Impact of Quantum Dot Lasers on Silicon Photonics

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The University of Tokyo

Main Collaborators:
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Mitsuru Sugawara, QD LASER Inc.

Outline

1. Overview of quantum dot lasers
2. Quantum dot lasers mounted on silicon substrate
3. Quantum dot laser array inside optical transmitter
4. Summary

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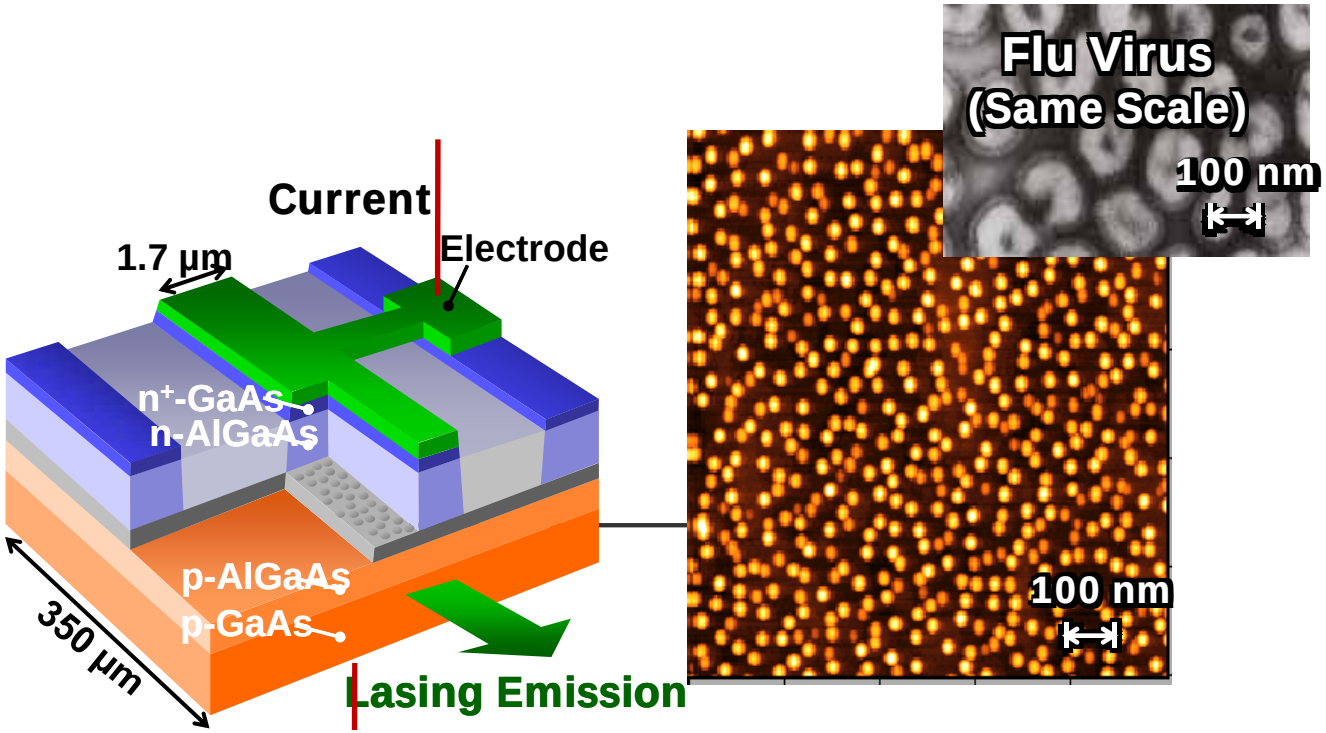
Quantum dot lasers

- High-performance semiconductor lasers with QD inside.
- Proposed in 1982.
- Self-assembled InAs/GaAs QDs emitting light of 1.3 μm in 1995.
- High density, multilayer, and uniform quantum dot ensemble
- Under mass production for optical communication by QD LASER Inc.
  - 2.5 million packages and chips shipped to commercial market



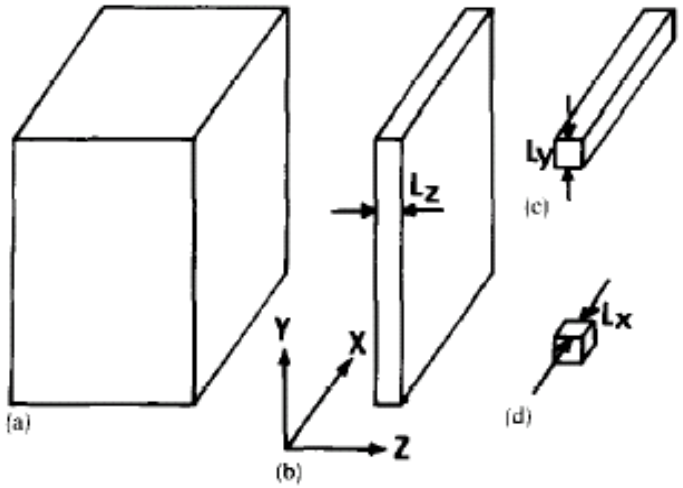
Quantum dot

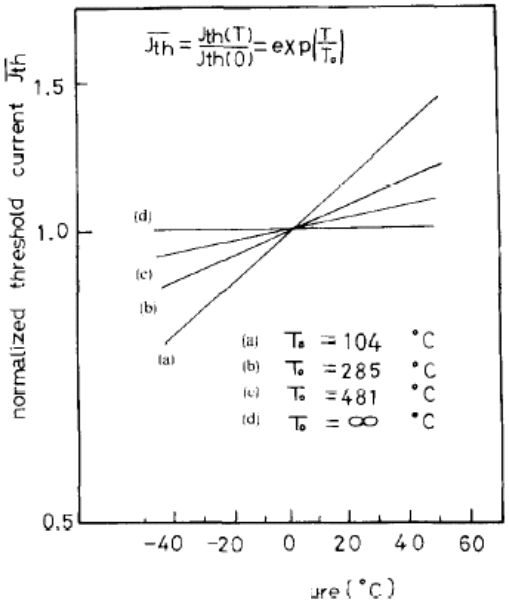
939 Appl. Phys. Lett. **40**(11), 1 June 1982 0003-6951/82/110939–03$01.00

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)

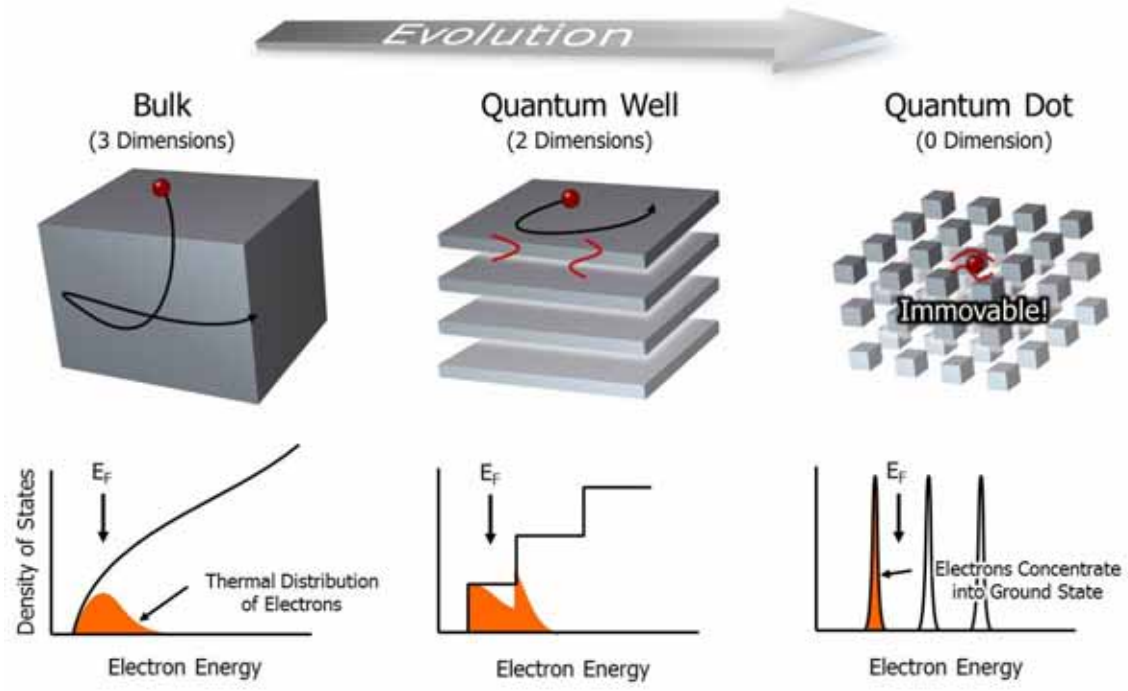




Cited more than 2,500 times

Calculated temperature dependence of normalized threshold current for bulk, QW, QWR and QD lasers near RT.

Research on quantum dot laser at early stage

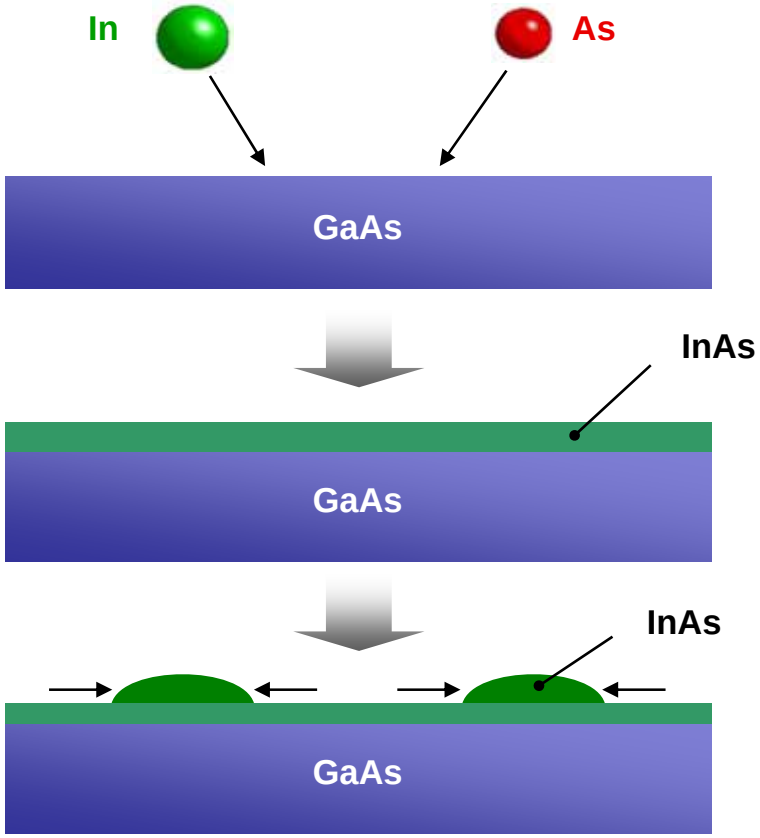


Theoretical work

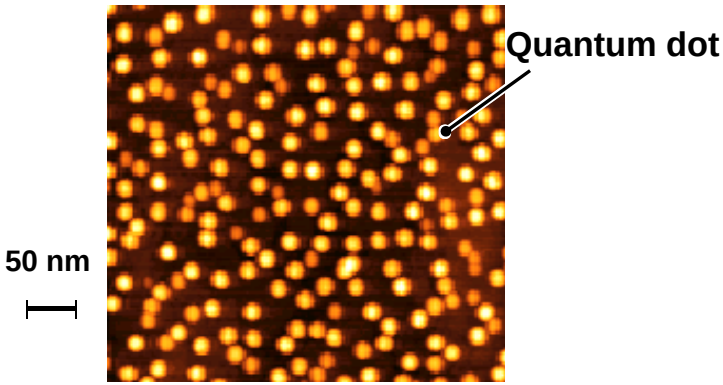
• The first proposal :	Arakawa, Sakaki (1982)
• Reduced temperature dependence:	Arakawa, Sakaki (1982)
• Enhanced differential gain:	Arakawa, Yariv (1984)
• Zero-α-parameter, low-chirping :	Arakawa, Yariv (1984)
• Lower threshold current density :	Asada, Suematsu (1986)
• p-doping:	Arakawa (1982, 1991)
• Tunneling injection:	Arakawa (1992)

Self-Assembled InAs Quantum Dots by MBE

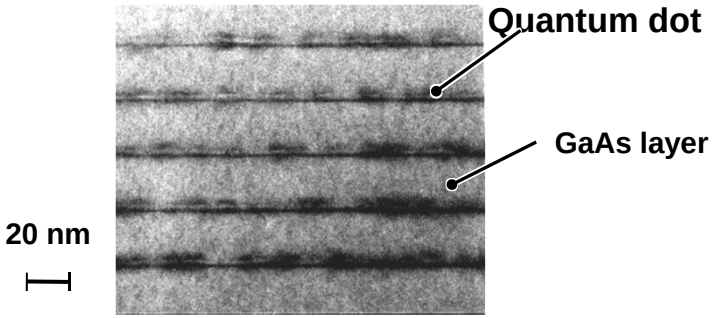
InAs islands on GaAs substrate under highly-strained epitaxy



Surface

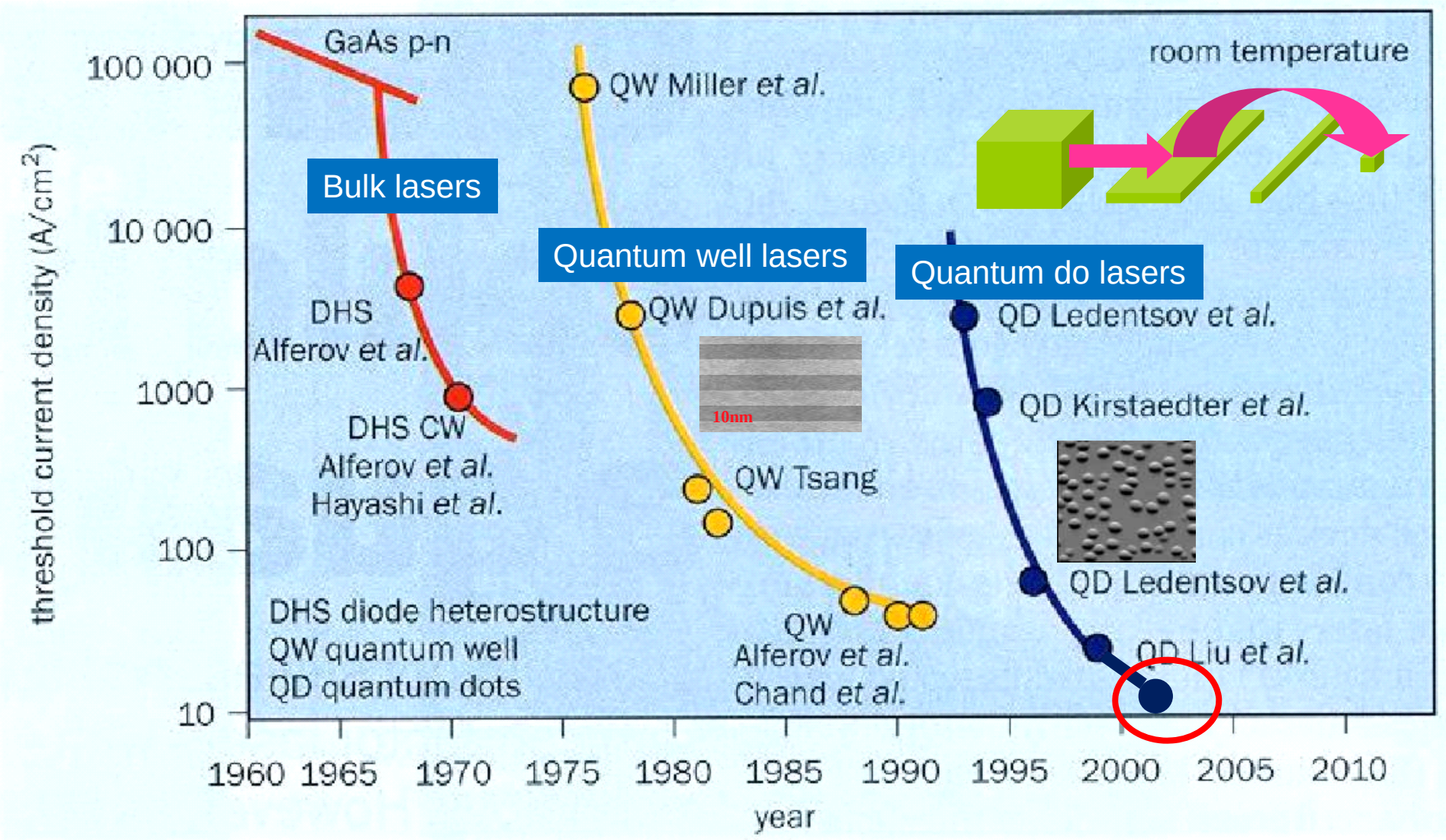


Cross section (multilayer)



By covering the islands with GaAs, we can repeat the growth to have multilayer QDs.

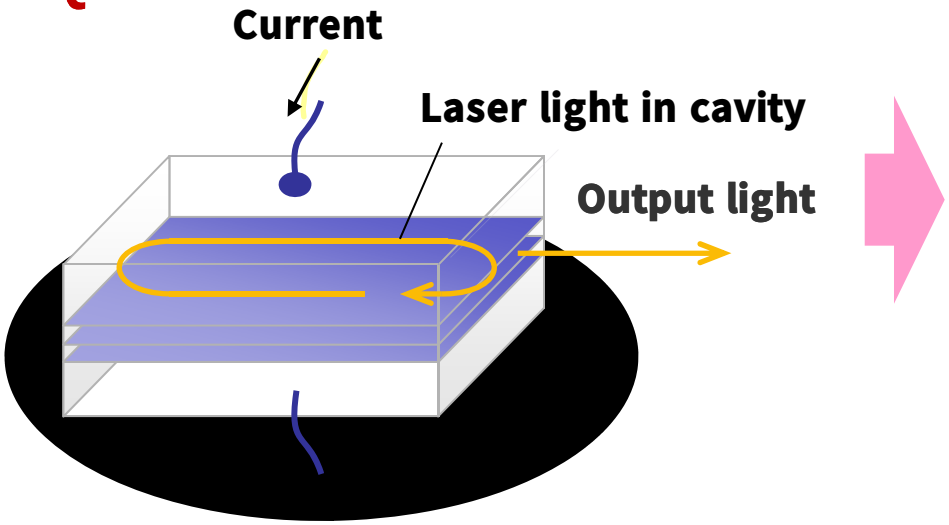
Evolution of semiconductor lasers

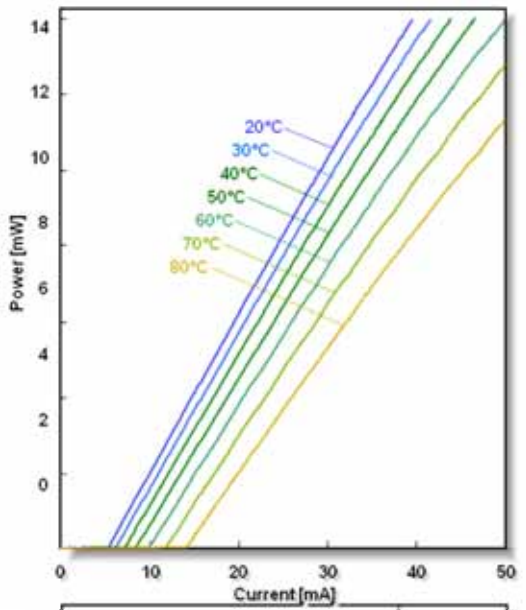


Ref. Opto & Laser Europe

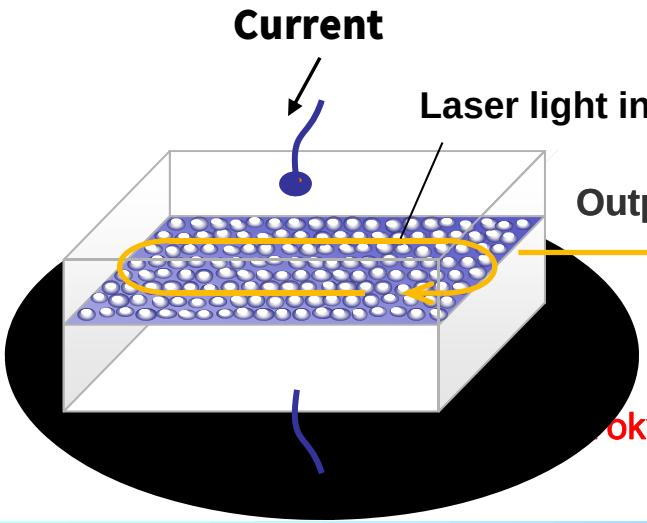
A technical breakthrough in quantum dot lasers

Quantum well laser

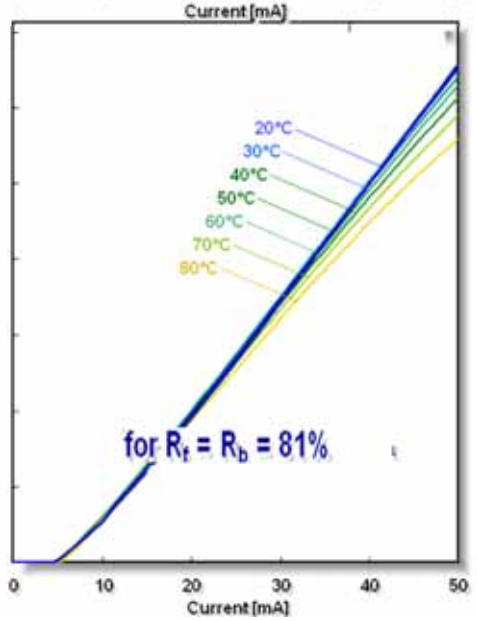




Quantum dot laser (p-doping)

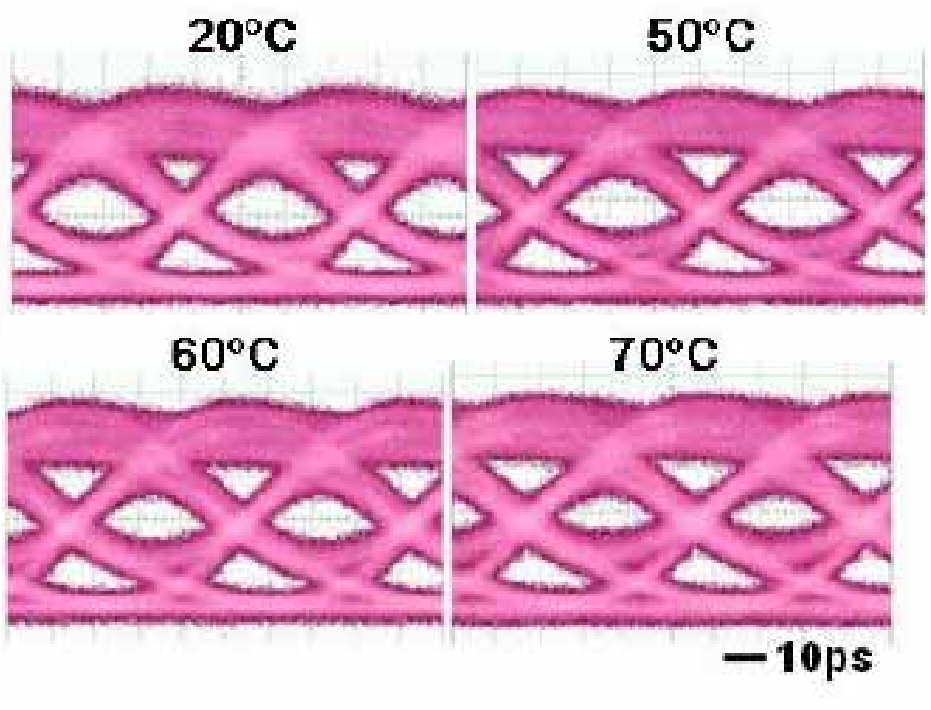


okyo and Fujitsu (2004)



Temperature stability

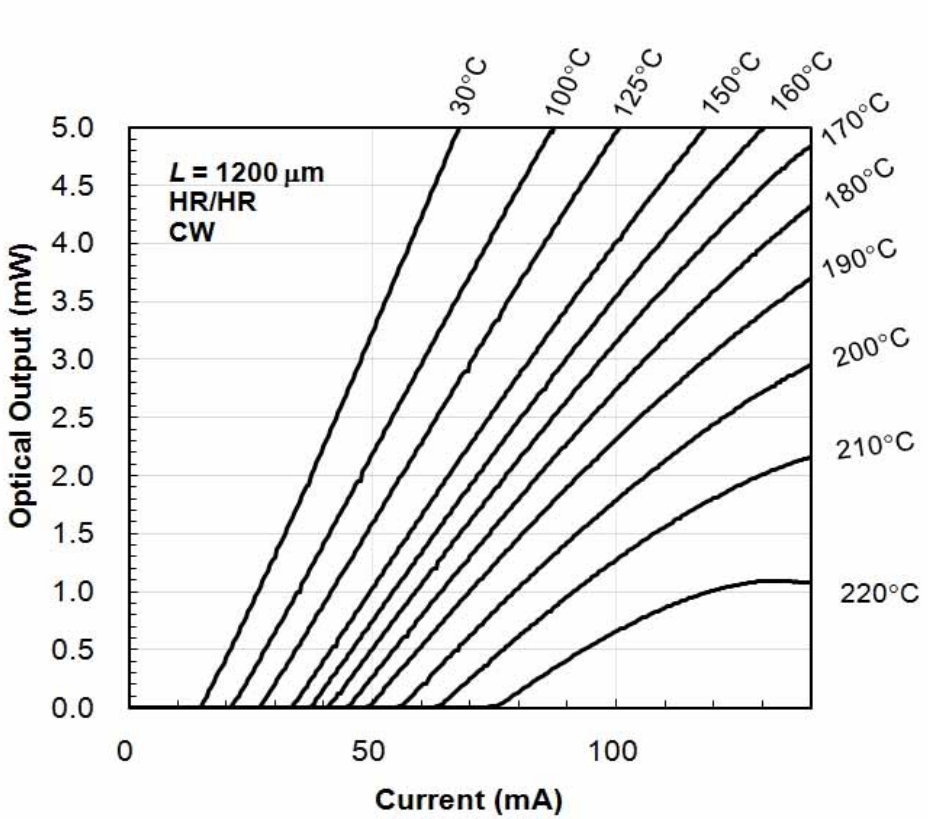
25Gbps modulation



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

M. Ishida *et al.*, CM1I, CLEO (2011)

High temperature operation



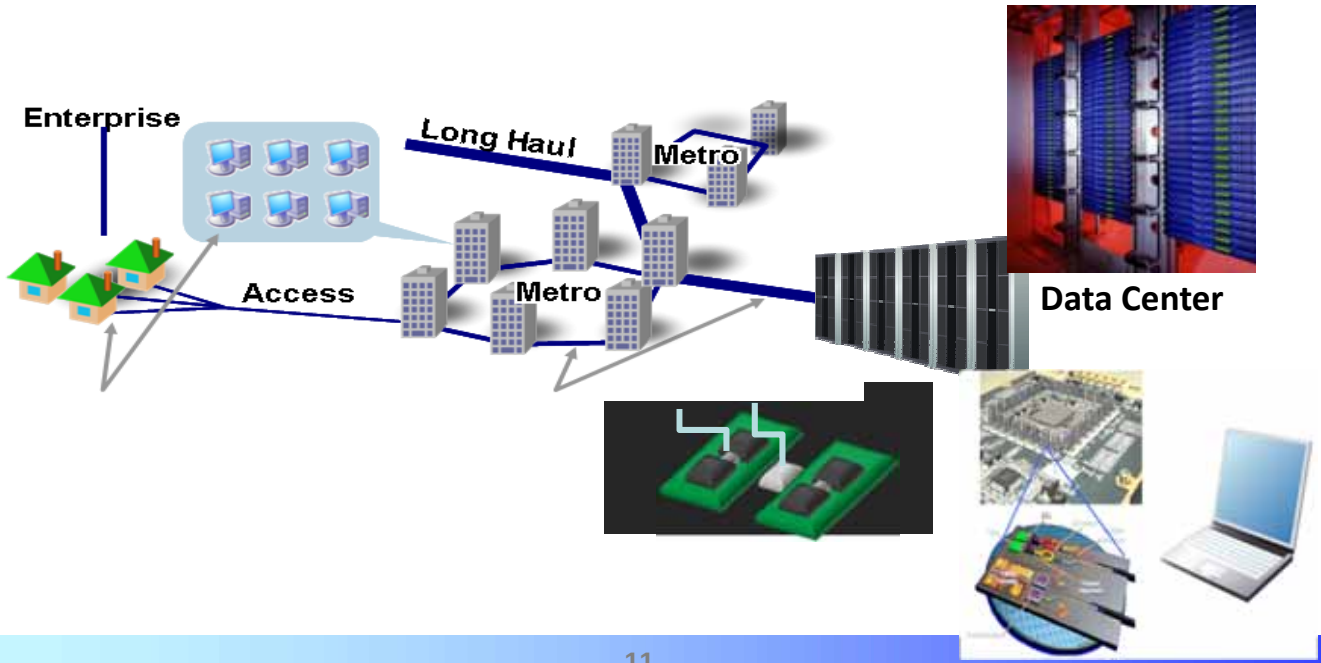
T. Kageyama *et al.*, CLEO/Europe and EQEC

Venture company: QD LASER Inc.

- Founded in April, 2006
- Spin-off from Fujitsu Laboratory
- Joint research collaboration with Univ. of Tokyo
- Mass Production for optical communication, 2011
- Total 2.5 Million of FP lasers for data com., 2015

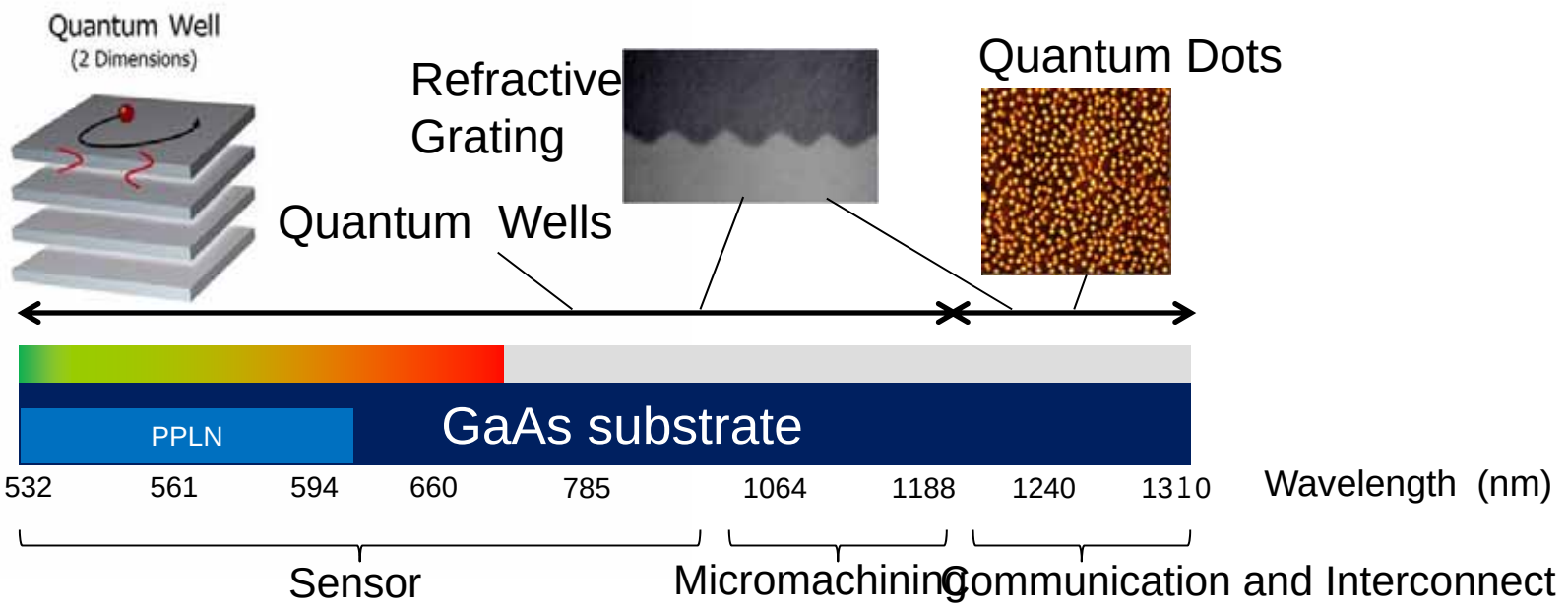
Optical Telecommunications over Fibers

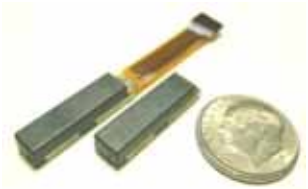
- ✓FTTH
- ✓LAN
- ✓Fiber Channel
- ✓Point to Point



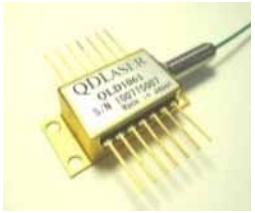
Core Technology and Products

- Core technology: Quantum dots/wells and refractive grating on GaAs
- Products : Semiconductor lasers with any wavelength on GaAs

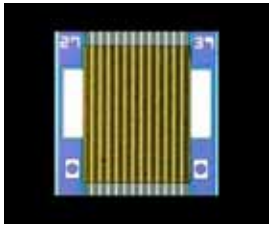




Green, yellow green, and orange laser modules



Short pulse DFB laser module



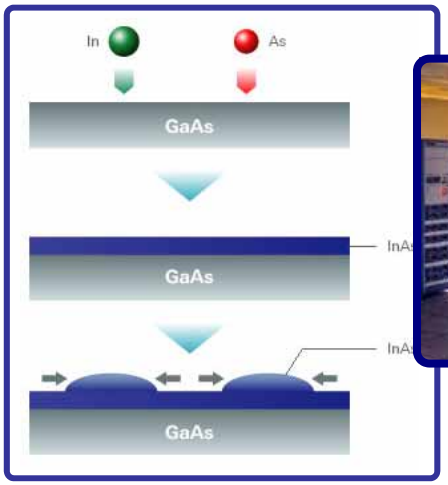
Quantum-dot laser TO can and chip array

Mass Production of GaAs-based Lasers

■Low-cost production from small to huge throughput based on horizontal specialization of processing.

QD Laser, Inc.

Inhouse state-of-the-art GaAs wafer and DFB grating technology
Quantum Dot crystals



MBE Reactors

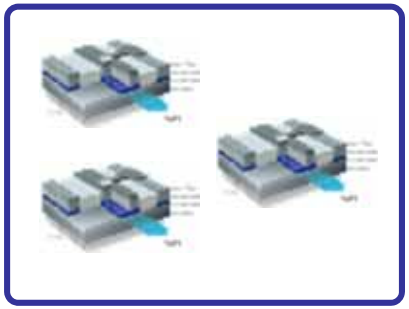
DFB Grating

GaAs QD and QW wafers

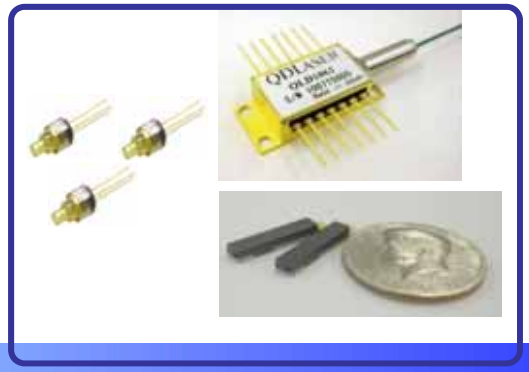
GaAs foundry / Partner

CD/DVD laser
mass production technology

Laser chips



Laser packages



Customers

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1. Overview of quantum dot lasers
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3. Quantum dot lasers inside the optical chip
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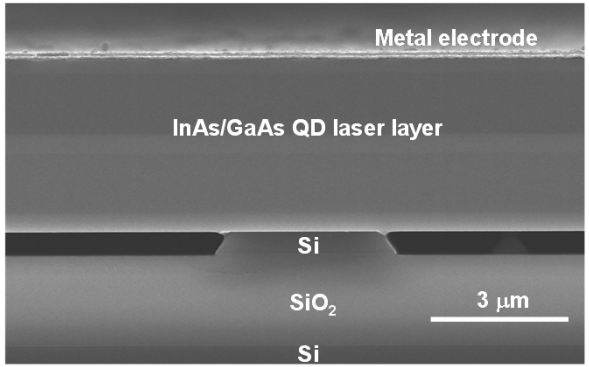
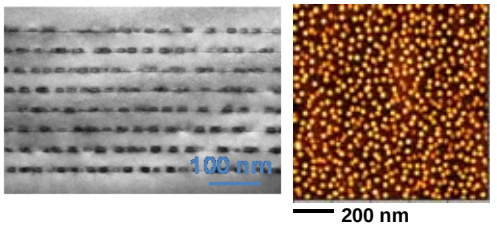
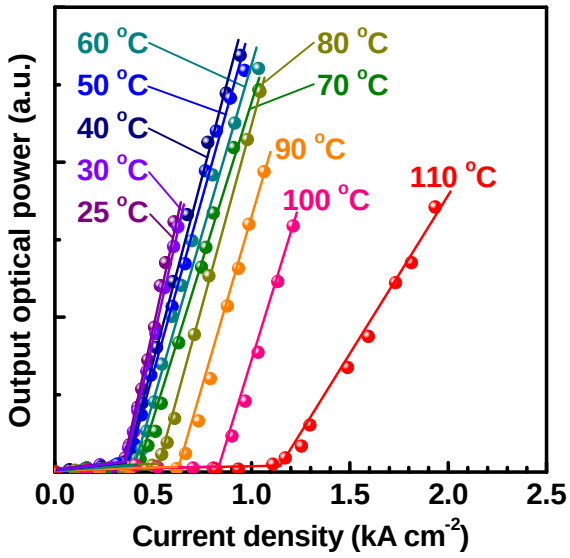
Light source engineering on silicon

- Direct silicon light sources
  - Ge lasers and LEDs
  - Si Raman lasers
  - Si-direct LEDs
  - nanocrystalline-Si LEDs
  - SiGe quantum cascade structure LEDs
- QD laser/Si hybrid integration
  - Heteroepitaxy (UCSB, Imperial College)
  - Wafer bonding and evanescent coupling (U. Tokyo)
  - Butt Joint coupling

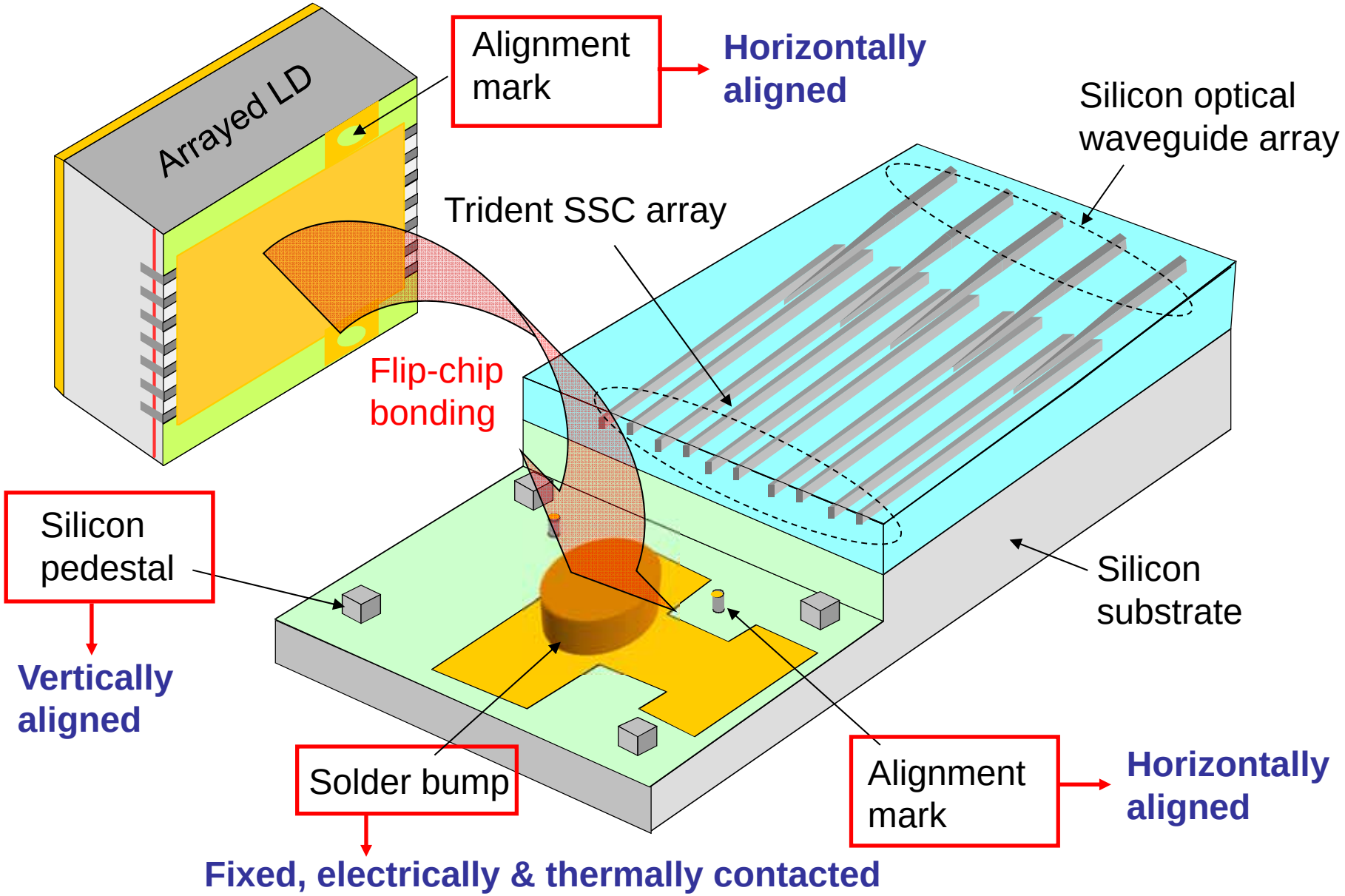




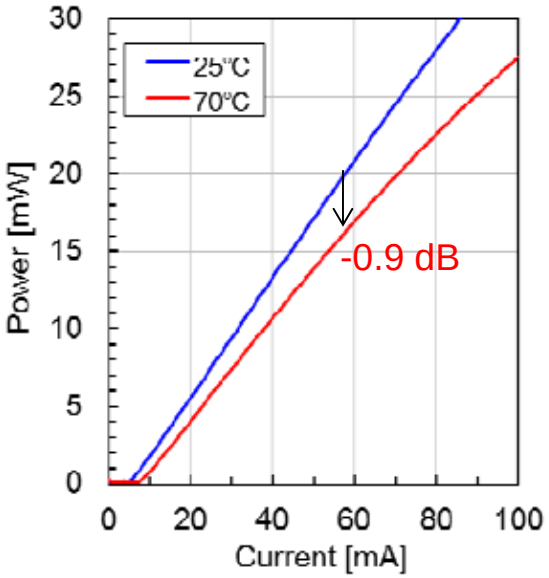


K. Tanabe and Y. Arakawa, CLEO, STh1G.6 (2014)

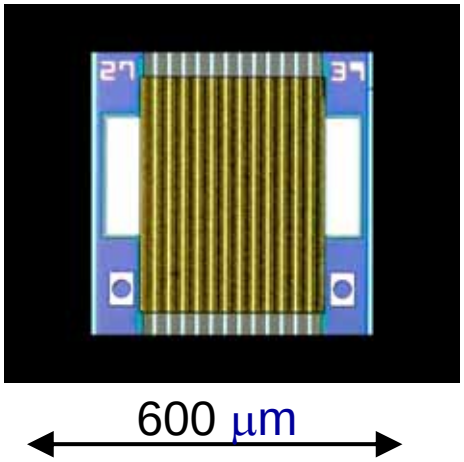
Hybrid QD laser array on silicon by flip-chip bonding



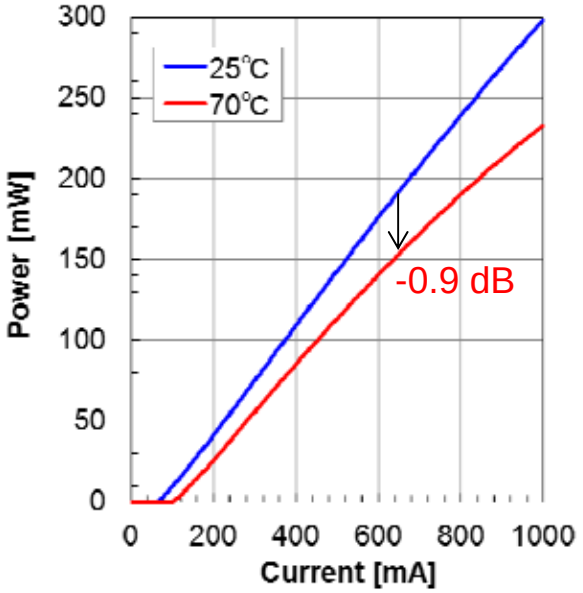
13-channel arrayed quantum dot lasers



Single-ch. QD-LD



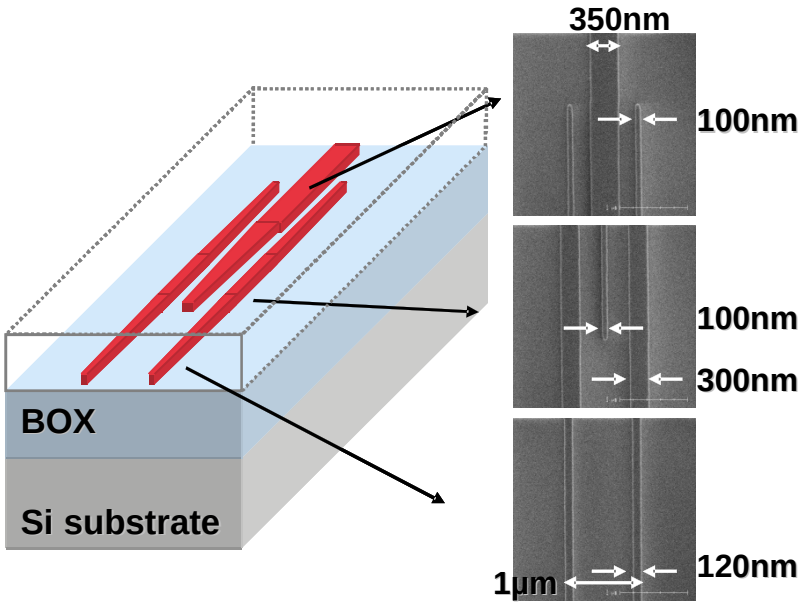
13-ch. arrayed QD-LD



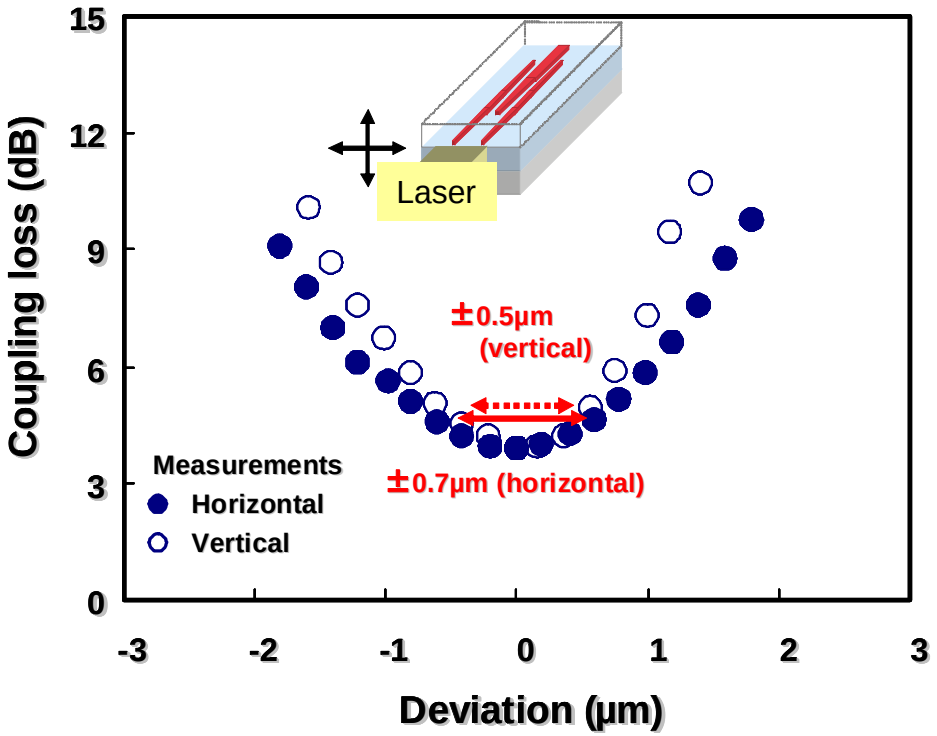
I-L characteristics

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

Trident spot-size converters



Schematic structure and SEM images



Alignment error tolerance

- No additional fabrication process
- Low coupling loss : 3.9 dB
- High alignment tolerance : ± 0.7 μm in horizontal, ± 0.5 μm in vertical directions (Enough for our passive alignment technique)

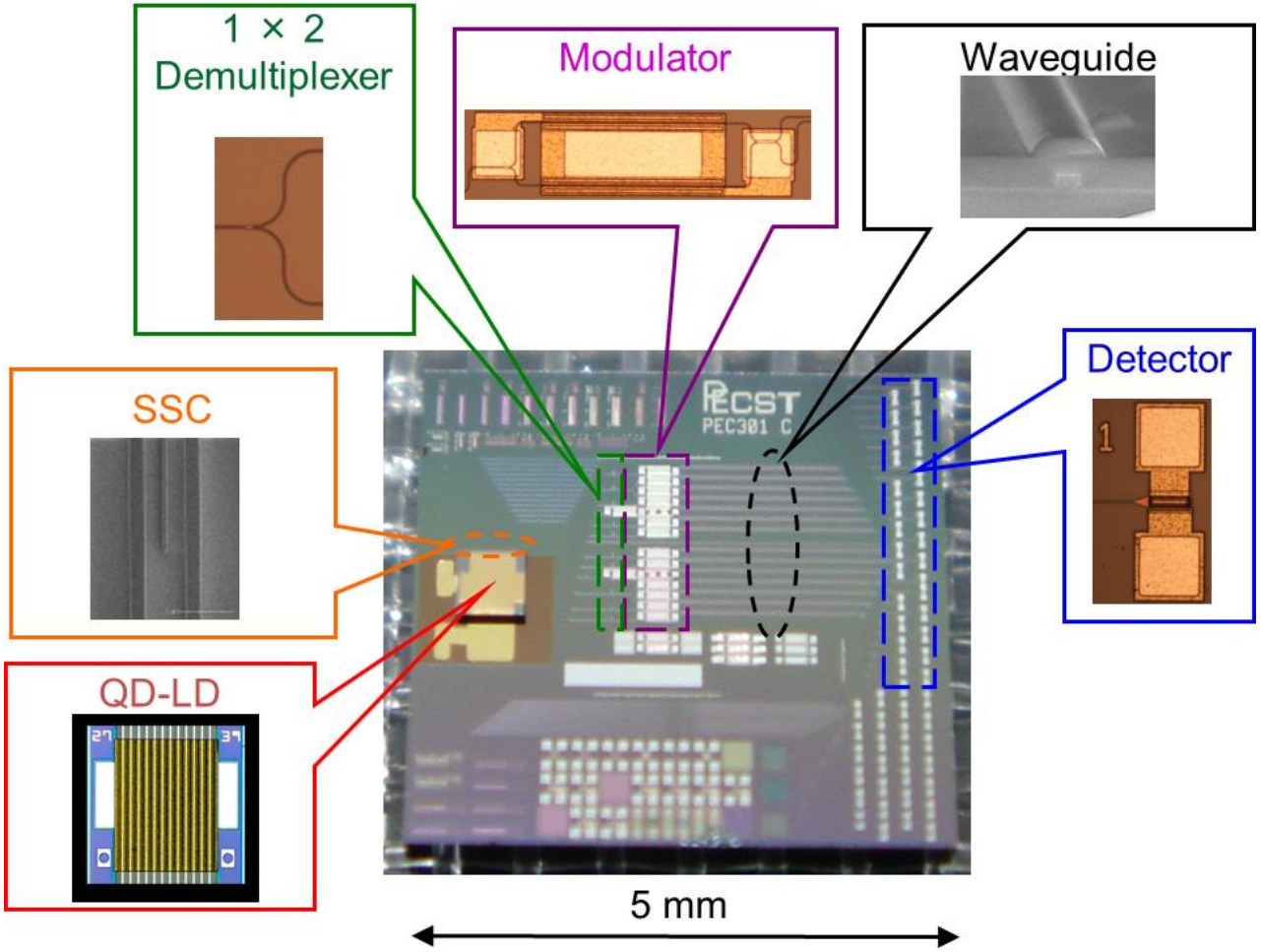
A few slides are not included in this file.

QD Silicon Hybrid Interposer

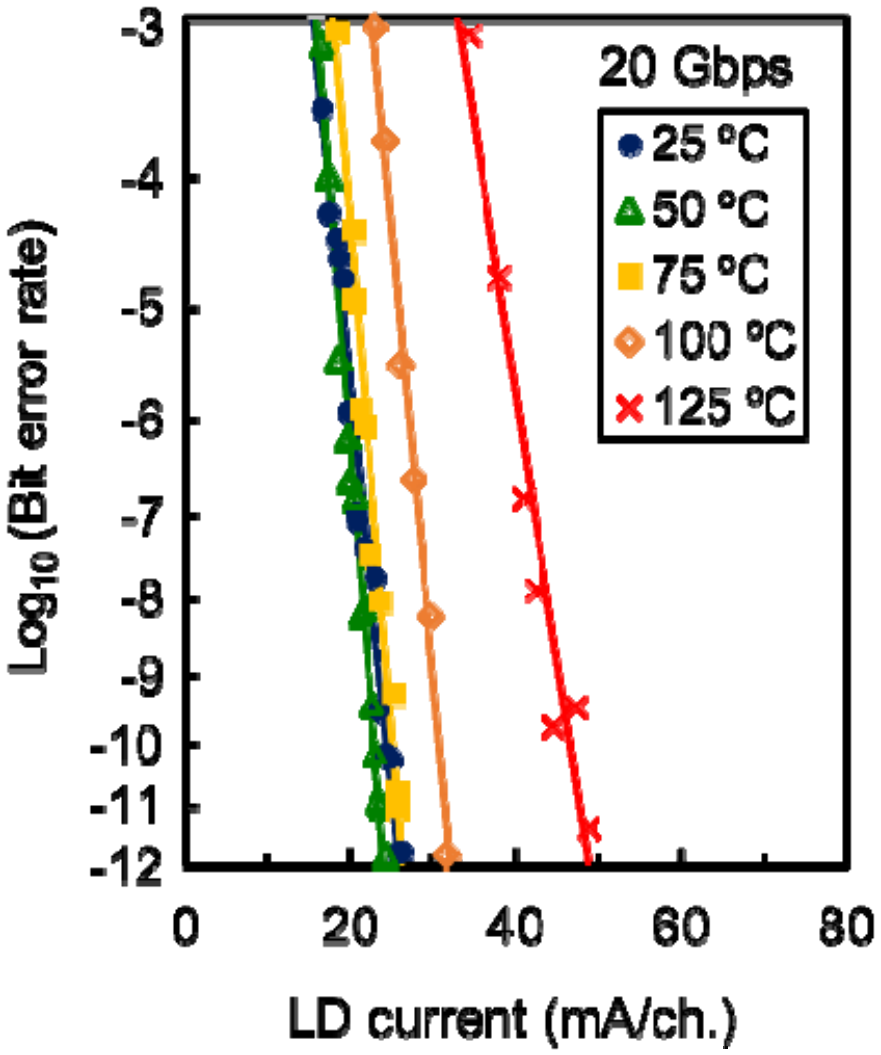
■Demonstration of high-capacity optical signal transmission on silicon

・ 20Gbps/channel, 15Tbps/cm^2 in total.

・Error free operation @ 25 to 125℃ without bias adjustment and isolator



20 Gbps data Transmission from 25 to 125 ºC



Y. Urino *et al.* Electronics Letters **50**, 1377 (2014)

Error-free data links up to 125 ºC without bias or signal adjustments

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A METI/NEDO project in Japan

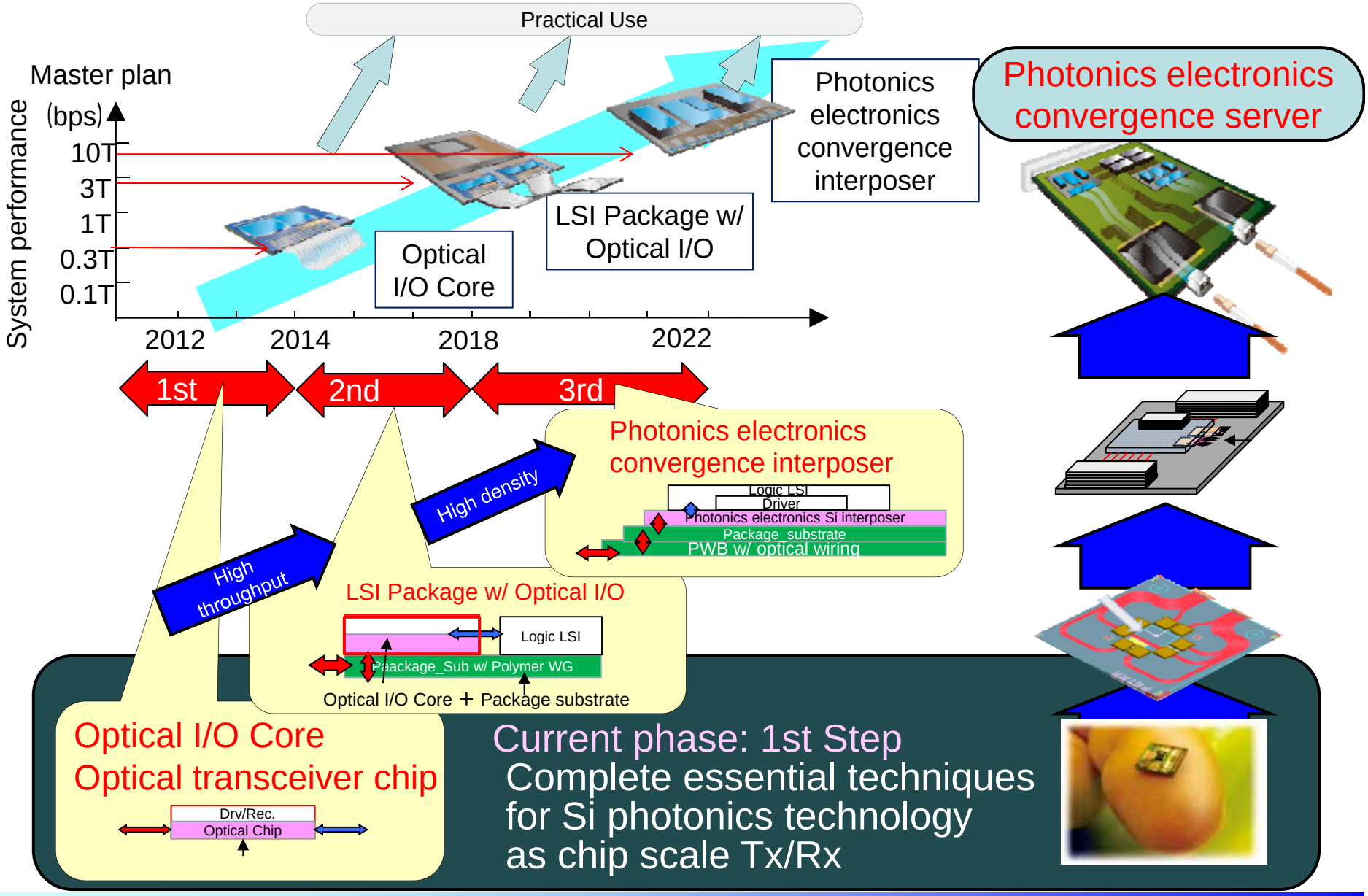
- Project Leaser: Yasuhiko Arakawa (The Univ. of Tokyo)
- Term：FY 2012～2021
- Sponsor: METI /NEDO
- Budget: ~300 Million US$ for 10 years.
- Research organization: PETRA
- Member companies:

  AIST, Fujitsu, Furukawa Electric, NEC, NEL, NTT, OITDA, OKI, Toshiba
- Academia:

  The Univ. of Tokyo, Kyoto Univ., Tokyo Institute of Technology, Yokohama National Univ., Waseda Univ.

METI: Ministry of Economics, Trade, and Industry
NEDO: New Energy Development Organization
PETRA: Photonics Electronics Technology Association

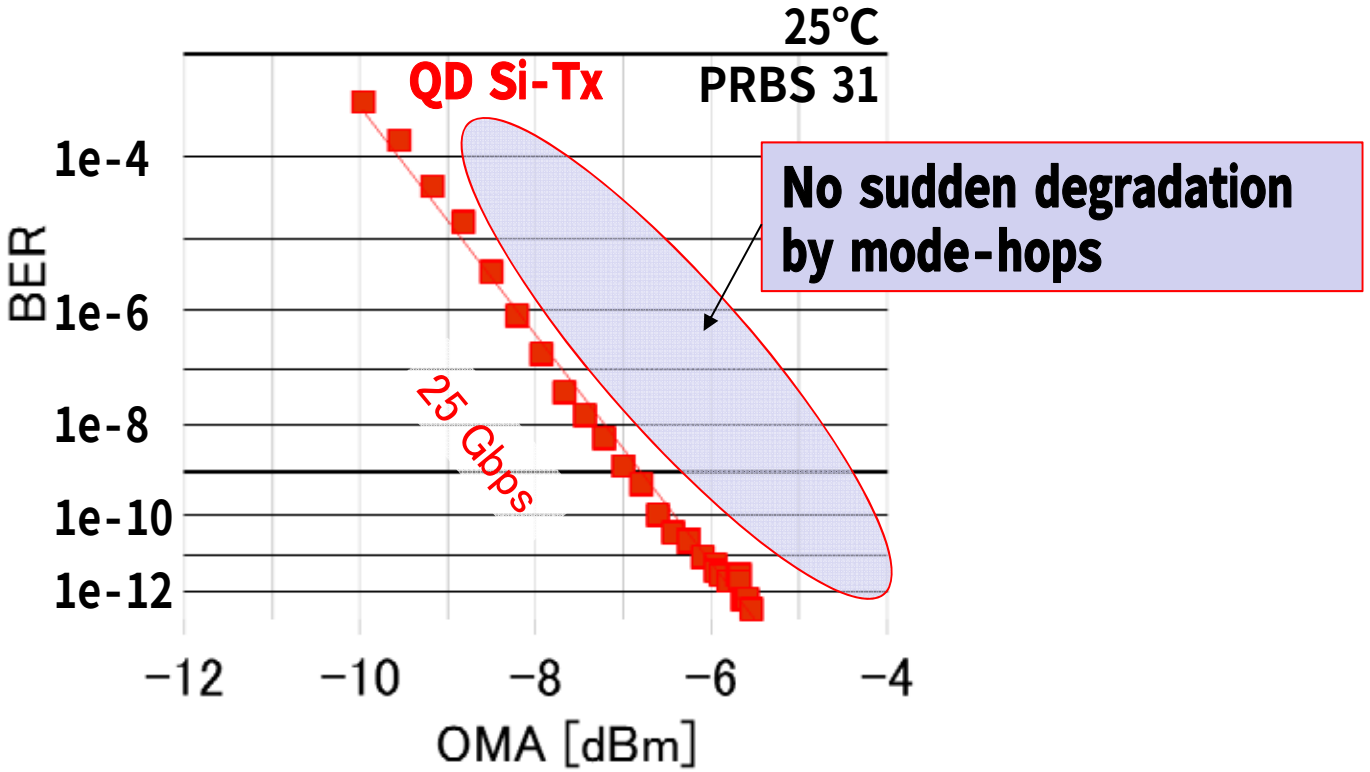
Technology Roadmap in PETRA



A few slides are not included in this file.

Data Link Property – BER -

- Error free operation over -5.7 dBm of OMA at 25 Gbps **without any sudden degradation** in the **QD-Tx**



BER vs. OMA

K. Mizutani[1] et al., 12th IEEE International Conference on Group IV Photonics, ThF3

Summary

- Quantum dot laser has been demonstrated to be a key device in silicon photonics technology
  - high temperature sensitivity
  - low power consumption,
  - high tolerance against feedback noise *etc.*.
- Error free operation over -5.7 dBm of OMA at 25 Gbps without any sudden degradation in the QD-Tx in optical I/O chip.

Acknowledgement :
This research is partly supported by the New Energy and Industrial Technology Development Organization (NEDO). Part of the fabrication was conducted at the Tsukuba Innovation Arena Super Clean Room and Nano-Processing Facility by AIST. We thank QD Laser, Inc. for providing the QD-LDs.