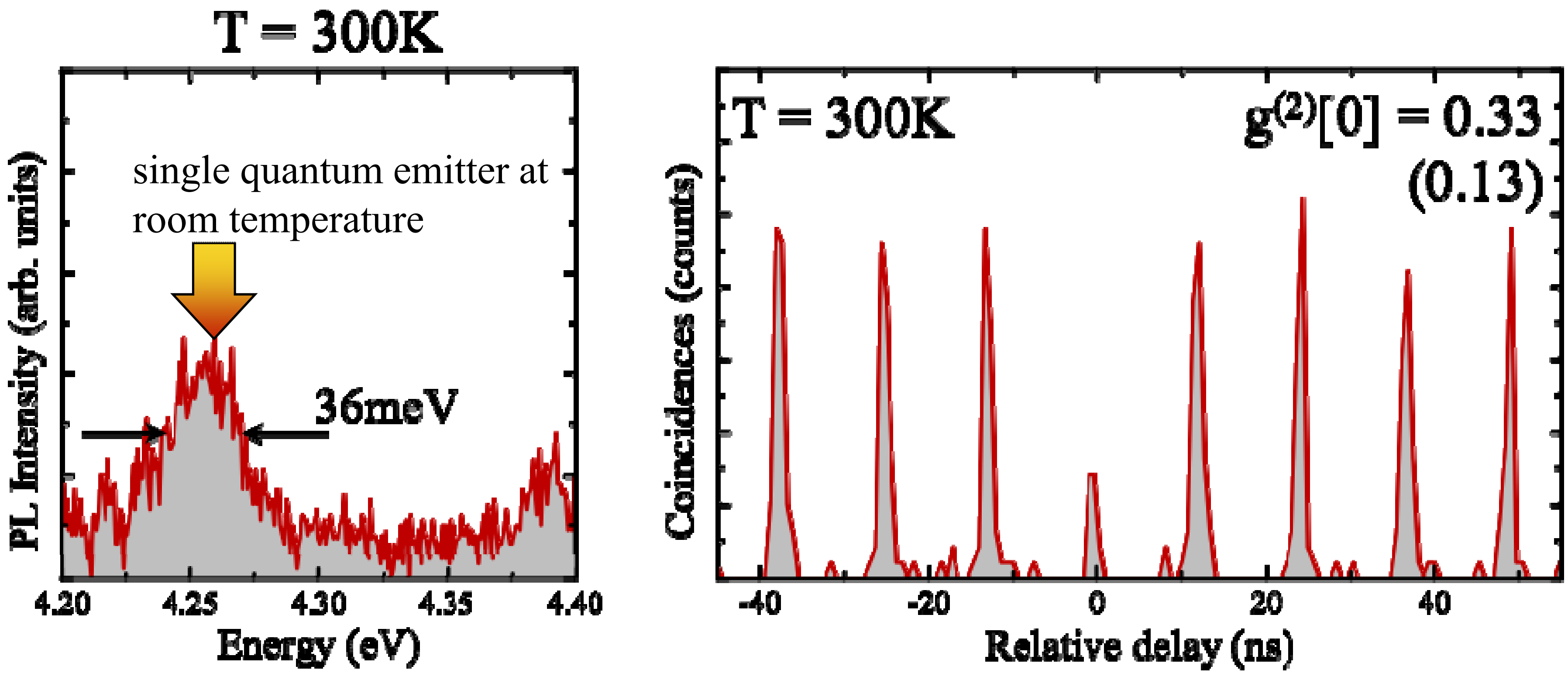


Following the trend in the literature for GaN QDs [Complex interplay of strain, internal field, configuration and Coulomb interactions].

Temperature dependence of emission spectrum



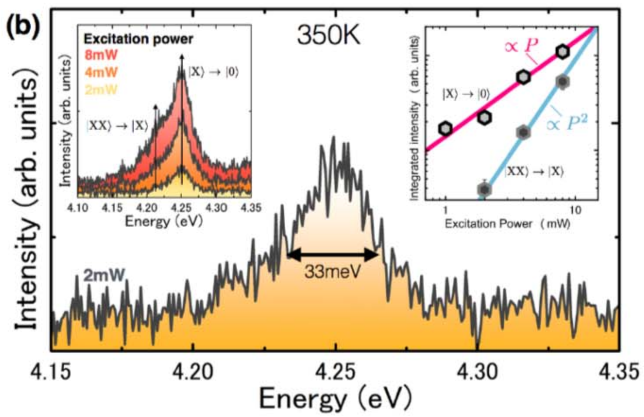
Single photon emission at 300K

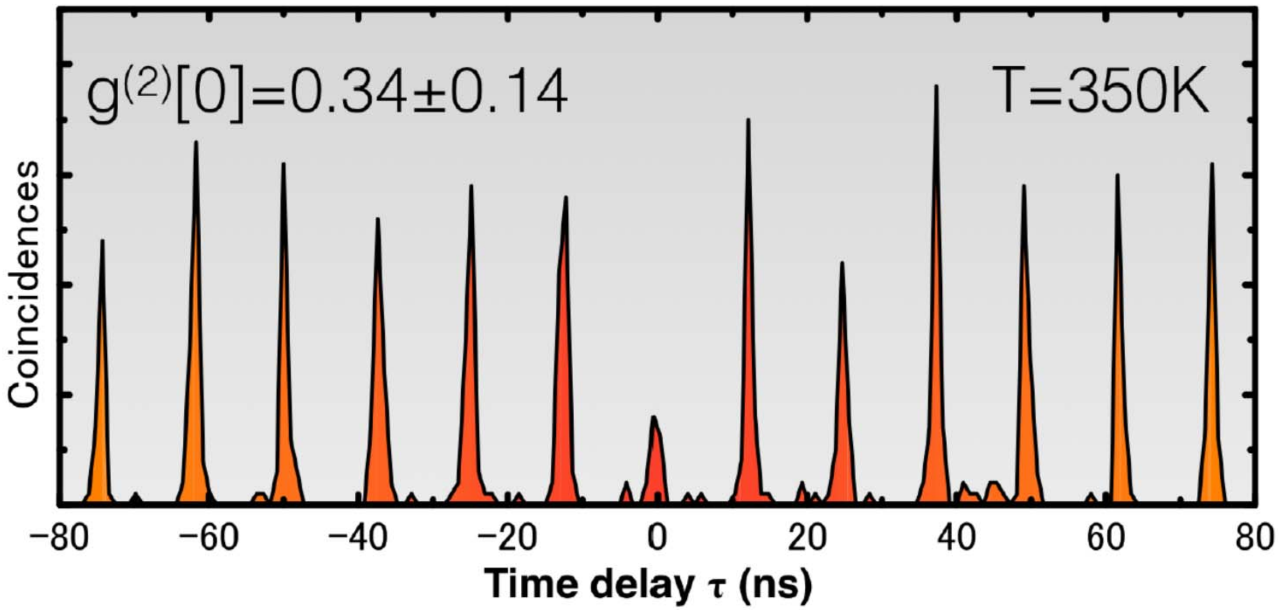


M. Holmes, K. Choi, S. Kako, M. Arita, and Y. Arakawa *Nano Lett.* **14,** 982 (2014)

NANO LETTERS

Single photon emission at 350K

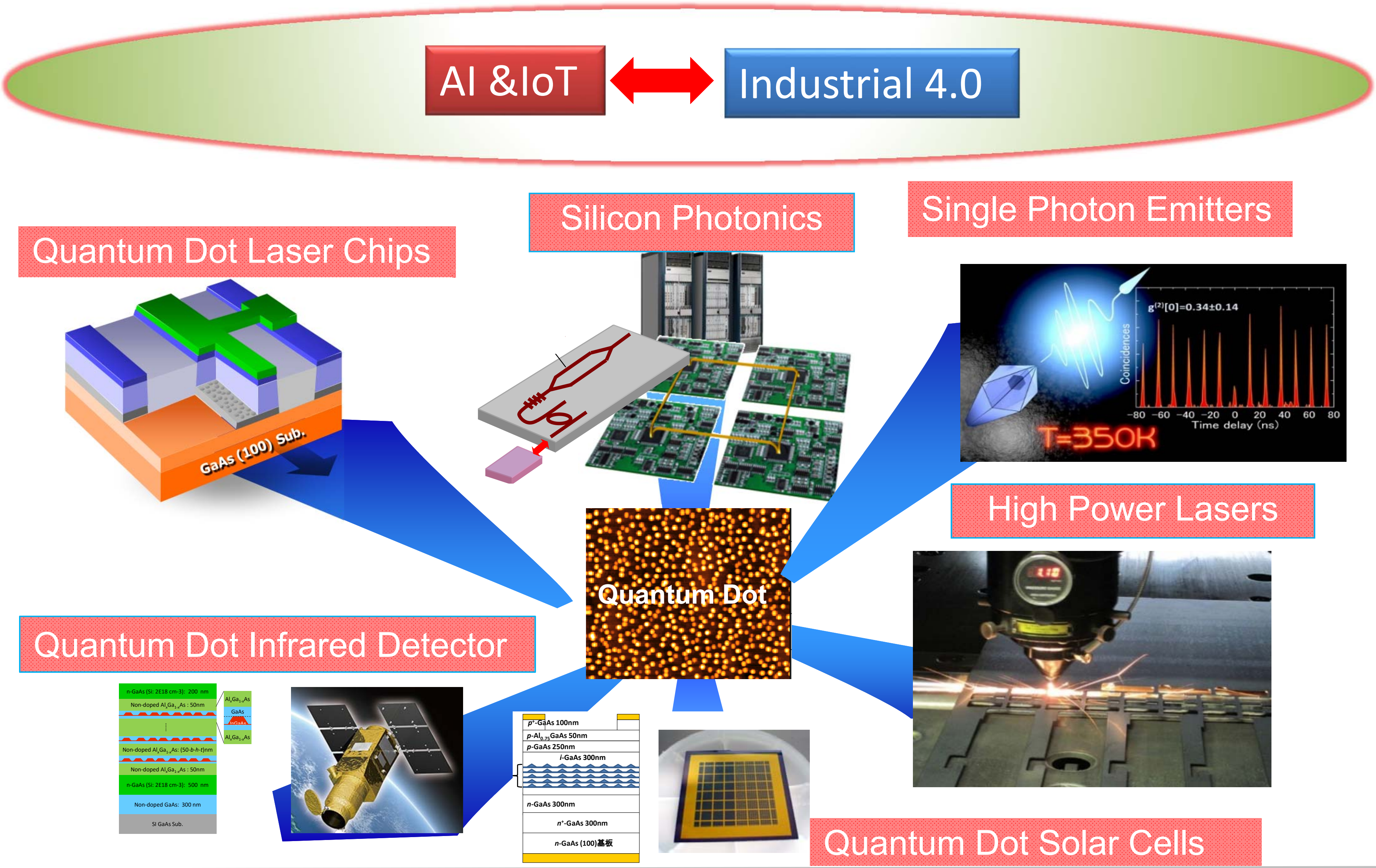




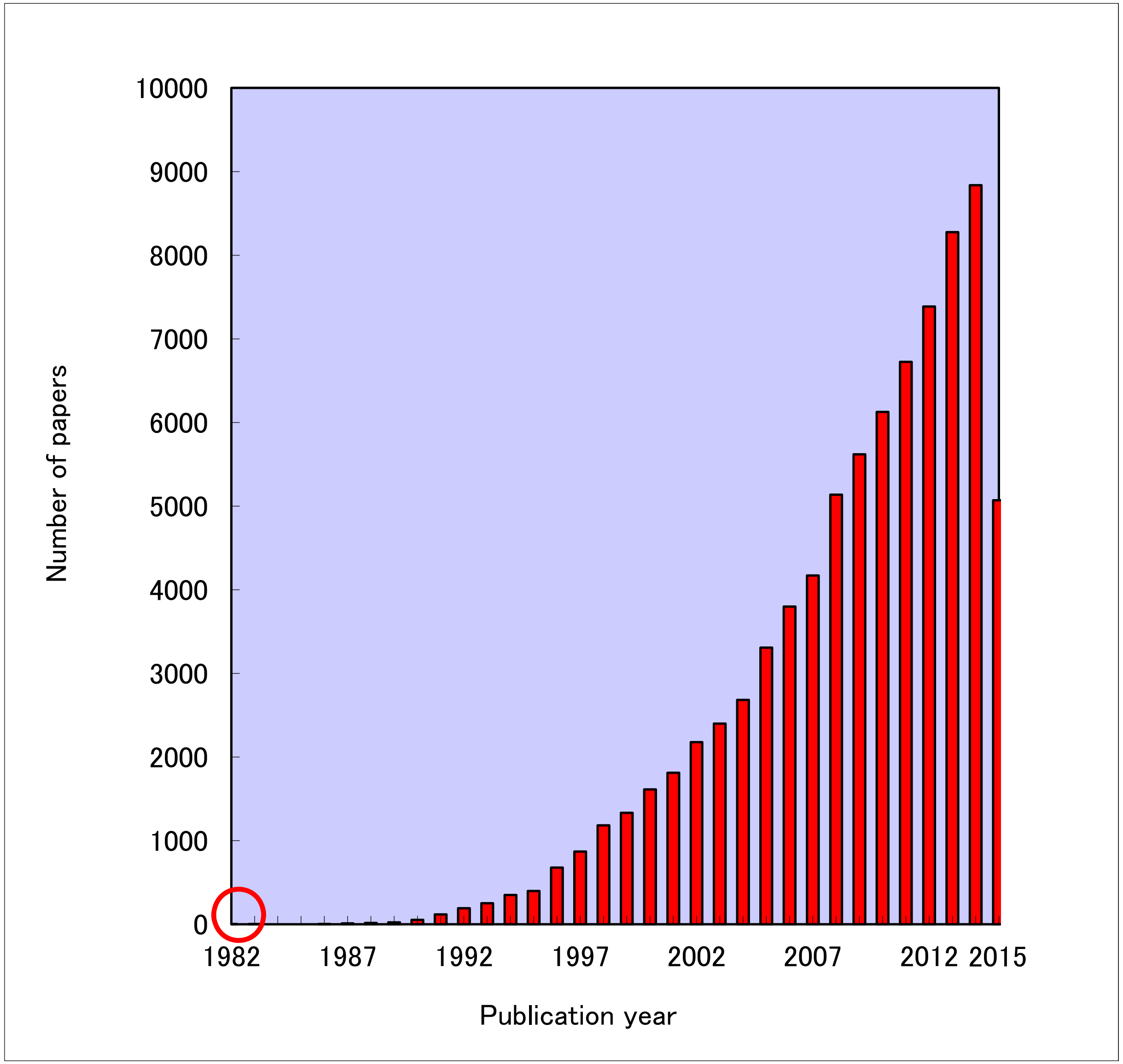
M. Holmes, K. Choi, S. Kako, M. Arita, and Y. Arakawa *ACS Photonics*. **3** 543–546 (2016)

Outlook

Evolution of quantum dot photonics



Statistics of published papers with “quantum dot”



Thank you very much for your attention !