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Heterogeneous Integration of Photonic Devices on Silicon

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PIC International 2024

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Outline

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- Semiconductor Lasers and PICs at UCSB
- UCSB Nanofabrication Facility
- Heterogeneous Integration of III-V Materials on Silicon
- Scaling and Commercialization Opportunities
- Summary and Outlook

Some Recent Laser PICs at UCSB

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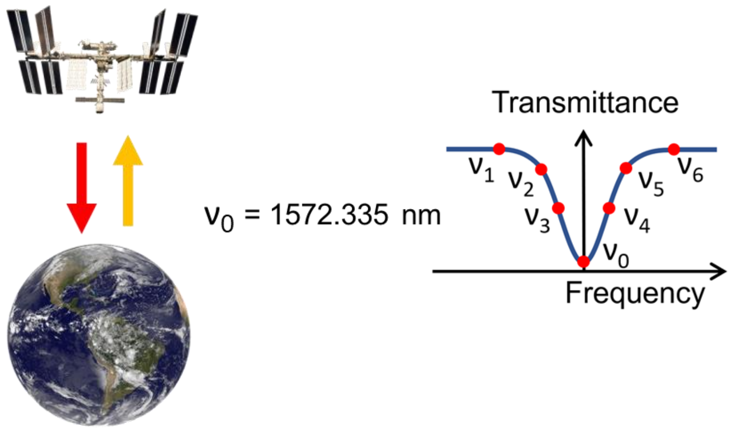
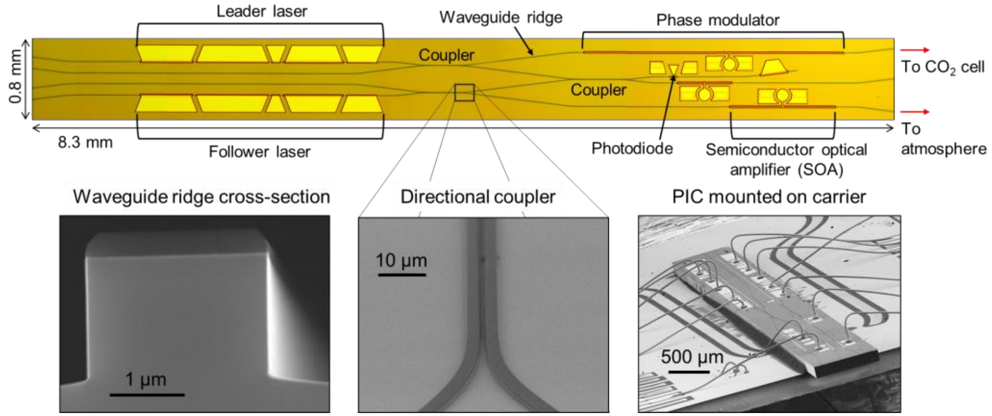
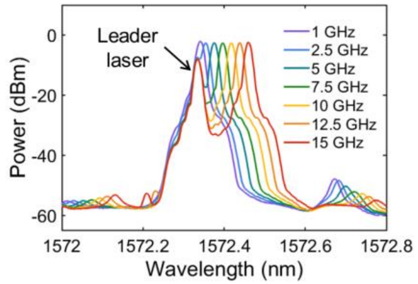
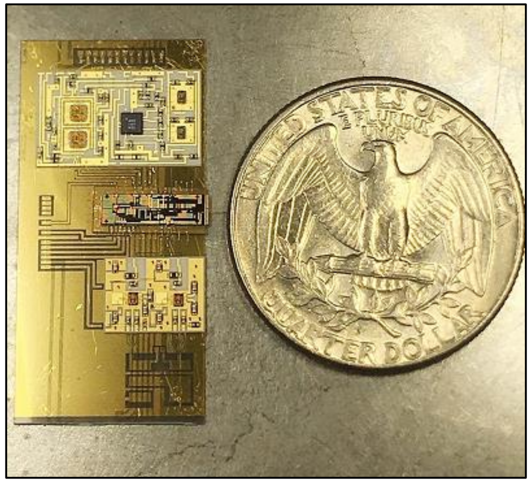
Dual SGDBR Laser 1572nm Photonic Integrated Circuit (PIC) for Atmospheric Gas Sensing LiDAR



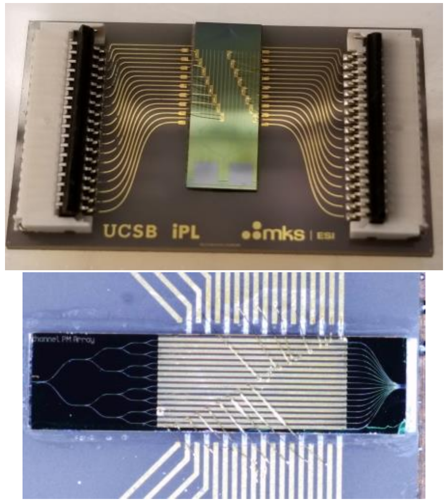




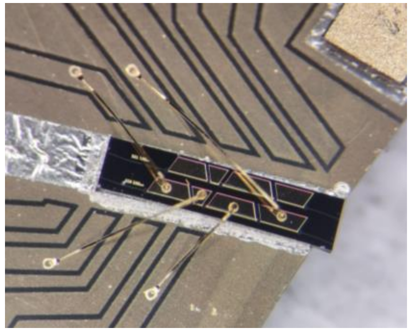
1550nm FMCW LiDAR PIC Transceiver

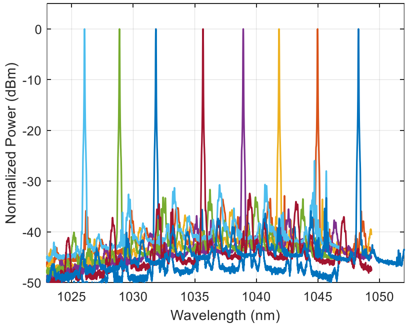


GaAs Optical Phased Array for Beam-steering Industrial Applications



Widely Tunable 1030nm SGDBR Laser for Topographical LiDAR





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The UCSB Nanofab

Jonathan Klamkin
Director, UCSB Nanofab
Electrical and Computer Engineering Department

University of California Santa Barbara

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UCSB Nanofab Overview

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What?

The UCSB Nanofab is an advanced **nanofabrication <u>user</u> facility**.

- Open access: Users are internal (UCSB) and external (other universities, government, and industry)
- Facility houses **~$60M of equipment**

When?

In operation for **more than 25 years**

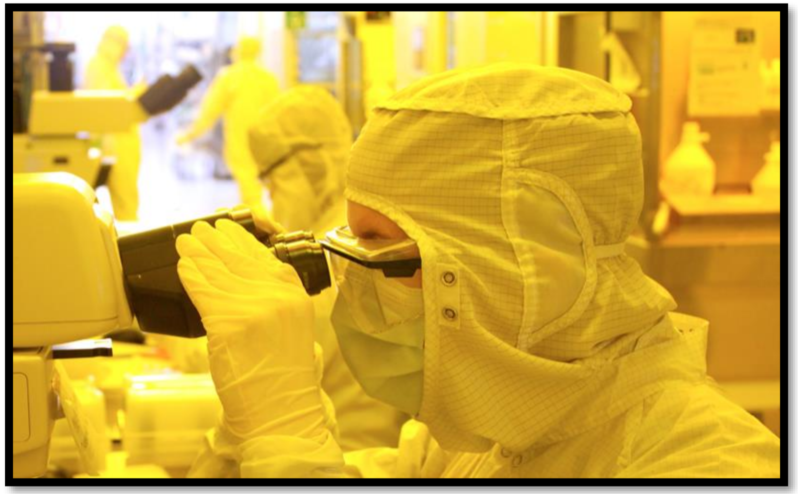
Why?

To support innovation

- User base is **>500 annual users** and **~50% of these users are from industry**
- To or knowledge, this is the largest industrial base supported by any university nanofabrication facility in the United States.

How?

The UCSB Nanofab is supported by user fees and operates without loss.



UCSB Nanofab Impact at a Glance

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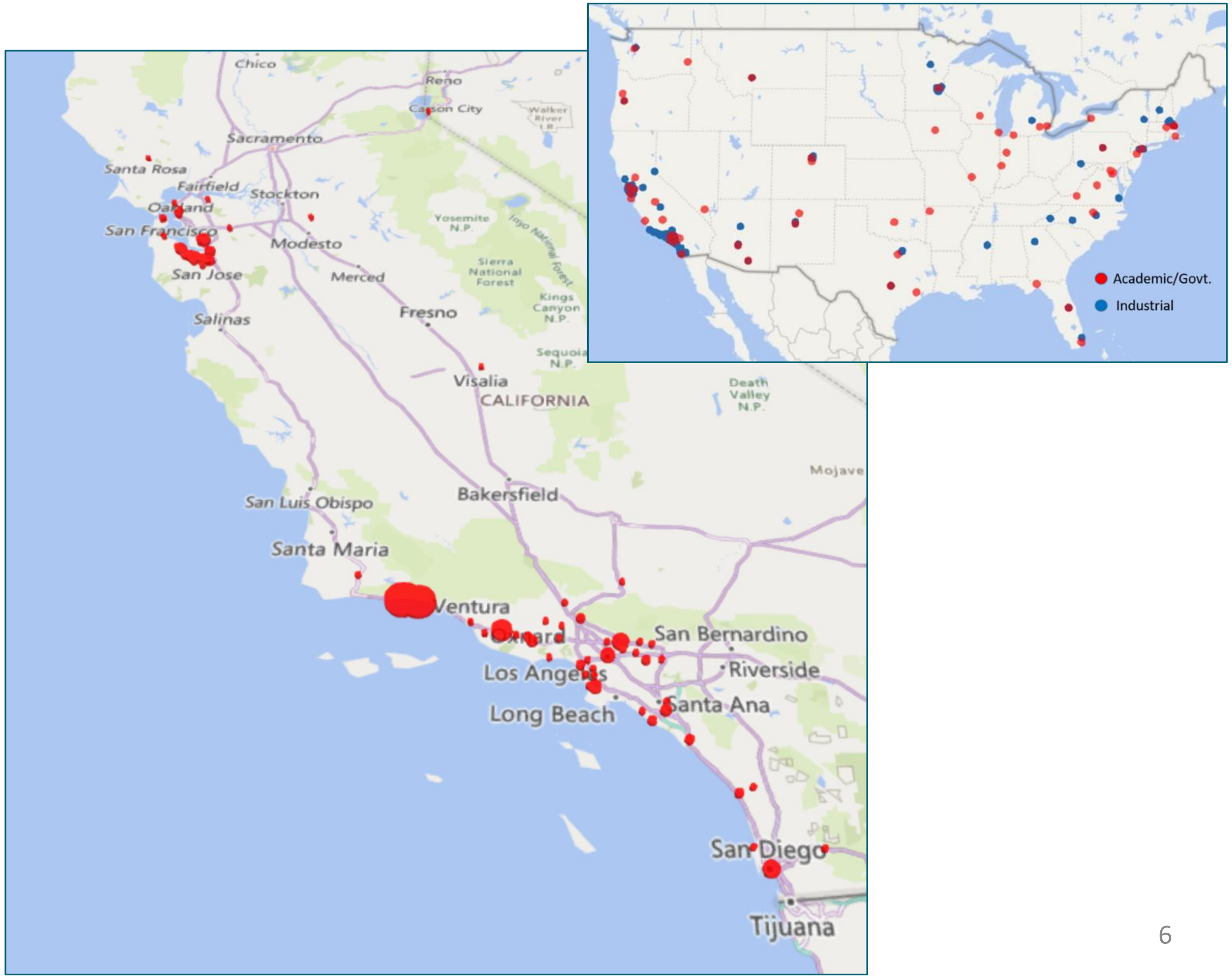
UCSB Nanofab by the Numbers

- ***State Impact***: UCSB Nanofab has been accessed by more than **200 California companies** since 2006
- ***National Impact***: **260 companies nationwide** have accessed the facility, and of these, **195 are small companies**
- **68 companies are local** (Goleta and Santa Barbara)
  - 29 of these companies were started and led by UCSB faculty and/or graduates
- **92 academic institutions** served nationally since 2006

Maps of UCSB Nanofab users



Summary of Capabilities: ≥100mm (up to 150mm)

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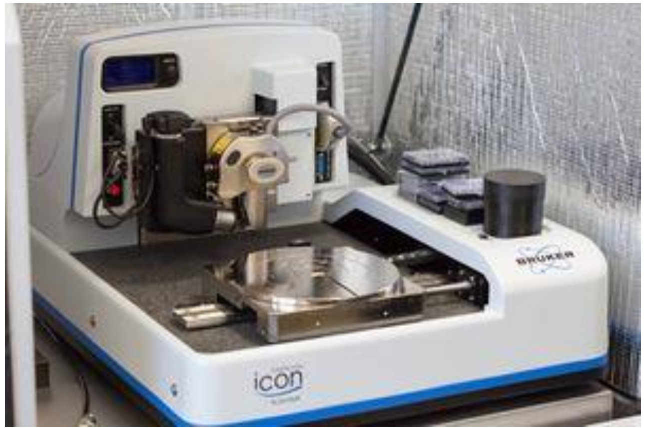


- **Full suite of advanced fabrication and characterization available for nanofabrication including: precision lithography, etching, deposition, integration and packaging**
- **Our facility is ≥100mm: All tools support 100mm, many support 150mm**

Sampling of Research Areas Leveraging UCSB Nanofab

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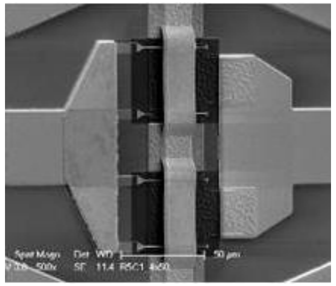
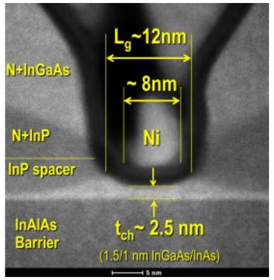
Electronics, Photonics, MEMs, Microfluidics, Materials, Physics, Chemistry, Bio, Quantum

GaN HEMTs

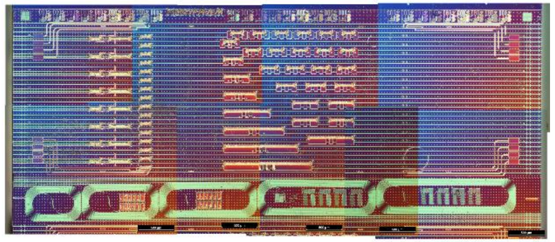


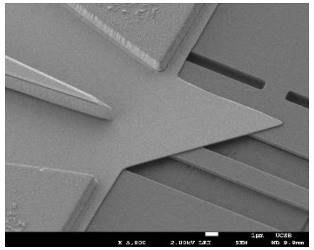
III-V MOS



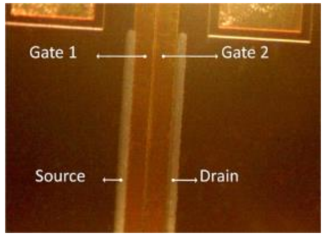
LEDs for Lighting

Silicon photonics

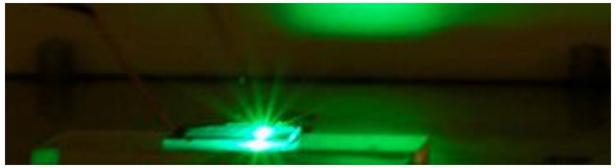




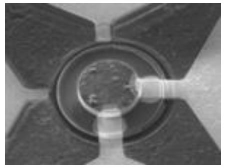
Organic FETs



Nitride-based lasers

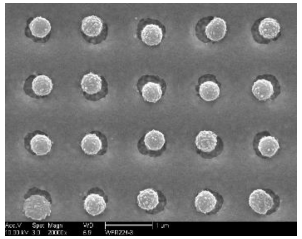


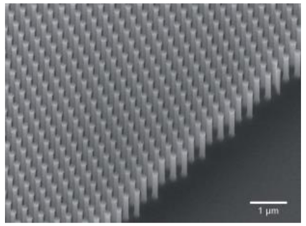
Photonic ICs



VCSELs

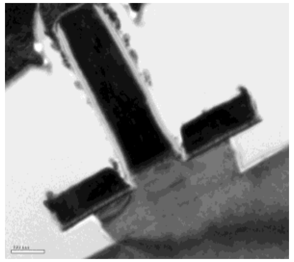
DNA Sequencing

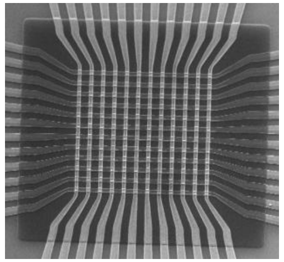




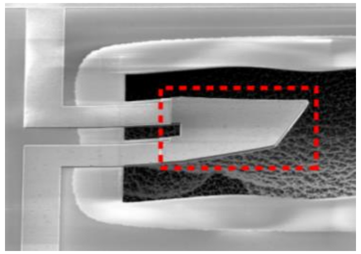
Chem. Sensing

THz transistors

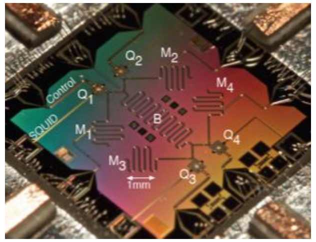




Phase-change memory

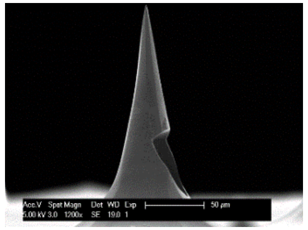


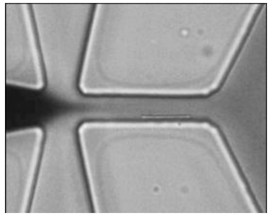
Quantum MEMs



Q-bits

Microneedles





Micro-Nanofluidics

Example Industrial Users and Commercialization Success

UCSB

ATTOLLO Engineering

- Imagers and range finders for defense and aerospace
- Processes developed at UCSB then transferred to production
- Founders are UCSB graduates
- 50 employees

SLDLASER

- Soraa and then SLD Laser develop LED and laser products for lighting, displays
- Founded by Nobel Laureate Shuji Nakamura, Steven DenBaars, James Raring (UCSB graduates and faculty)
- Acquired by Kyocera and >200 employees

Aeluma™

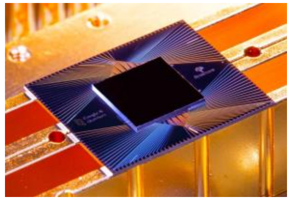
Autonomous Vehicles

Industrial Automation and Machine vision

Robots

- Scalable, cost-effective sensors for automotive and industrial LiDAR
- Founders are UCSB graduates and faculty
- Company went public in 2021

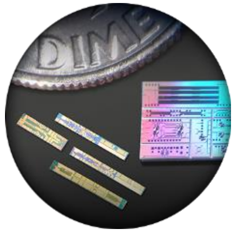
Google AI



- Quantum computing technology spun out of UCSB to Google
- Fabrication development at UCSB Nanofab

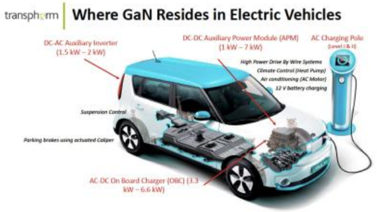
FREEDOM PHOTONICS

A LUMINAR COMPANY



- Lasers and photonic integrated circuits for communications and sensing
- Processes developed at UCSB and transferred to foundry
- Founders are UCSB graduates
- Company acquired by Luminar

transphorm



- GaN power electronics and RF devices
- Automotive market focus
- Founded by UCSB graduates and faculty
- Processes developed at UCSB and transferred to production
- Company went public in 2020

- Ultra-low noise crystalline mirrors for spectroscopy and sensing applications
- Processes developed at UCSB Nanofab
- Founded by UCSB graduate
- Acquired by Thorlabs

Birds Eye View of Economic Impact: Industrial Users

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PhysioLogic Devices, Inc; GenXComm Inc; Ideal Power Inc; Spectron Laser Corp; LW Microsystems; Rodman Scientific; Technicolor HES; Pendar Technologies; AdTech Photonics; Nano Precision Medical; Nanoshift LLC; Lam Research Corporation; Ultima Genomics; Garmin International, Inc.; Lockheed Martin, Santa Barbara Focal Plane; Toyon Research Corporation; **Aurrion** (purchased by Juniper Networks); **Laxmi Therapeutic Devices**; Advanced Modular Systems; Aeonian Semiconductor Technology Corporation; Owl Biomedical Inc.; Sientra Inc; SurForce Corporation; Brad Herner; Momentum Optics, LLC; Facebook Technologies, LLC; SRI International; Parthian Energy; Terray Therapeutics; RLC Solutions; Magic Leap; Astrileux Corporation; Omniome, Inc.; Ayar Labs; Corning Technology Center; **Nexus Photonics**; Anasys instruments; **Fluency Lighting**; **Numerical Design, Inc**.; Applied Materials; ELR Systems LLC; Infinera; Juniper Networks; Laser Components DG Inc; Global Communication Semiconductors; Spectradyne LLC; Applied Nano; Zephyr Photonics; Sumitomo Electric Device Innovations USA; Skinfrared, LLC; Emcore Corporation; Nextinput; Illumitex; Nanohmics, Inc; Bandwidth 10, Inc; Lumenz; Advanced Device Sciences; AdvR; Promerus LLC; Drinksaavy; InfraredVision Technology Corp; Photronix; RedShift Systems; TelAztec; Goodrich Corporation; 3DCD; **Attollo Engineering, LLC**; Advanced Photonix; Interlink Electronics; Johanson Technology, Inc; Nano Precision; Polyfet RF Devices; Rocketstar Robotics; Sensor Creations; Zinc Matrix Power; Cambridge Electronics Inc.; Imagine TF; Luxtera; Ostendo Technologies; Source Photonics; AdTech Optics; AISthesis Products, Inc.; Xradia; Apic Corporation; Apple; Oxford Defense North Carolina LLC; LabSys LLC; NVE Corp.; Simax Lithography BV; Invenlux Corp; The Aerospace Corporation; Gamma Company; VoxtelNano; Seagate Technology; Royole Corporation; Optoplex Corporation; Silicon Clocks; **Antora Energy**; Modern Microsystems; Glenair; **Nitres, Inc.** (merger with CREE in 2000); **Google Quantum** (part of Google Inc, Mountain View); Autoliv; DuPont Displays; FLIR Commercial Systems; Mitsubishi Chemical Research & Innovation Center; Raytheon Infrared Operations; Raytheon Vision Systems; **Agile Materials & Technologies**; **Calient Networks**; **Freedom Photonics, LLC; PacketPhotonics; Soraa Laser Diode, Inc; Soraa, Inc.; Transphorm**; Acumen Scientific; CBrite; Diode Solutions, Inc.; iCRco, Inc.; Innovative Micro Technology; LaunchPoint; Santa Barbara Nanotech; Sensors in Motion; Solution Deposition Systems; Spectrafluidics; Space Exploration Technology; Advanced Integrated Photonics; Akoustis, Inc; Replicell Inc.; Atom Nanoelectronics; SDC Technology; PrimeGen Biotech; Carbon Technology, Inc; Silicon Designs, Inc.; Bridgelux; Haylcyon Molecular; Advanced Nanostructures; Aneeve ; ruubix; Millibatt Inc.; HI LLC; Hughes Research Laboratories; Carbonics Inc.; Tribogenics; Dallas Quantum Devices; SRI International, Micro Science Engineering Laboratories; TE Connectivity, Silicon Valley Campus; Pacific Biosciences; **Agility Communications** (purchased by JDSU in 2006); KLA-Tencor Corporation; KLA-Tencor Inc; Grandis, Inc; Terrella Energy Systems Ltd.; ImagerLabs, Inc. ; Protea Biosciences, Inc.; Applied Nanostructures, Inc; Cambrios Technologies; Fultec Semiconductor; Alcatel-Lucent Bell Labs; Lucent; QmagiQ; Coriant Advanced Technology, LLC; **Crystalline Mirror Solutions LLC** (purchased by THOR Labs 2020); Kaiam Corporation; Opto Diode Corp; Meso Engineering, LLC; RF Nano; Commerce One; GE Global Research; Tivra Corporation; Lockheed Martin, Missiles & Fire Control; Partow Technologies LLC; Poole Ventura; Lockheed Martin Aerospace; HP Labs; Nano and Micro Technology Consultants; Robert Bosch LLC; Rhombus Power Inc.; Avery Dennison; Jet Propulsion Lab; Aonex Technologies; Etamota Corporation; SRU Corporation; ARMS; Crystalline Mirrors (Vixar); Phononic Devices; Northrop Grumman Corporation; Genapsys Inc; Triquint Semiconductor; Senspex; Cymer; Greenstar Micro Technologies; Lumedyne Technologies; Nanomedical Diagnostics; SensorMetrix; Cambrian Genomics; ColdLogix; LED Engin; Solar Junction Corporation; Complete Genomics Inc.; Meggitt Endevco; NexGenSemi; ATK Mission Research; Continental Advanced Lidar Solutions, Inc; **Innovative III-V Solutions; PiMEMS Inc.; Praevium Research;** Advanced Scientific Concepts; Angstrom Science; Aptitude Medical Systems Inc; Asylum Research; CytomX; Epoxtal; Inlustra Technologies; Invenios; MEMS Precision Technology; Next Energy Technologies, Inc.; PLT; Resonant Wireless; Serry Enterprises; Solar3D; Superconductor Technologies, Inc; **Quintessent Inc; Ultra low-loss Technologies; Mirios Inc.; Precision Semiconductor;** Intel; Collinear Corporation; Crossbar Inc.; Keysight Technologies; Soligie; Avio Scientific, LLC; Atomate Corporation; 3M; SemiSouth Laboratories; Molecular Electronics Corp; OEpic Semiconductors, Inc.; SAMCO Inc.; Xerical Sciences; **Quintessence Photonics;** Spectrolab; Teledyne Scientific & Imaging; Kavana Technology; Tyco Electronics; Physical Optics Corporation; Bruker Metrology; Veeco Metrology; Design West Technologies, Inc.; 3D-Sensir Inc (Acqubit); **Aerius Photonics** (purchased by FLIR in 2012); Arctic Silver; Laxense, Inc.; Cynvenio Biosystems; InterPhases Research; Uriel Solar; Advanced Research Corp; Olympic Precision; **Pseudolithic, Inc.;** Northrop Grumman Guidance & Electronics; **Aeluma, Inc.**; OptiComp;

Silicon Photonics and Laser Integration

Silicon Photonics (SiPh) Background and Applications

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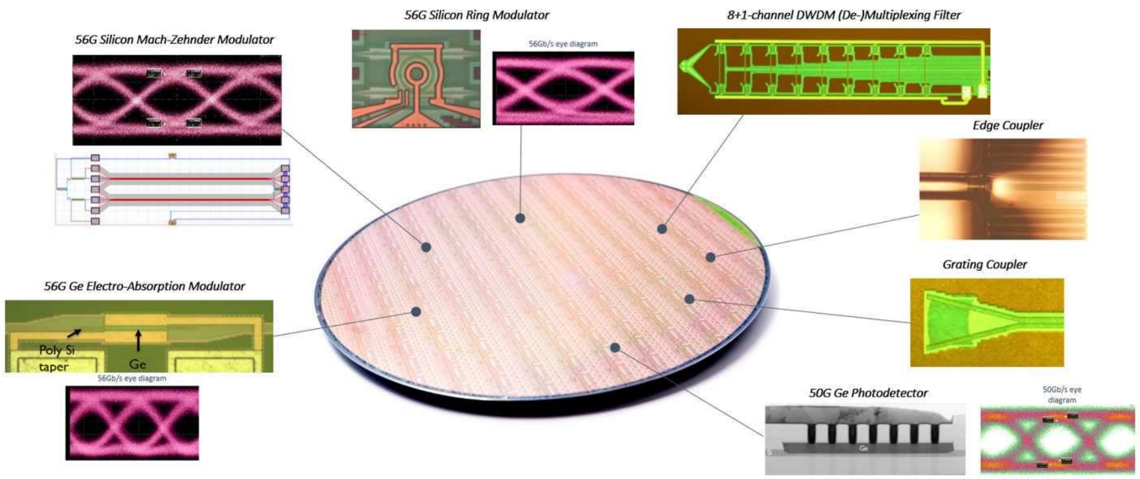
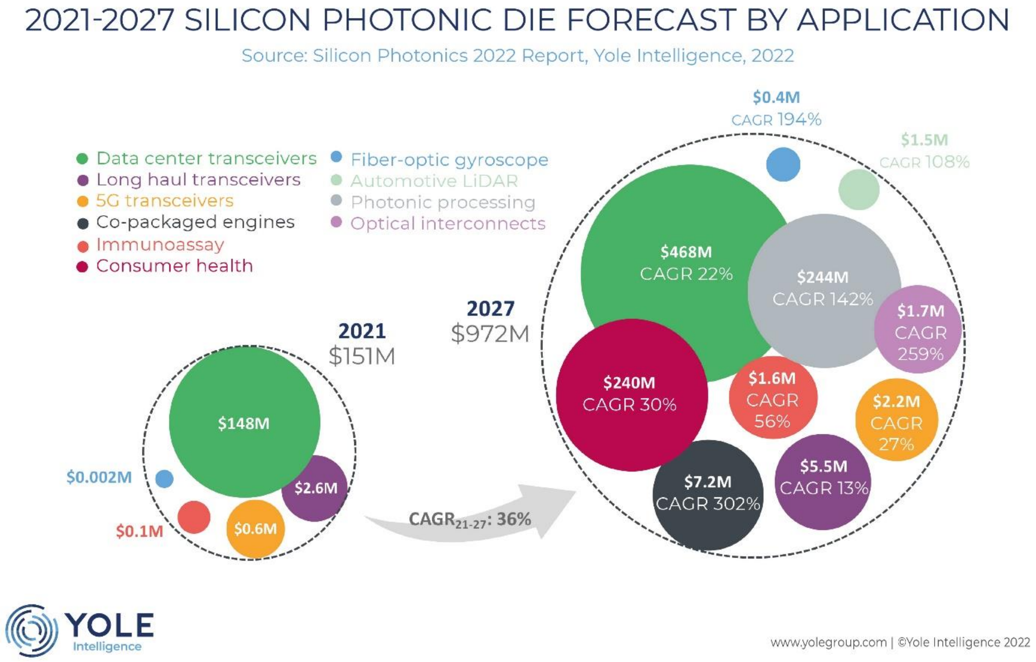
Silicon Photonics Platform



*Source: IMEC's 56 Gb/s silicon photonics on 200 and 300 mm wafer

Applications and Market Forecast



*https://www.yolegroup.com/product/report/silicon-photonics-2022/

- SiPh leverages silicon on insulator (SOI) for waveguiding
- Platform includes actives (Si modulators, Ge photodetectors, thermal phase shifters, etc.) and passives (filters, splitters, loop mirros, edge couplers, grating couplers, etc.)
- Laser/gain integration complex and not monolithic

- SiPh already deployed widely in telecom and data center transceivers
- Emerging applications of SiPh include: co-packaged optics and edge computing, AI/ML, LiDAR, quantum photonics, photonic processors, consumer health, navigation and timing

Laser/Gain Integration Approaches

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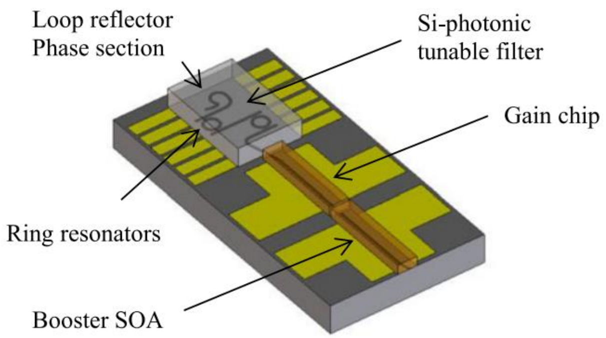
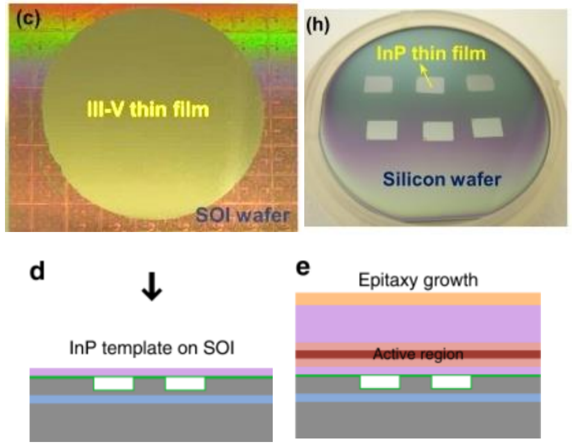
Hybrid Flip Chip



* Kobayashi et al., JLT, 2015

- ✓ Mature and commercialized
- ▪ Limited scalability and requires precision alignment

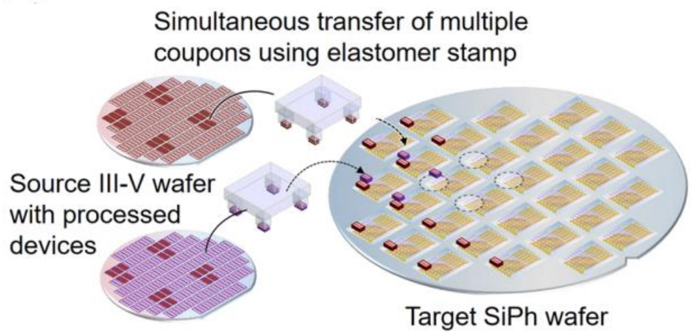
Wafer or Chiplets Bonding



*Hu et al. Light, 2019

- ✓ Small footprint and scalable
- ▪ Evolving into commercialization
- ▪ Inefficient usage of material

Micro-Transfer Printing (MTP)



*Zhang et al., APL Photon., 2019

- ✓ Small footprint and scalable
- ✓ More efficient usage of material
- ▪ Not yet commercialized

Motivation for Direct Epitaxial Growth

Table 1. Comparison between different heterogeneous integration strategies on silicon *Wang et al., LPR, 2017

	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

Challenges and Approaches for Heteroepitaxy on Si

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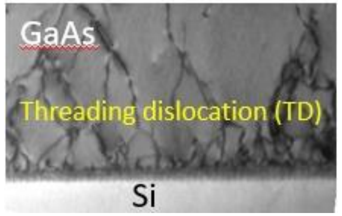
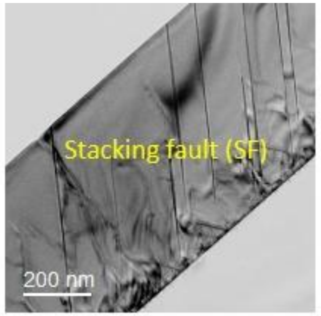
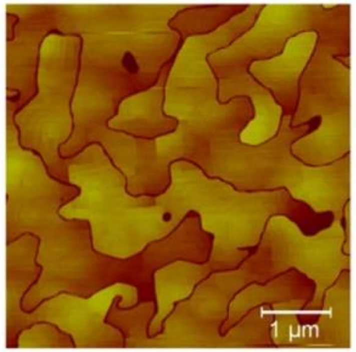
- Large lattice mismatch
- Large thermal mismatch
- Polarity mismatch

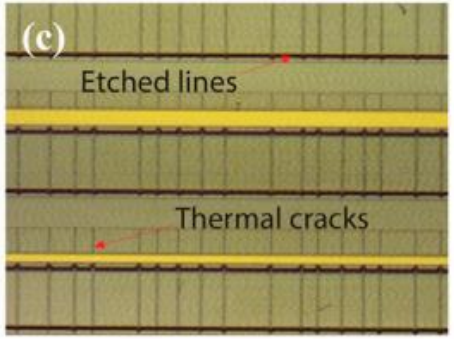




*Source: IEEE spectrum

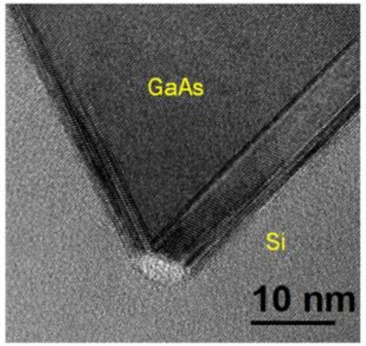


*Shi et al., Semicond., 2019

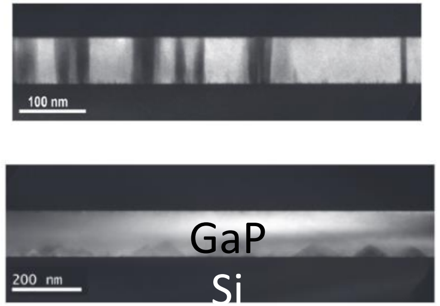


*Pan et al. J. Semicond., 2019

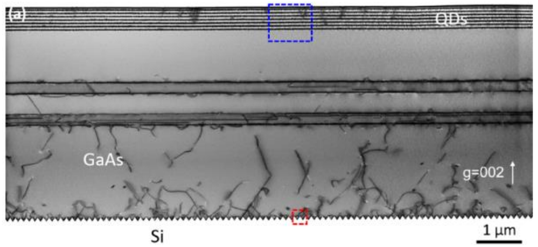
- **To eliminate APBs**
  - Use of nano V-grooved (001) Si
  - GaP, GaAs on small miscut (001) Si via surface engineering
  - Large miscut Si (4°-6°)
- **To reduce defects**
  - Dislocation filters: interlayers, strained layer superlattices (SLSs), QDs
  - Thermal cycle annealing (TCA) or in-situ anneal
  - Transition or compositionally graded buffer
- **To avoid cracking and minimize bowing**
  - Slower cooldown process
  - Thick Si substrate
  - Thinner buffer



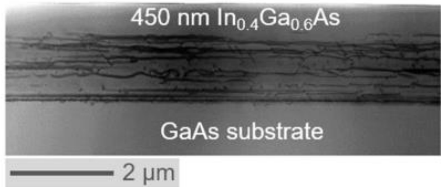
* Li et al., APL, 2015



* Volz et al., JCG, 2011



* Shi et al., APL, 2019



* Shi et al., JAP, 2020

Motivation for QDs for Lasers on Si

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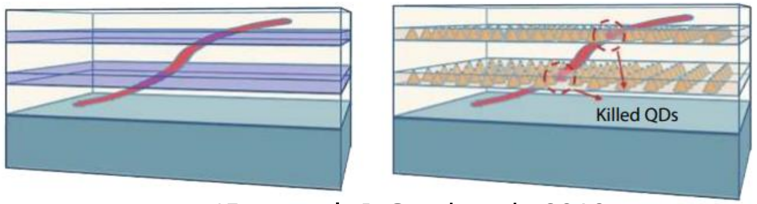
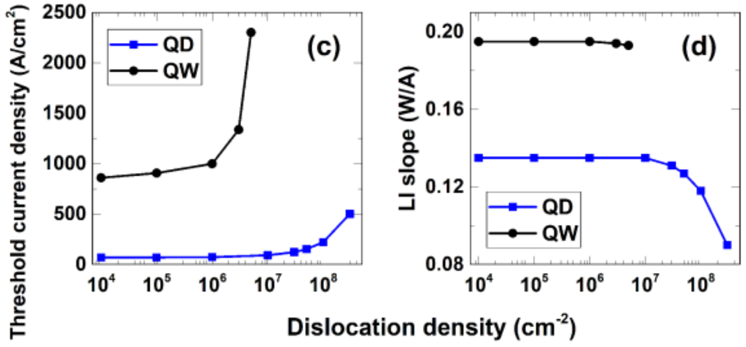
- **Advantage of QDs over QWs**
  - Lower threshold, higher differential gain, higher temperature stability
  - Lower linewidth enhancement factor, lower RIN
  - Less sensitive to optical feedback
  - P-modulation, N-modulation doping feasible

- **Additional advantage for QD lasers grown on Si**
  - Higher tolerance to dislocations

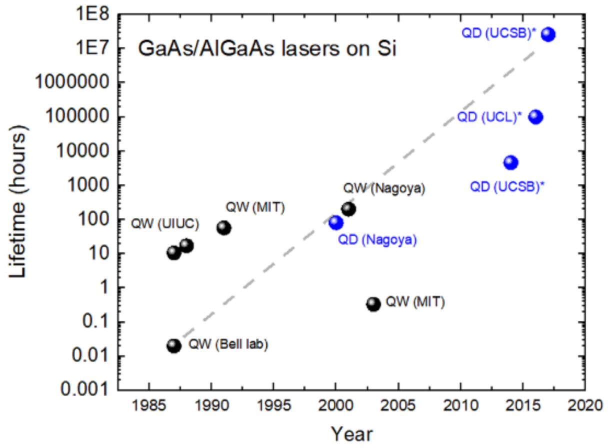


*Pan et al. J. Semicond., 2019



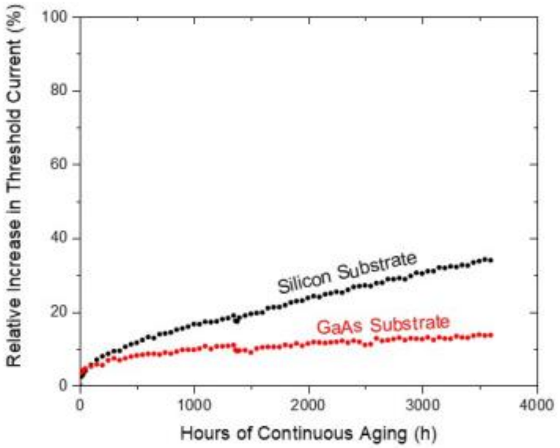
*Liu et al. JLT, 2019

Better reliability for QD laser on Si



*Jung et al. PSSA, 2018

Approaching QD laser on native GaAs



*Norman et al. JSTQE, 2019

High Performance MOCVD QDs on Native Substrates and Micro-Transfer Print Integration

All-MOCVD QD Laser on GaAs Substrates

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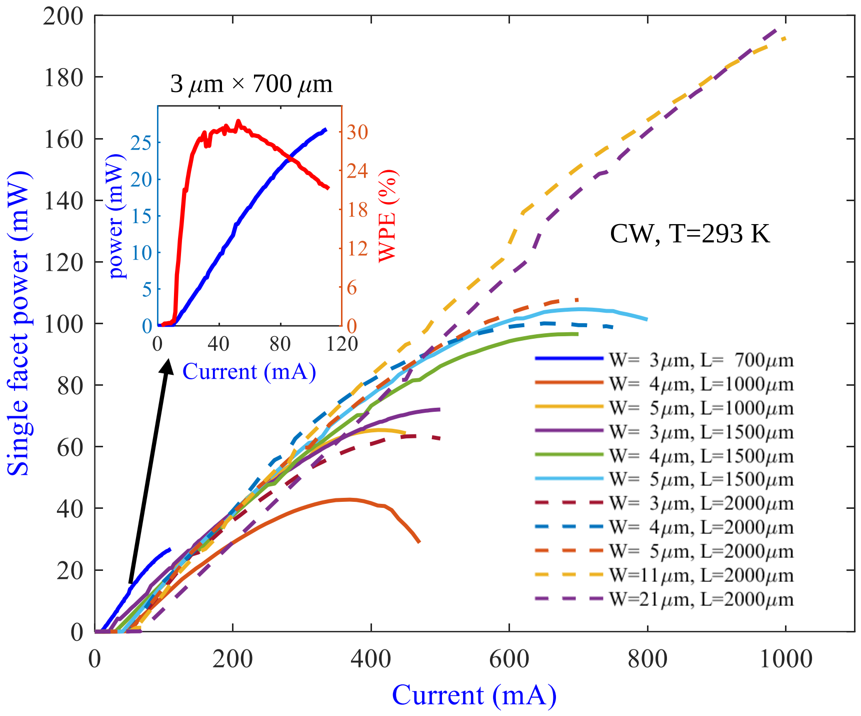
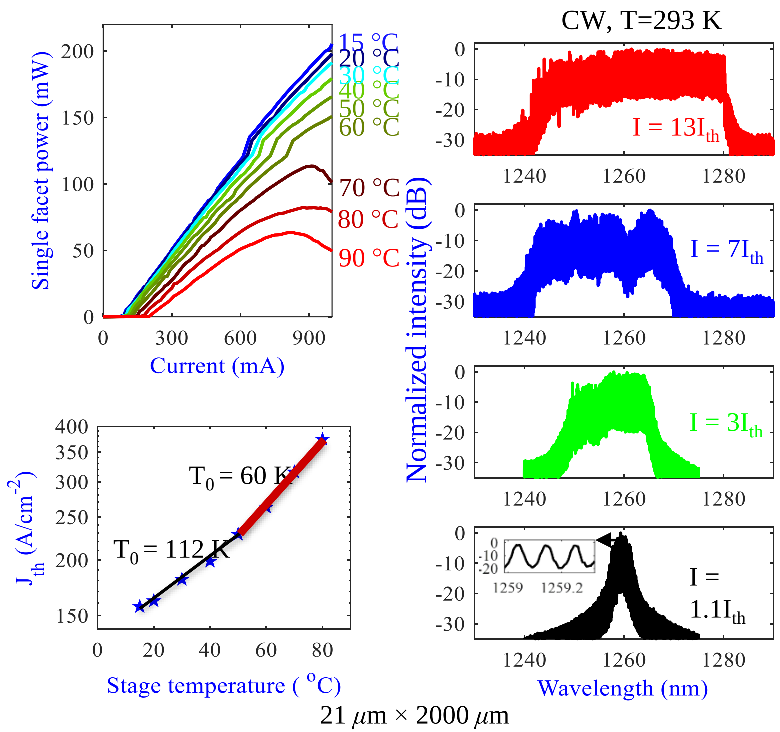
Light-current characteristics for various laser geometries



- High output power ~200 mW from single facet for >10 μm wide laser
- High wall plug efficiency ~32% for narrow width lasers

Thermal performance and spectral data



- High characteristic temperature (112K from 15-50℃, 60K from 50-90℃)
- No excited state lasing at maximum current injection level of 13*I_{th}

*Wang et al., OFC 2020

Aging Test of MOCVD QD Lasers on GaAs Substrates

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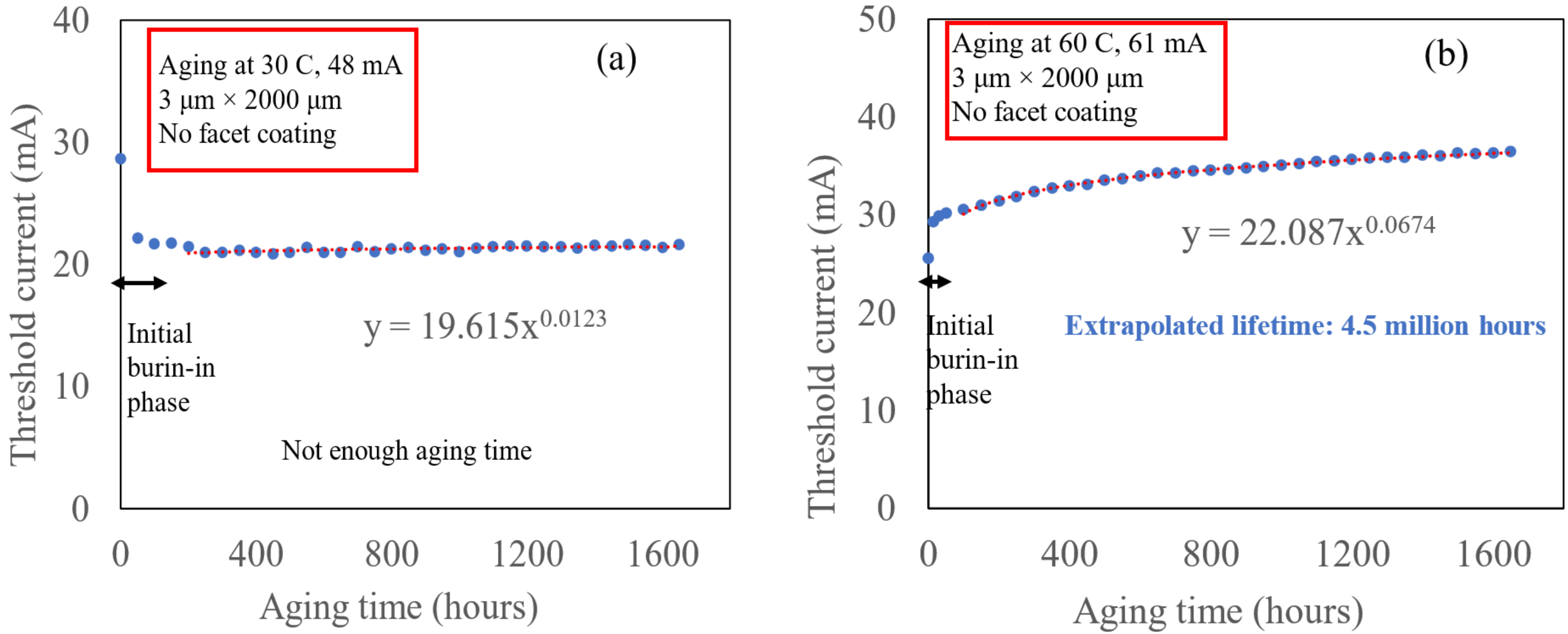
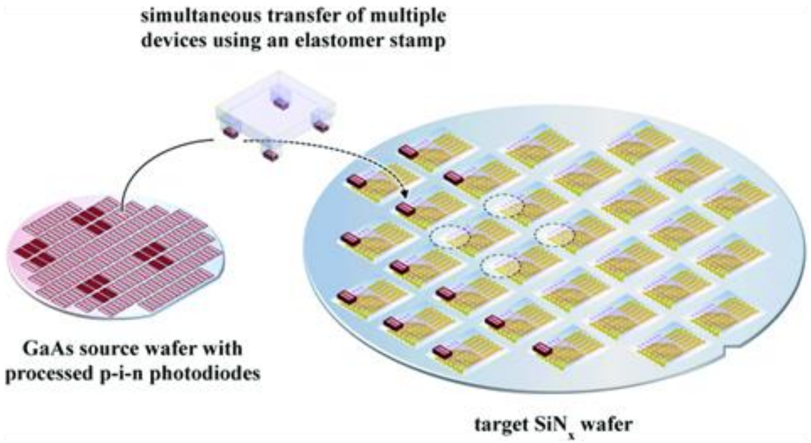


Micro-Transfer Print Integration of QD Gain

UCSB

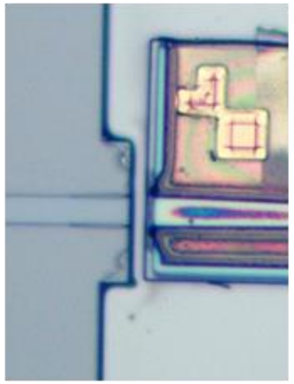
Micro-Transfer Print (MTP) Integration

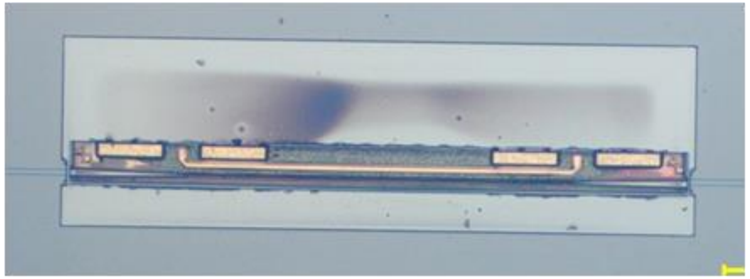


G. Roelkens, et al., OFC 2019

- Group III-V components fabricated on native substrates with etch release layer to enable pick of coupons
- Butt coupling integration leveraged to enable high power performance and high coupling efficiency
- Developed sophisticated etched-facet process, optical facet coating, and coupon formation process

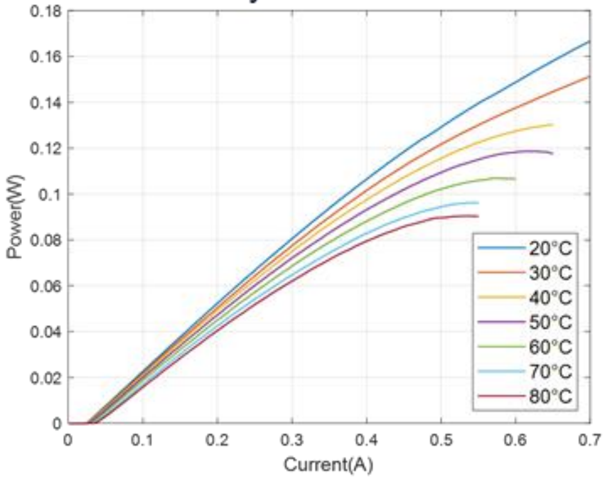
Example Printed Coupon in Recess



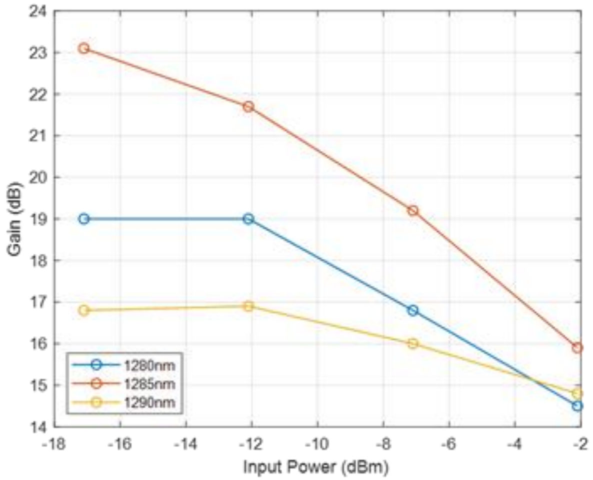


Recently fabricated Quantum Dot Gain for MTP

Fabry-Perot Laser



Semiconductor Optical Amplifier



Micro-Transfer Print Integration of QD Gain

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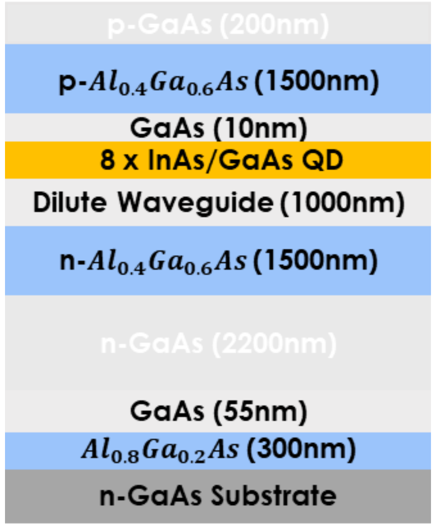
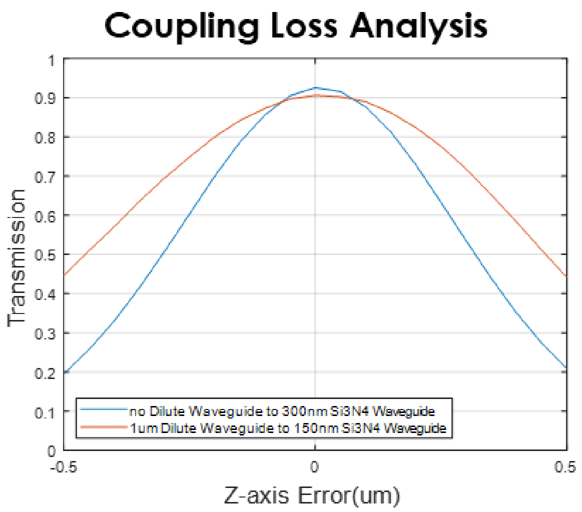
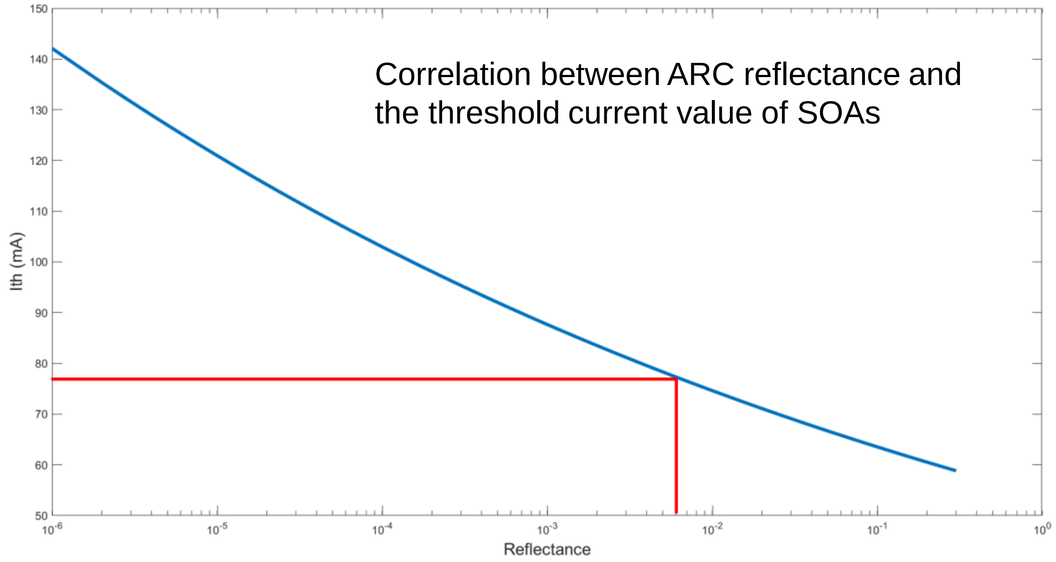
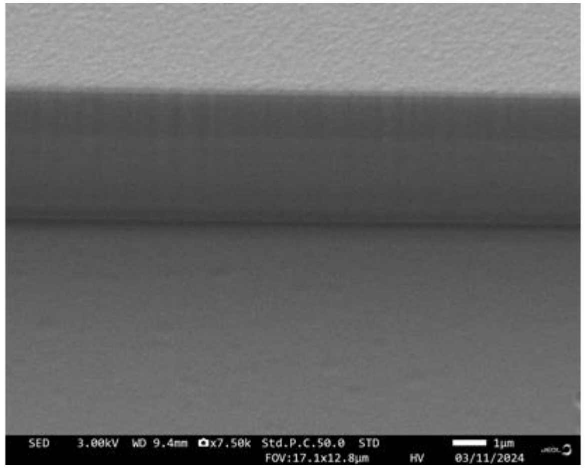


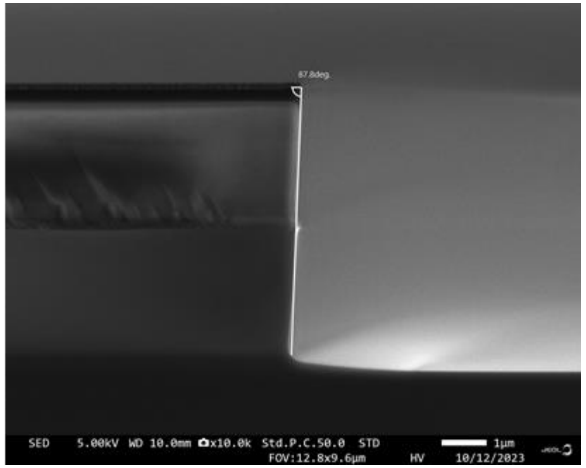




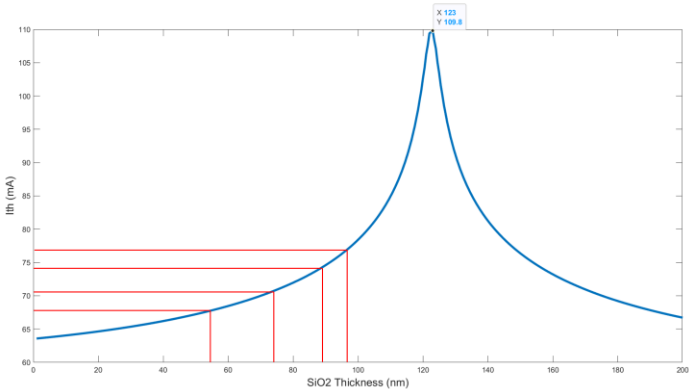
Correlation between ARC reflectance and the threshold current value of SOAs

High quality inductively-couple plasma reactive ion etching for etched facet formation





ARC with 0.6% reflectance on real device

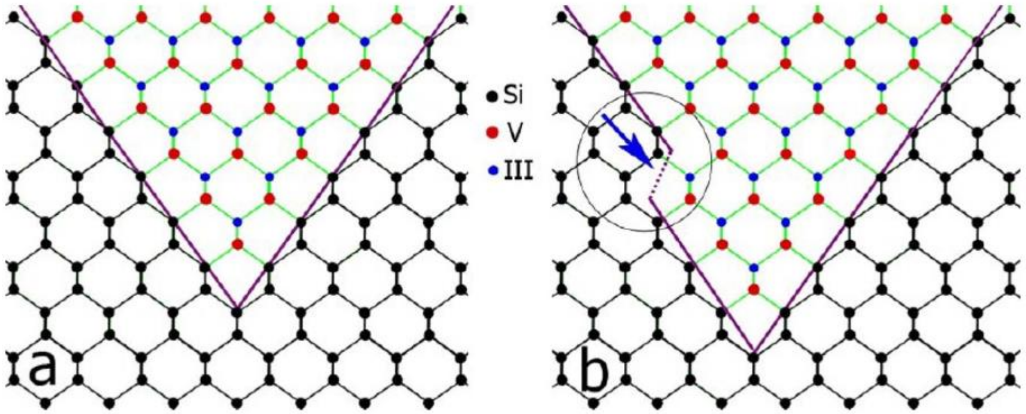


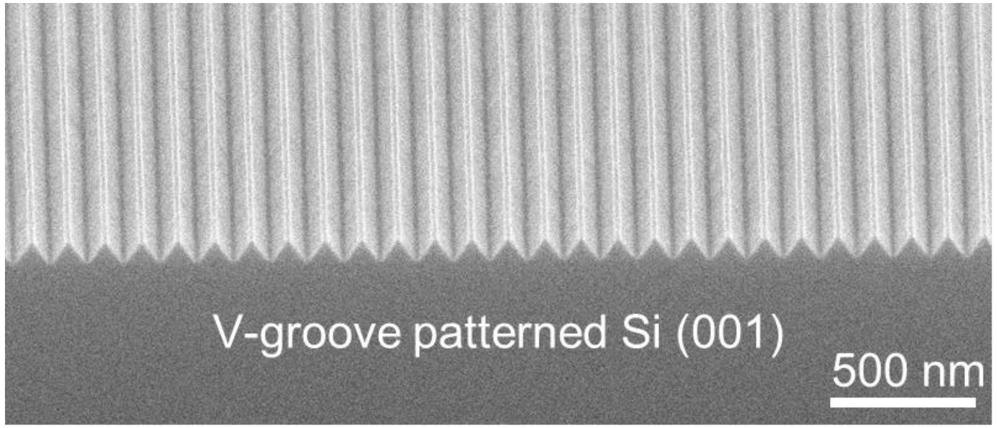
Two-layer ARC (Ta_2O_5 and SiO_2)
Iterate SiO_2 deposition and threshold current measurement to precisely control the ARC thickness

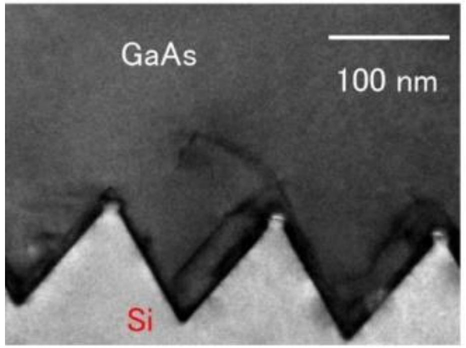
Lasers on Silicon by Direct Heteroepitaxy

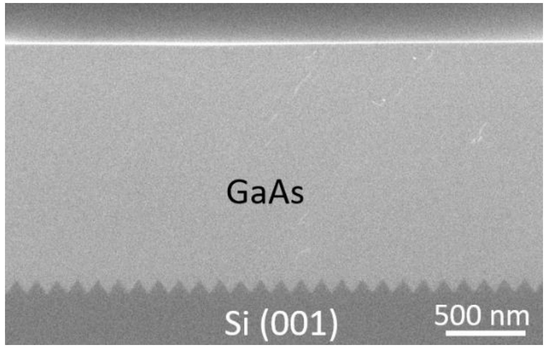
III-Vs on Nano-V-Groove Patterned Si

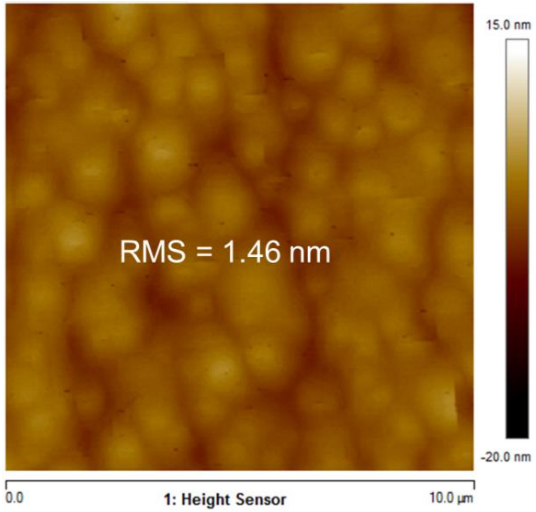
UCSB











- Double-step Si terraces created by (111) Si plane
- APBs can be completely eliminated, most TDs annihilated near V-grooves

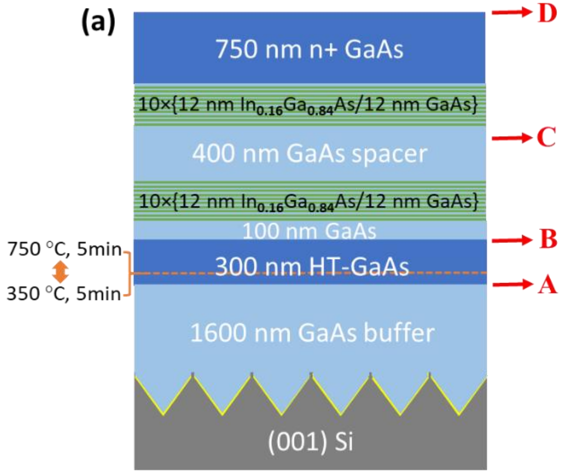
- V-grooves formed by KOH wet etching
- Smooth and high-quality GaAs buffer

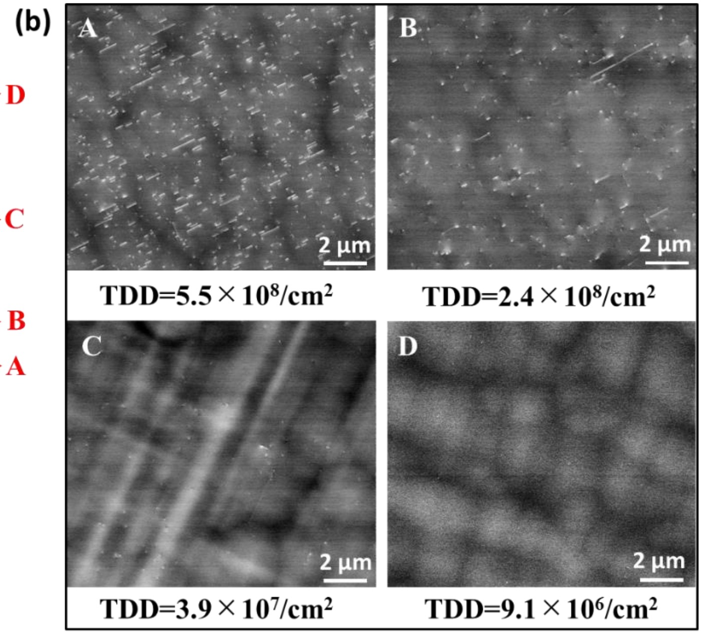
*Paladugu et al., Cryst. Growth Des. 12, 4696−4702 (2012)
*Li et al., Appl. Phys. Lett. 106, 072105 (2015)

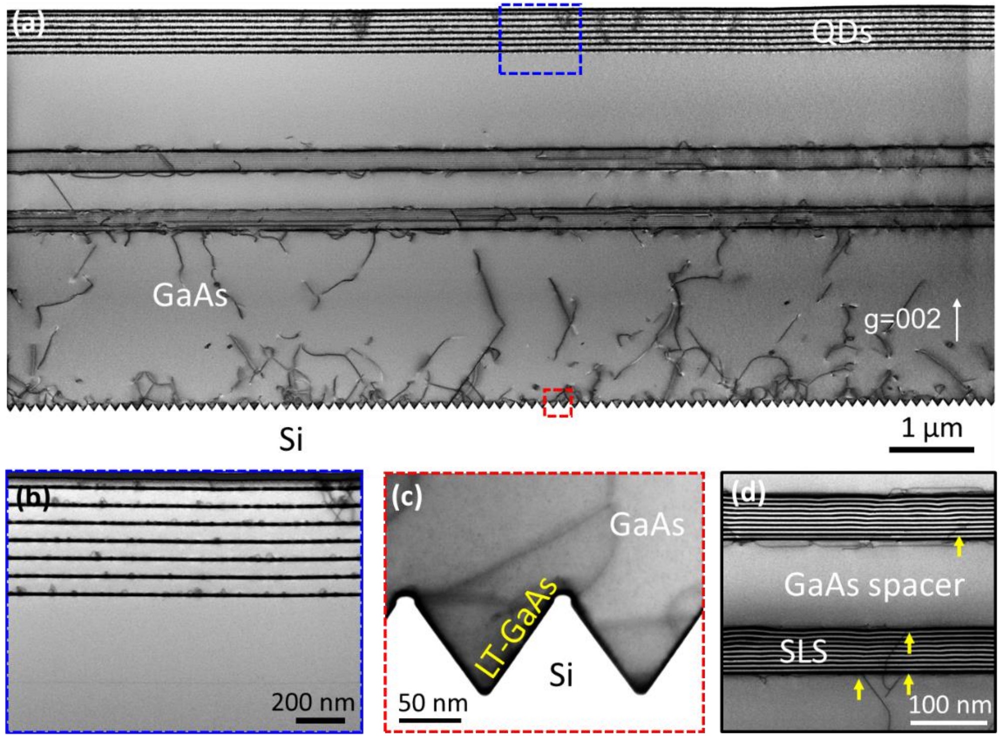
*Shi et al., Appl. Phys. Lett., 114, 172102 (2019)

Low Dislocation Density GaAs on V-Groove Si (GoVS)

UCSB



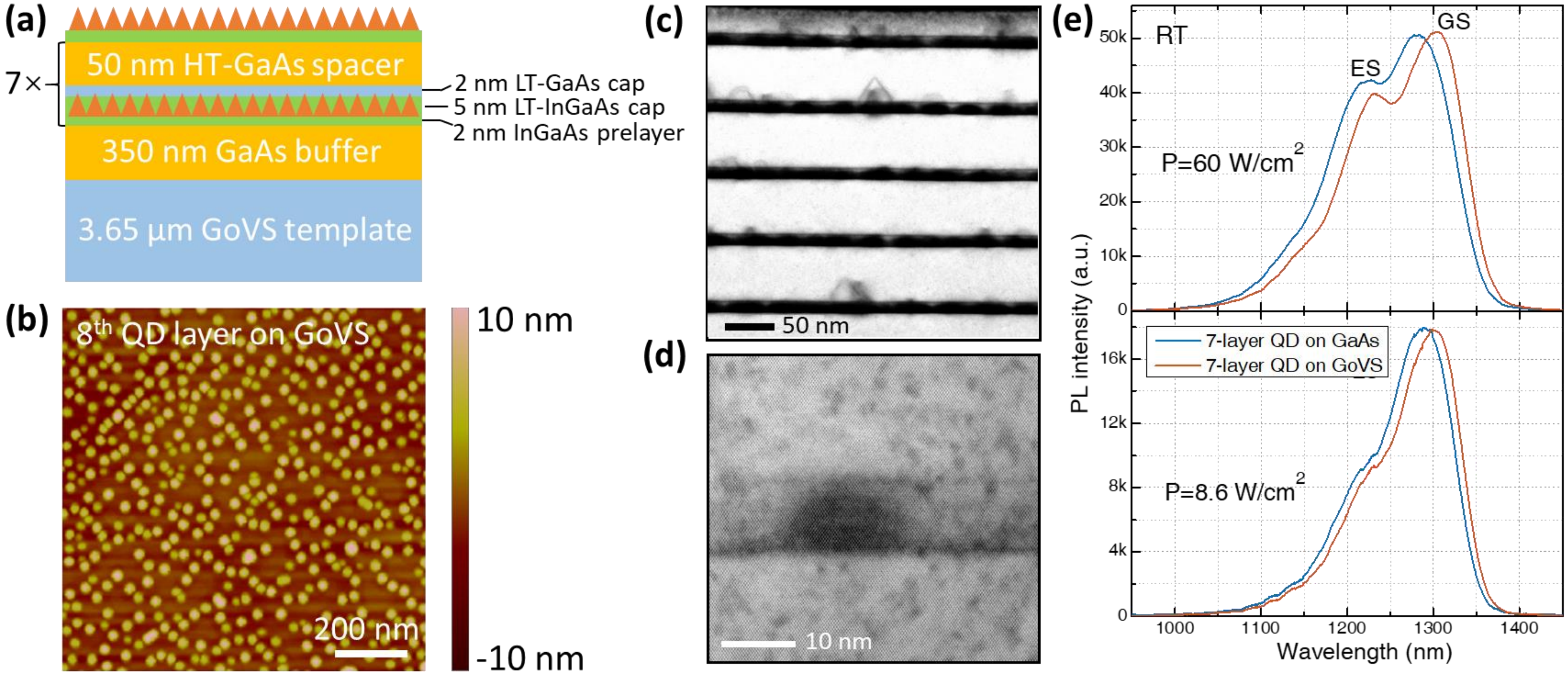




- TCA and SLSs inserted as dislocation filters
- Threading dislocation density (TDD) analysis by electron channel contrast imaging (ECCI)
- Cross-sectional Scanning Transmission Electron Micrograph (STEM) to observe dislocation evolution
- Total GaAs buffer thickness can be lowered to 2.5 μm while maintaining defect density
- TDD in the range of 4 - 9 $\times$ 10^6 cm^{-2}

Multi-Layer MOCVD grown QDs on GoVS Template

UCSB



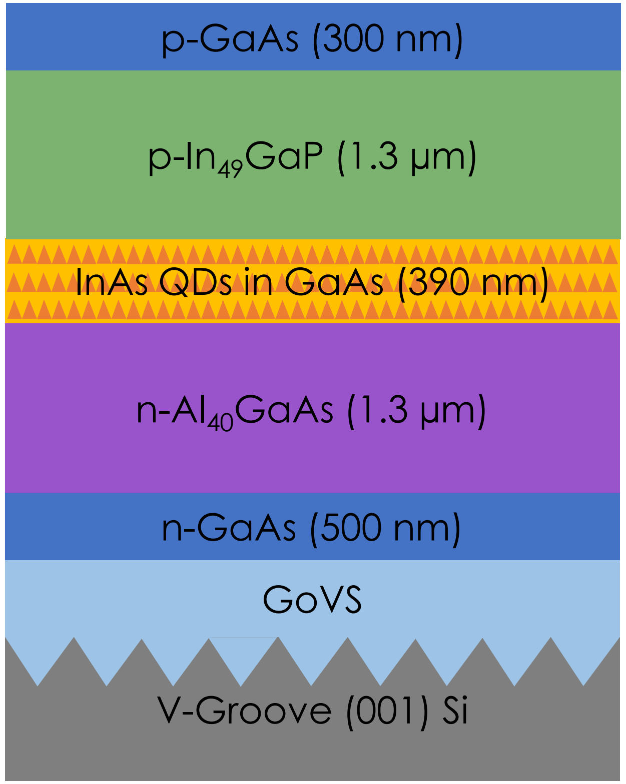
GS: ground state
ES: excited state

- Room temperature (RT) photoluminescence (PL) intensity and full width at half maximum (FWHM) identical for QDs on Si and on native GaAs, suggesting defect forgiving characteristics
- No QDs clustering

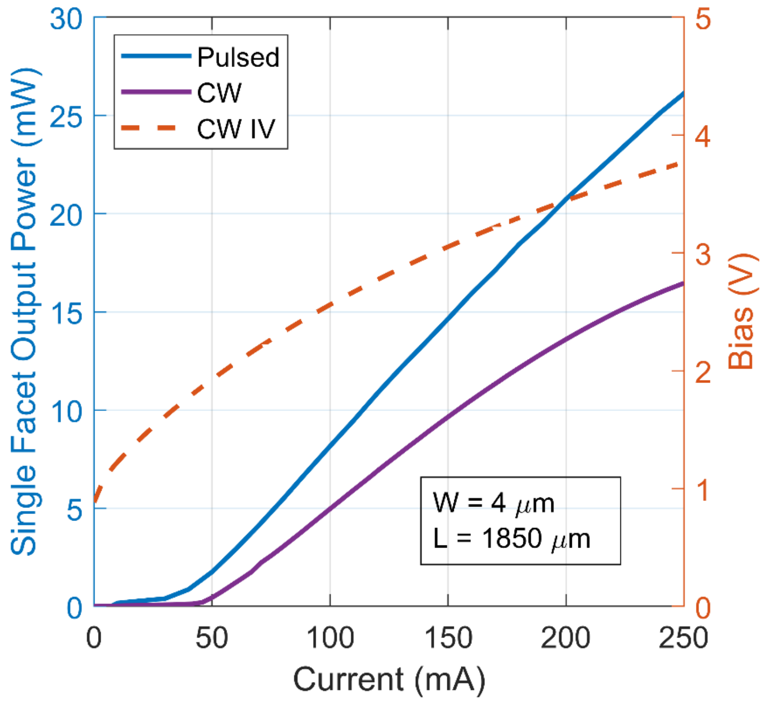
*Shi et al., Appl. Phys. Lett., 114, 172102 (2019)

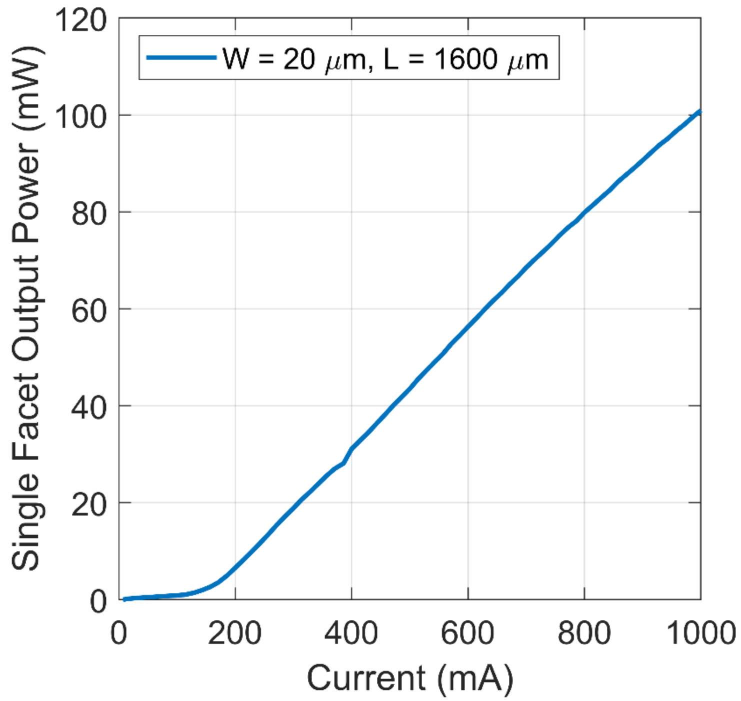
All-MOCVD QD Laser Grown Directly on Si

UCSB



LIV Characteristics





- 20 µm broad area laser
  - Pulsed operation up to 100 mW per facet
- 4 µm narrow ridge laser
  - 25 mW per facet pulsed
  - 16 mW CW output

- Higher than expected series resistance → degraded CW performance due to self-heating
- Lasers still demonstrate reasonable light output and threshold

All-MOCVD QD Laser Grown Directly on Si

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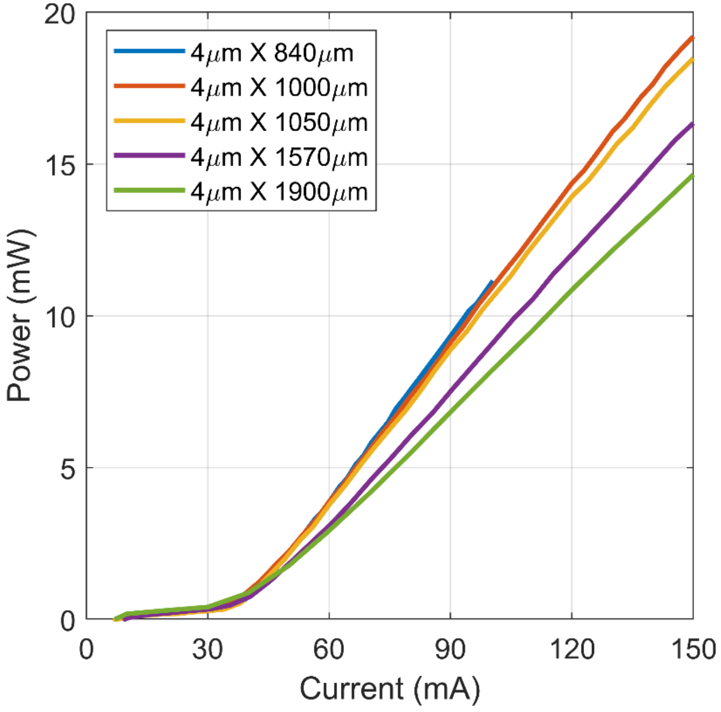
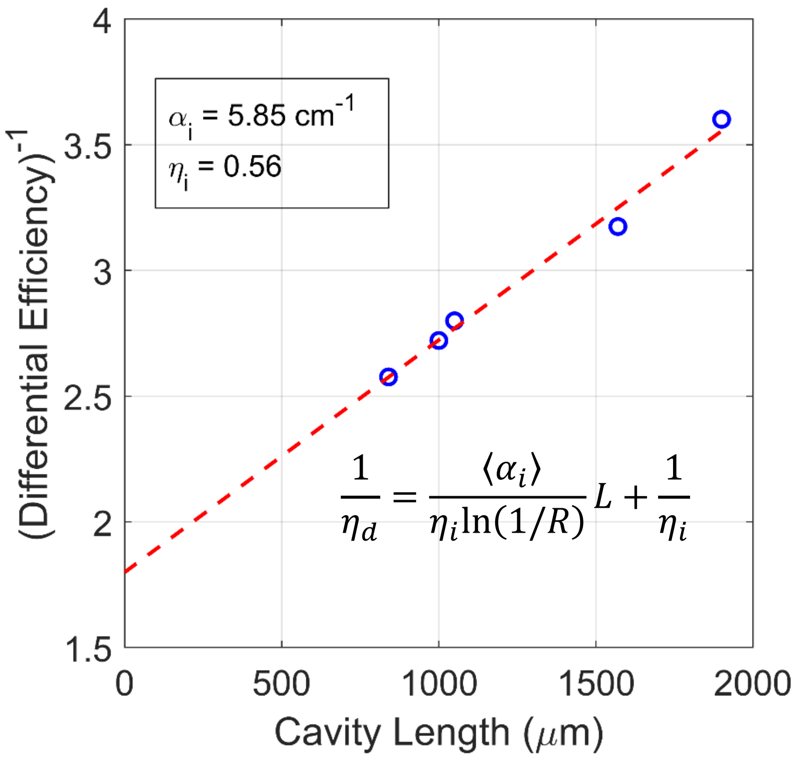
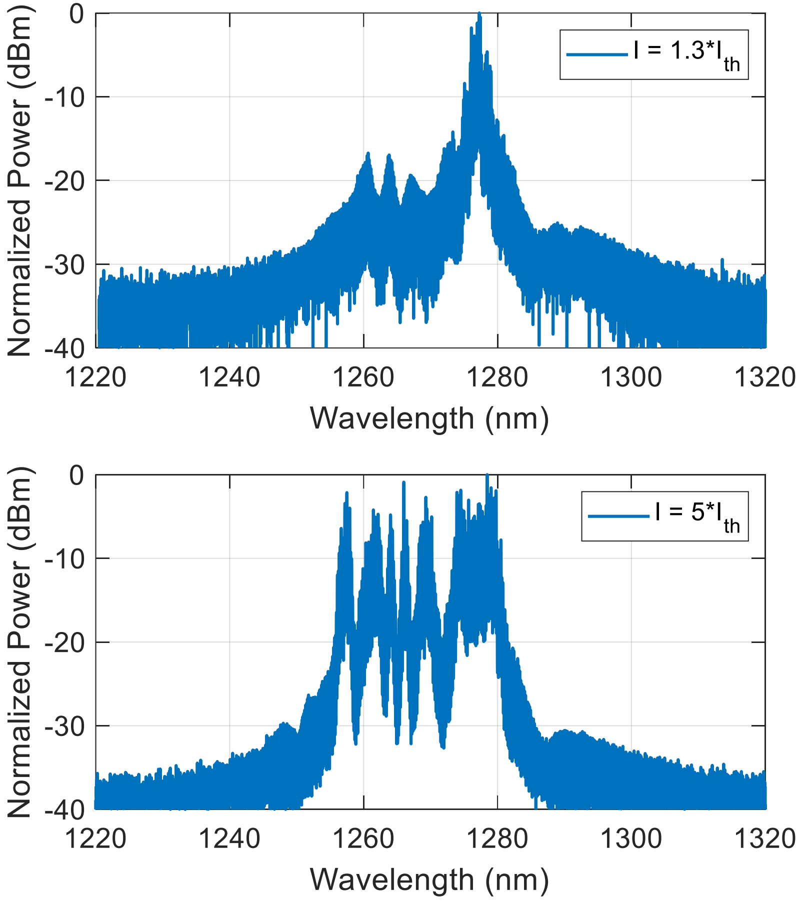
Pulsed Light-Current



Parameter Extraction



Lasing Spectra



- Extracted injection efficiency, η_i, and internal loss, a_i from pulsed LI data

Selective Area Heteroepitaxy for Scaling and Process Integration

Selective Area Heteroepitaxy (SAH) on Silicon

UCSB

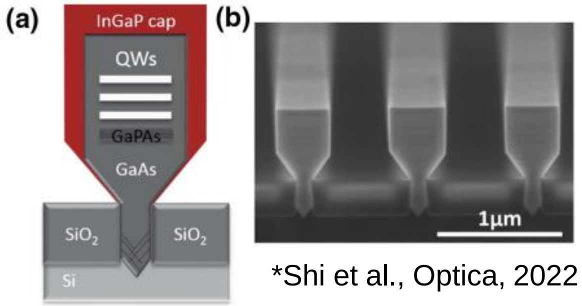
❑ Advantages

- III-V materials deposited only where needed
- High integration density possible
- Thermal stress relief avoids film cracking
- Reduction of dislocations by aspect ratio trapping (ART)
- Enables process integration and coupling to waveguides

❑ Challenges

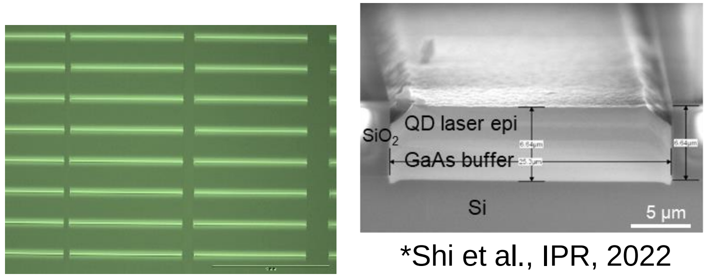
- Growth conditions differ from blanket deposition
- Challenges associated with maintaining selectivity and minimizing parasitic deposition (limitations on materials, ex. AlGaAs)
- Thickness uniformity with controlled faceted growth
- Crystalline defects and surface morphology

Nanoridges on nano V-grooved Si



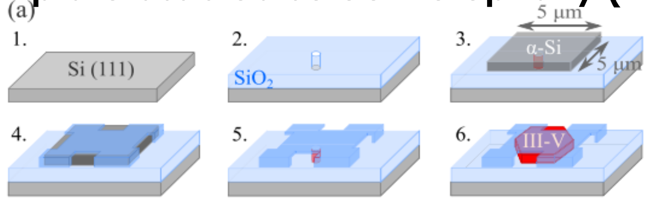
*Shi et al., Optica, 2022

QD laser on Si in recess by SAH



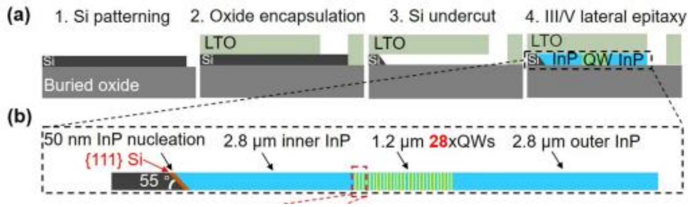
*Shi et al., IPR, 2022

Template assisted selective epitaxy (TASE)



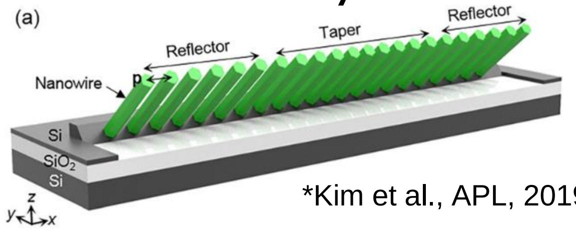
*Mauthe et al., JSTQE, 2019

Confined epitaxial lateral overgrowth (CELOG)



*Li et al., JLT, 2022

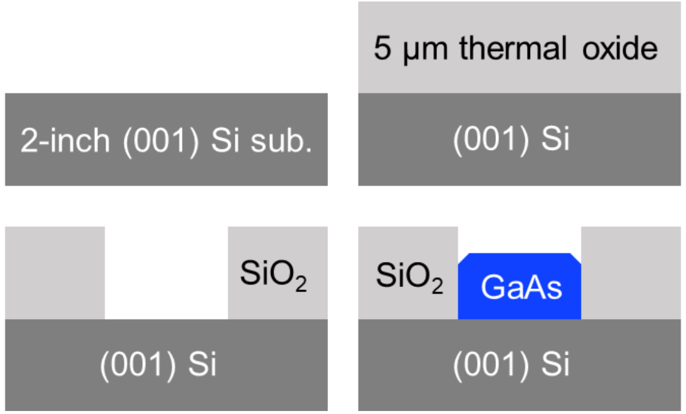
Nanowire array on SOI

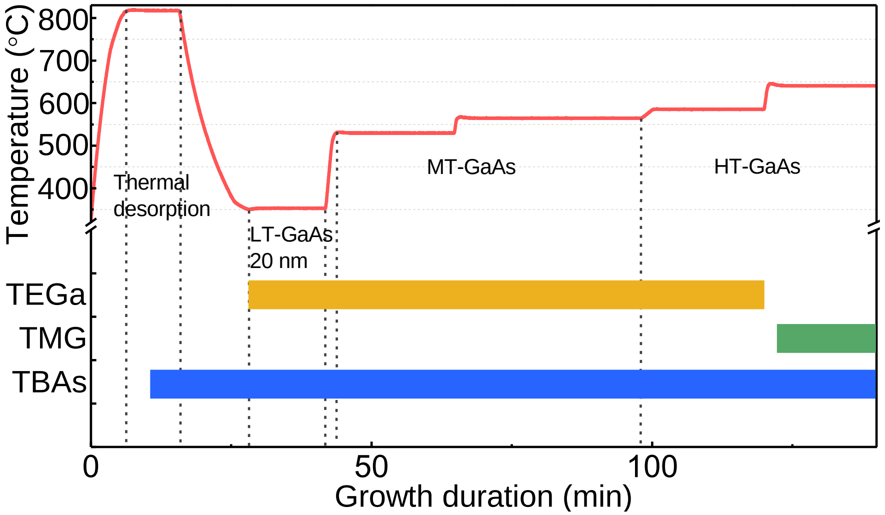


*Kim et al., APL, 2019

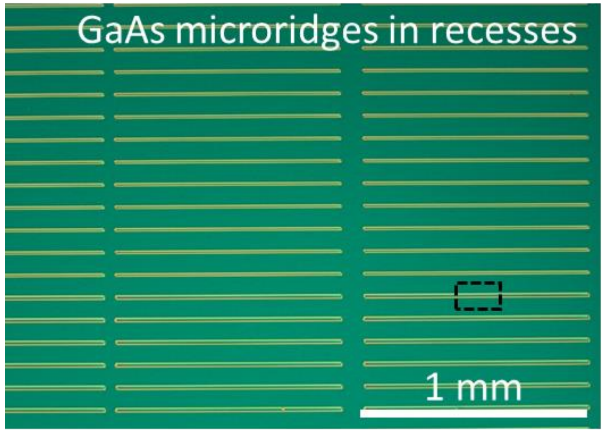
SAH of GaAs on Flat-bottom Si Recess

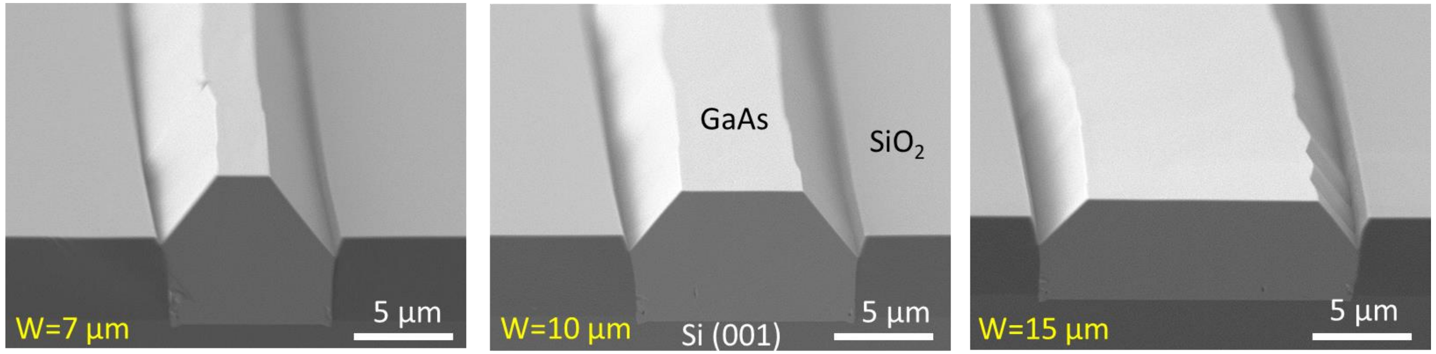
UCSB





*Shi et al., APL, 2021





- Recesses form by etching SiO_2 to expose/etch Si substrate
- Pattern fill factor of ~10% with recess widths varying from 7 to 15 µm, lengths from 250 µm to 1500 µm
- Excellent selectivity across wafer and achieved **APB-free GaAs surface for up to 15 µm wide trench**

GaAs SAH on Nano V-groove Si Recess

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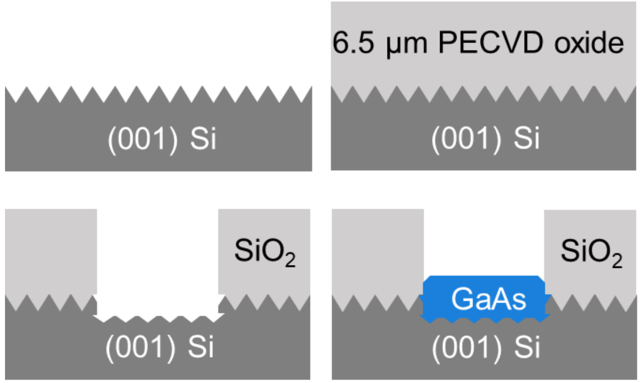
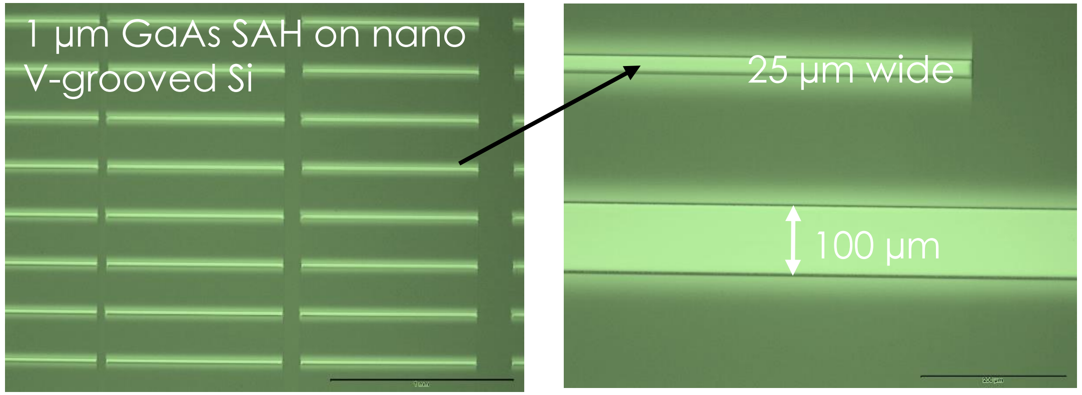
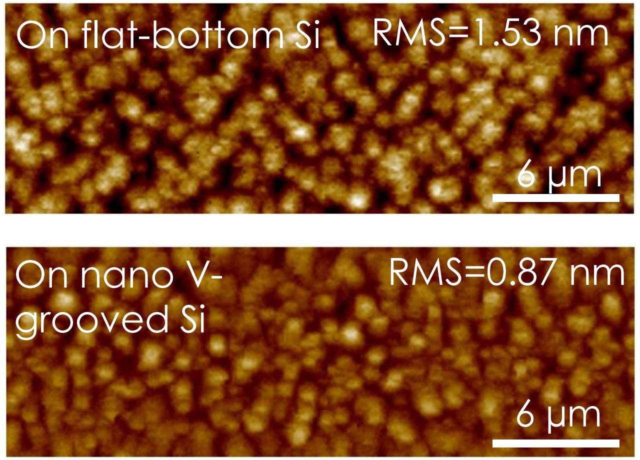
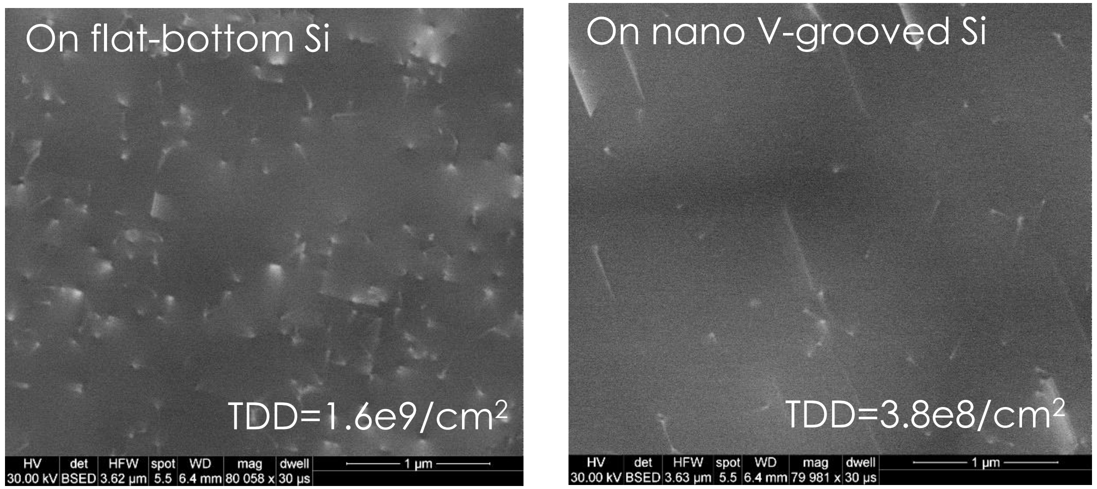






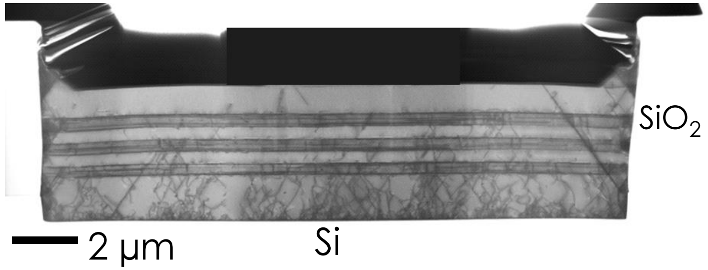


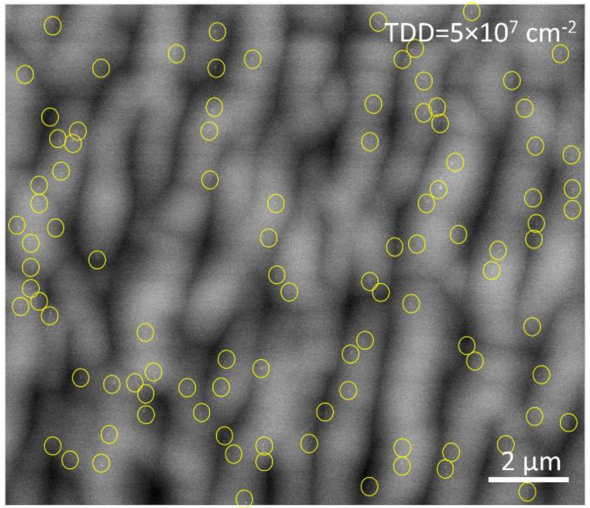
- Smoother surface achieved for nano V-groove Si with oxide recess
- APB-free for nano V-grooved Si with any width (APB-free on flat-bottom Si only up to 15 µm wide)
- Lower overall dislocation density achieved with V-grooves in recess

*Shi et al., IPR, 2022

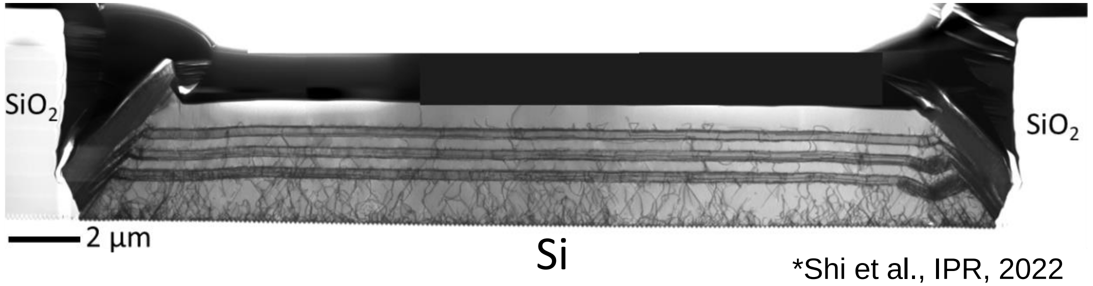
SAH on Flat-bottom vs. Nano V-groove Si

15 µm wide GaAs on flat-bottom Si

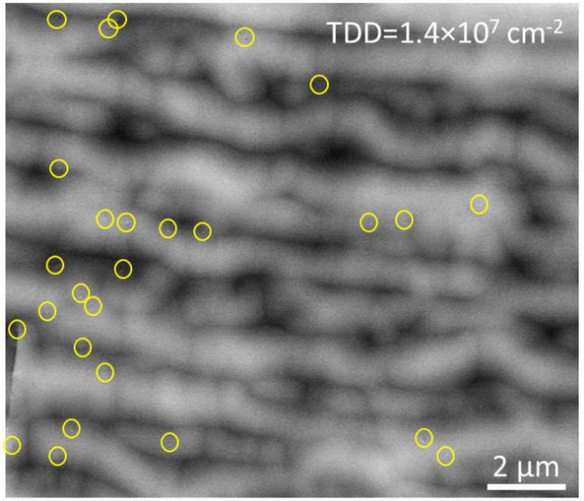


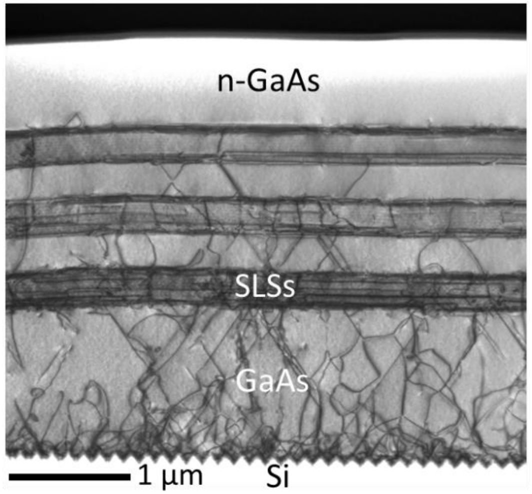


25 µm wide GaAs on nano V-grooved Si



*Shi et al., IPR, 2022





- 5x TCA between 735°C and 355°C, and InGaAs/GaAs strained layer superlattices (SLSs) inserted
- Evident dislocation termination and annihilation by SLSs in SAH, surface defect density on the order of 1e7 cm^{-2}

Microdisk Lasers (MDLs) on Flat-bottom vs. Nano V-groove Si

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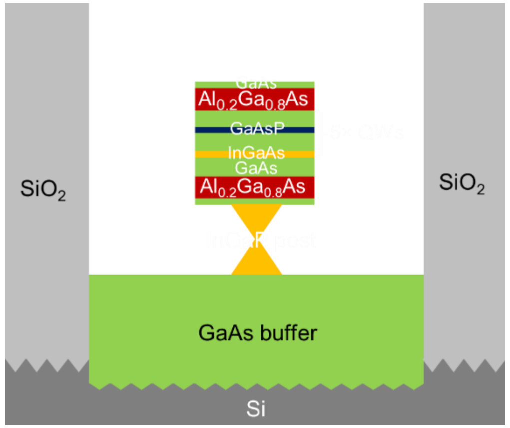

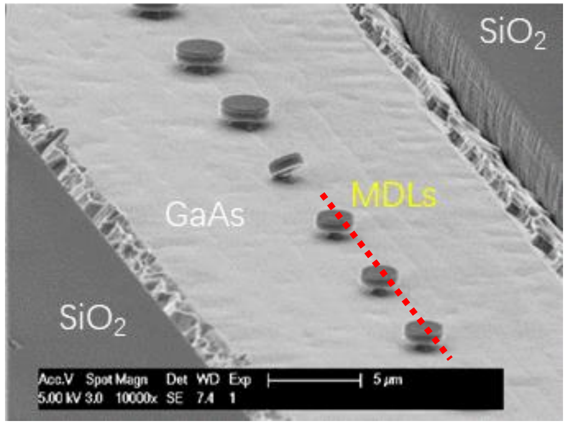

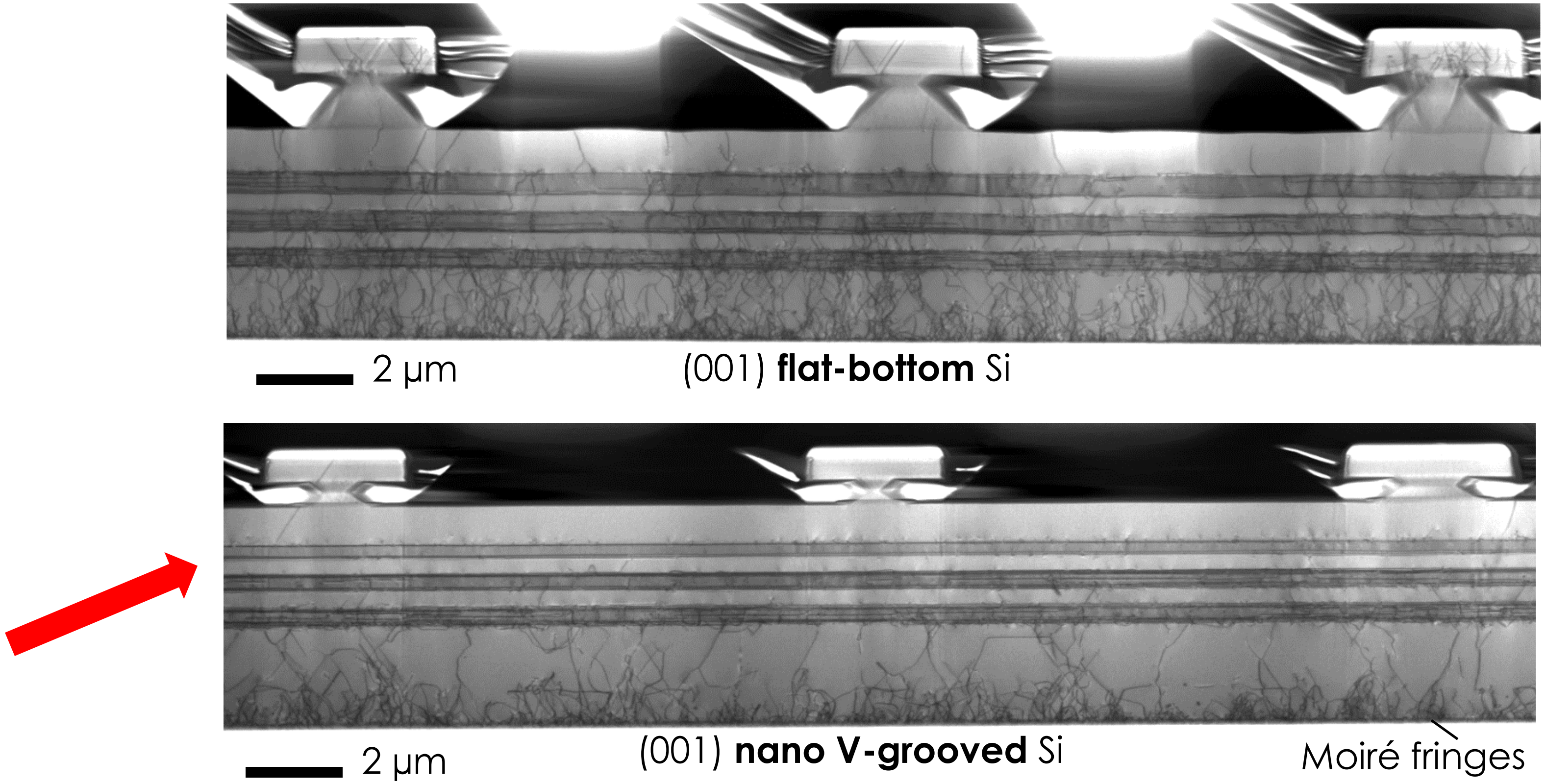

*Shi et al., IPR, 2022

- Dislocations in MDLs on flat-bottom Si partially due to inferior QW/InGaP interfaces
- Fewer dislocations inside disk regions when growing on nano V-grooved Si
- QW as gain elements since QW is more sensitive to dislocations

MDL Performance Comparison

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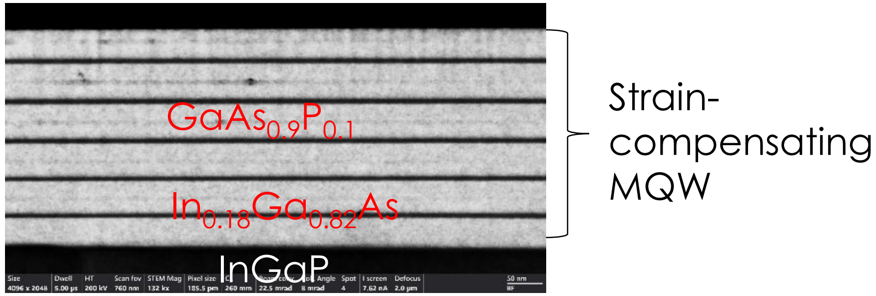
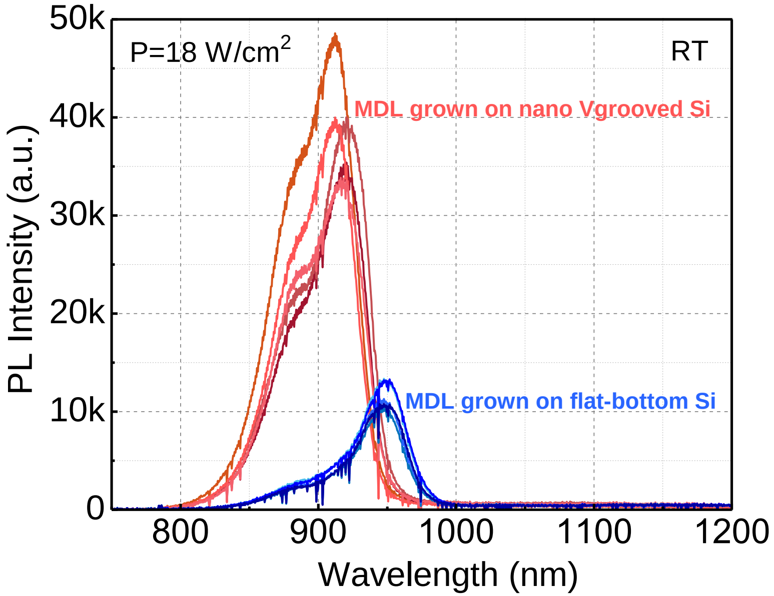
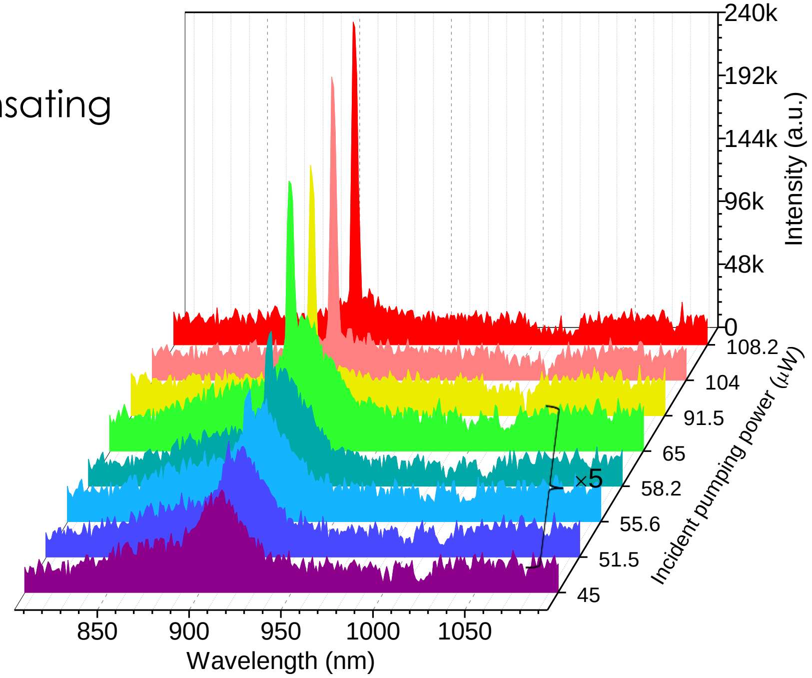
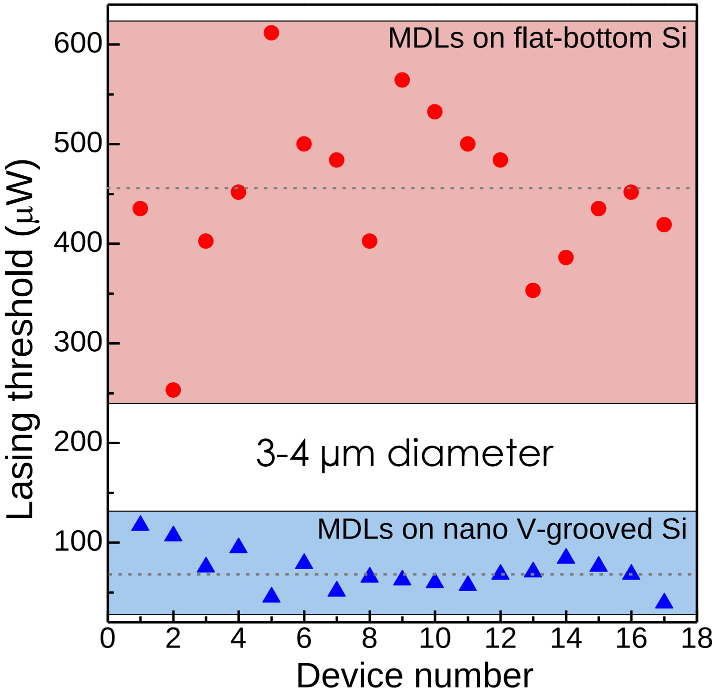






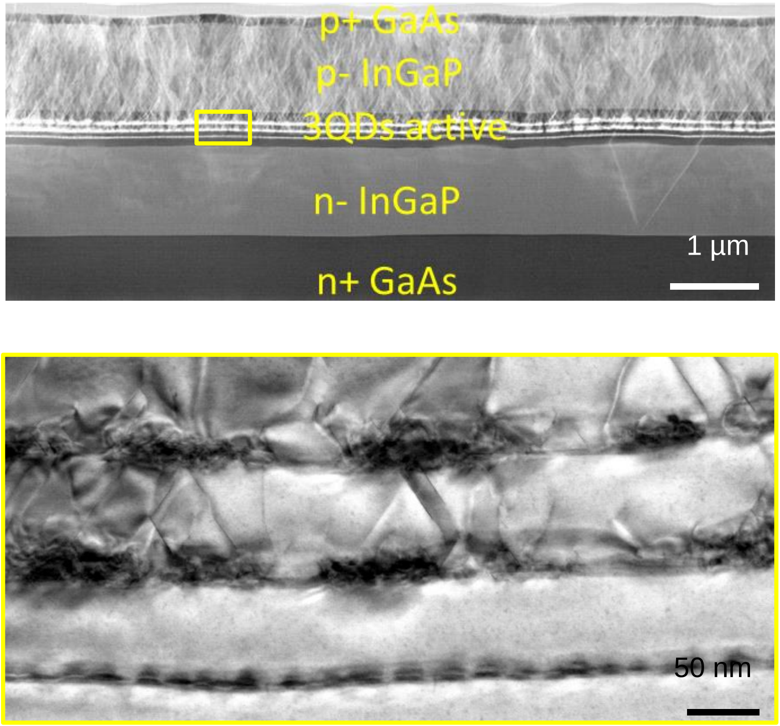


*Shi et al., CSW, 2022

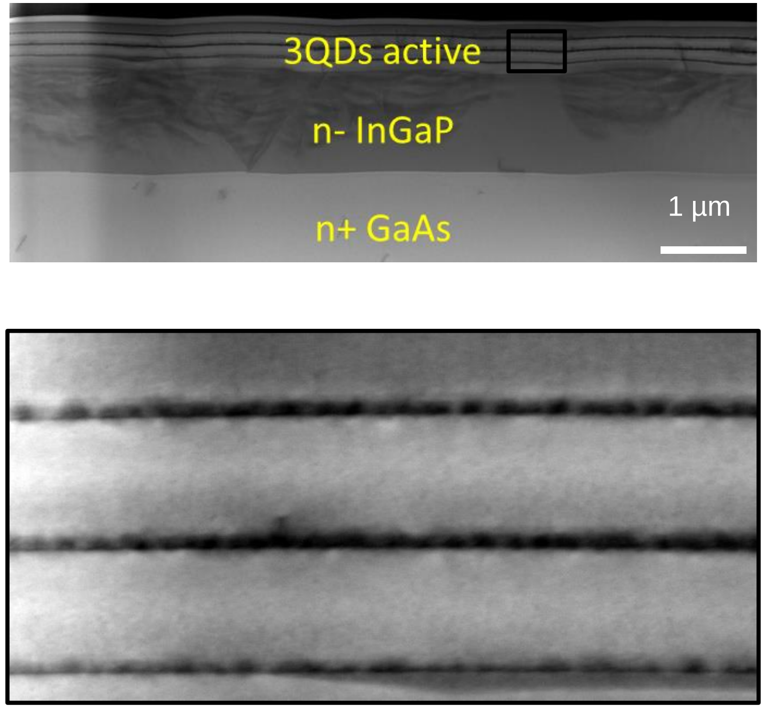
- QW optimized by increasing barrier thickness, higher growth temperature and strain-compensating InGaAs/GaAsP QW/Barrier
- Note that the shorter peak wavelength is due to thinner QW and lower Indium composition (wider recess on nano V-Si)
- **Lower density of dislocations leads to higher PL intensity and lower statistical lasing thresholds (6.5X lower)**

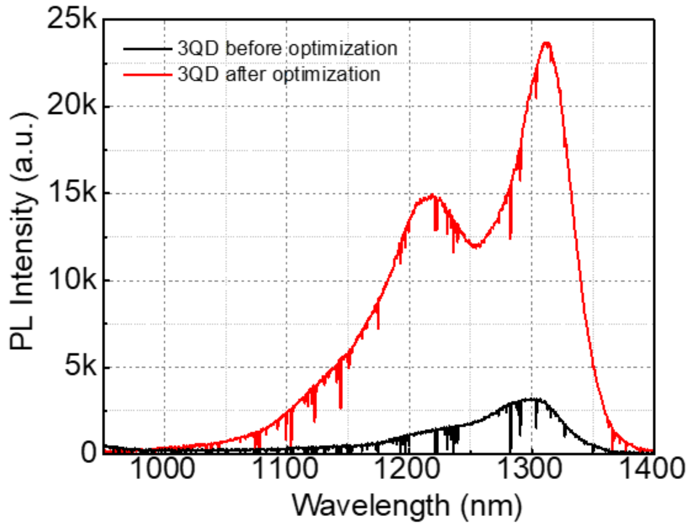
Multi-layer QDs Stacking

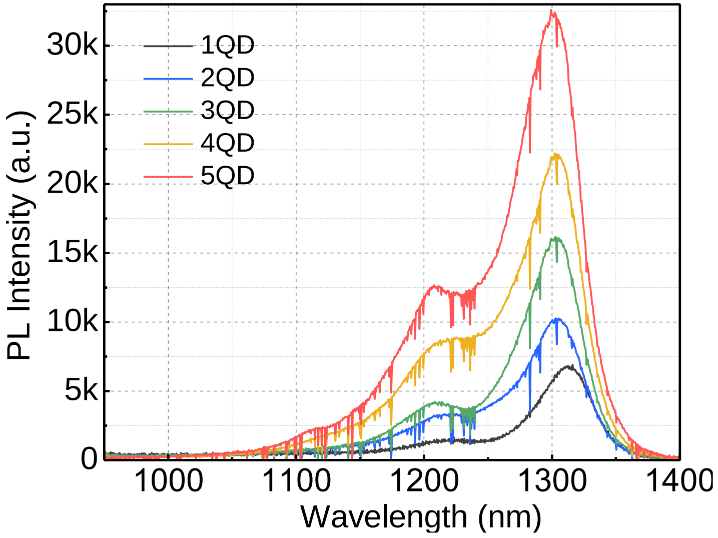
2.7 ML QDs



2.3 ML QDs







- Capable of stacking 5 layers of QDs with enhanced PL emission, by reducing QD deposition amount
- PL center wavelength near 1310 nm with narrow FWHM (32 meV)
- Clear ground state and excited state emission separated by nearly 100 nm

*Shi et al., IPR, 2022

Zero-Gap and Coupling Simulations

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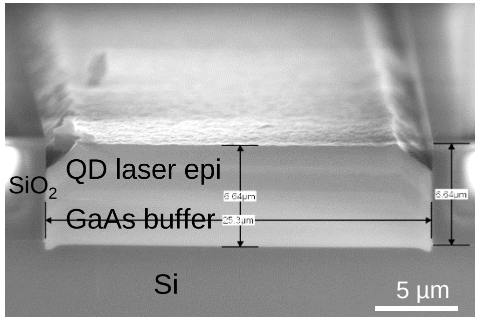
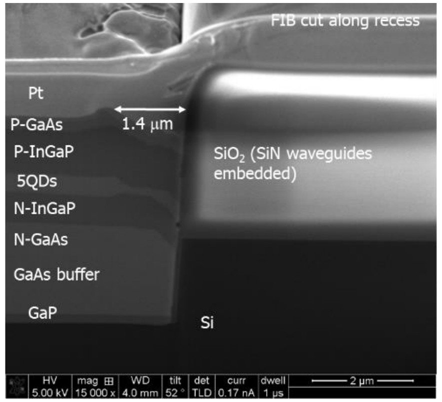
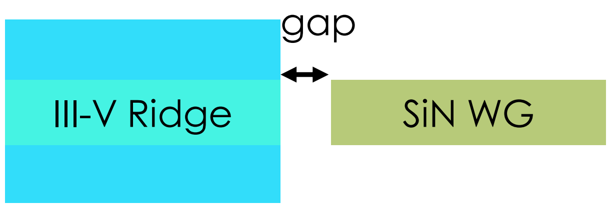
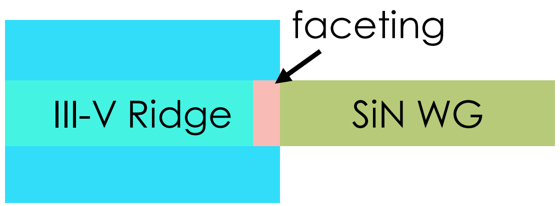
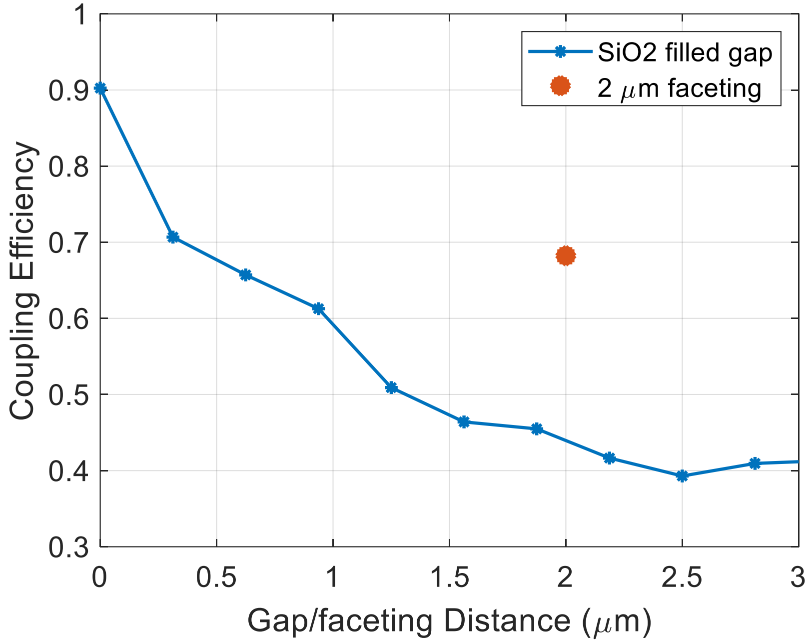
- Zero gap between III-V and SiN/Si waveguide to facilitate coupling
- Simulate the effect of faceting on coupling efficiency
- Compare to coupling with gap (filled with SiO_2)



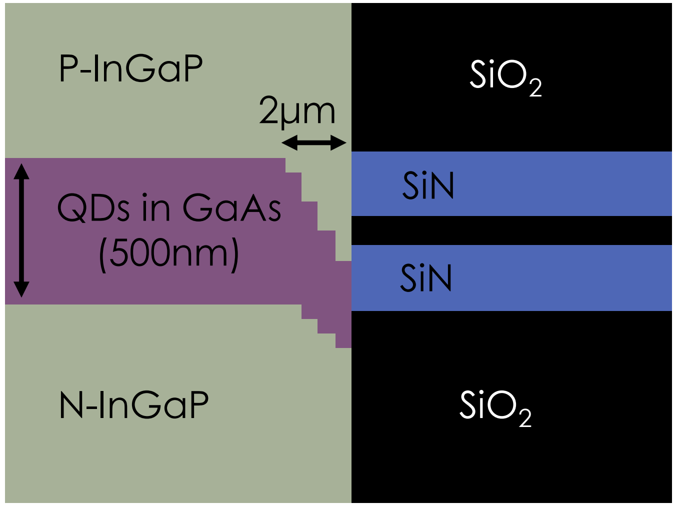


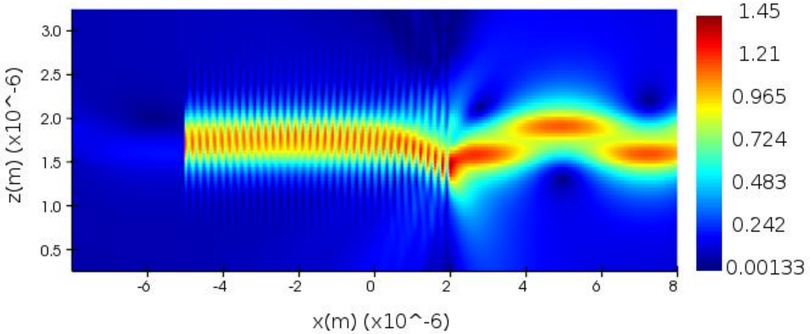






FDTD Simulation (side view)





- Zero gap minimized butt coupling loss from laser to waveguide
- Faceted growth within 2 µm from end face
- ~70% coupling efficiency possible with 2 µm faceting at interface
- Etched facet might be necessary to avoid non-uniform QWs and InGaP claddings

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Comparing MOCVD and MBE for Scaling and Process Integration

Hybrid MOCVD+MBE

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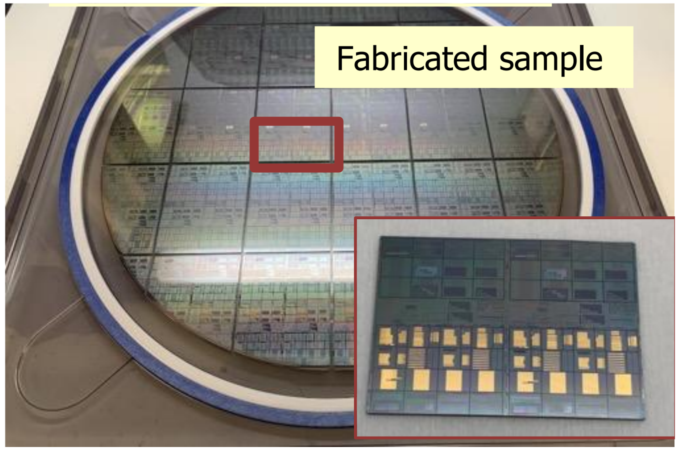
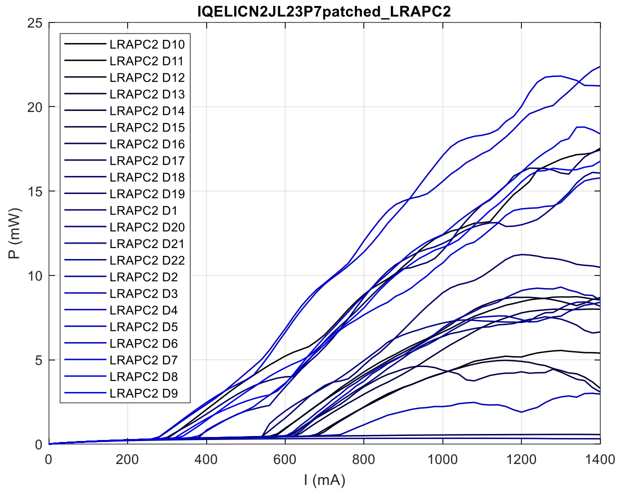
MOCVD+MBE growth on 300mm SiPh
Fabrication on small die

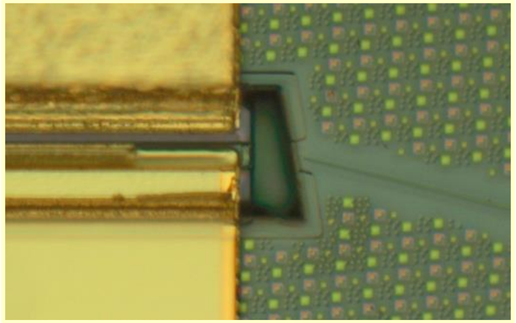


Many working quantum dot lasers



Bowers, et al., UCSB

Low coupling efficiency due to large gap between III-V and SiN



- MOCVD required for initial growth on standard silicon and in recess
- MBE growth not selective therefore CMP process required to remove unwanted material
- MBE quantum dot growth process is mature but large gap between III-V and Si/SiN waveguide leads to high coupling loss
- MOCVD has higher growth rate and selective/conformal growth for scaling and process integration

Hybrid (MO)CVD+MBE and All MOCVD

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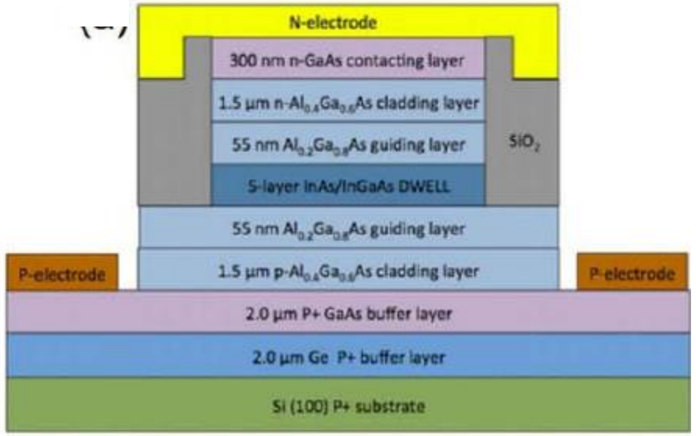
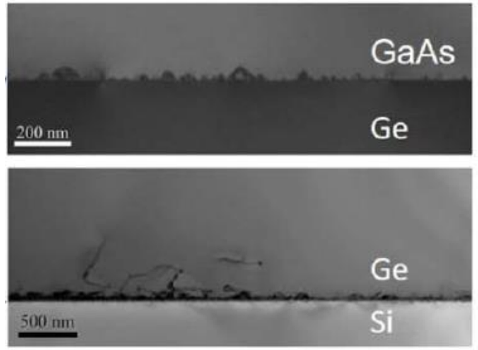
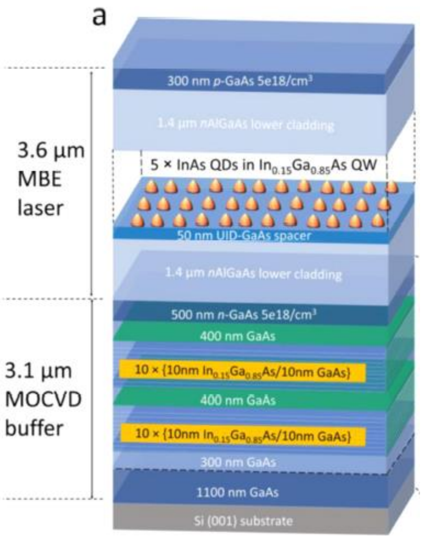
CVD Germanium-on-Silicon followed by **MBE** QDs

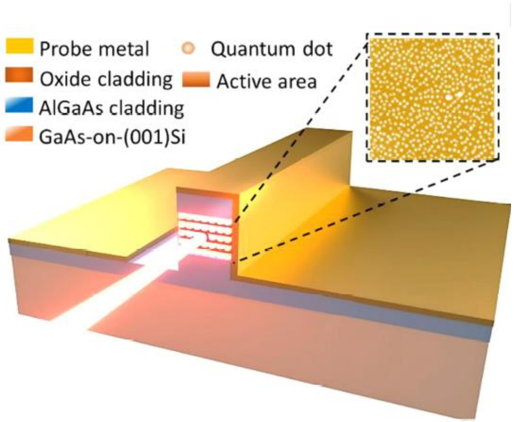




* M. Liao *et al* 2018 *Semicond. Sci. Technol.* **33** 123002

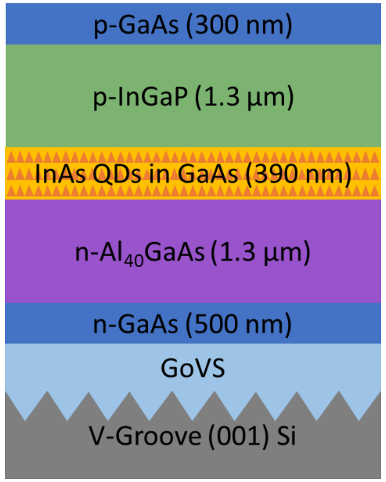
MOCVD GaAs-on-Silicon followed by **MBE** QDs

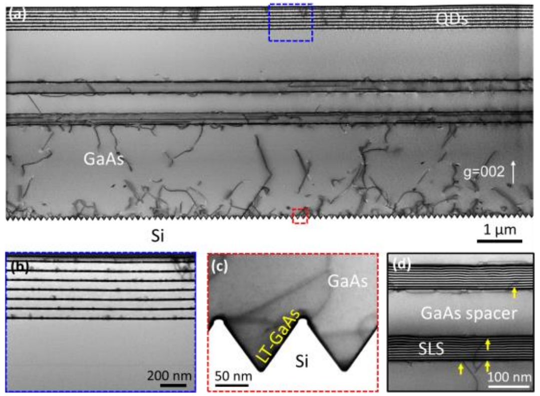




*Y. Wan et al., IEEE *J. Sel. Topics in Quantum Electron.*, vol. 26, no. 2, (2020)

MOCVD laser GaAs-on-Silicon followed by **MOCVD** QDs





*P. Verrinder, et al., CLEO (2023)

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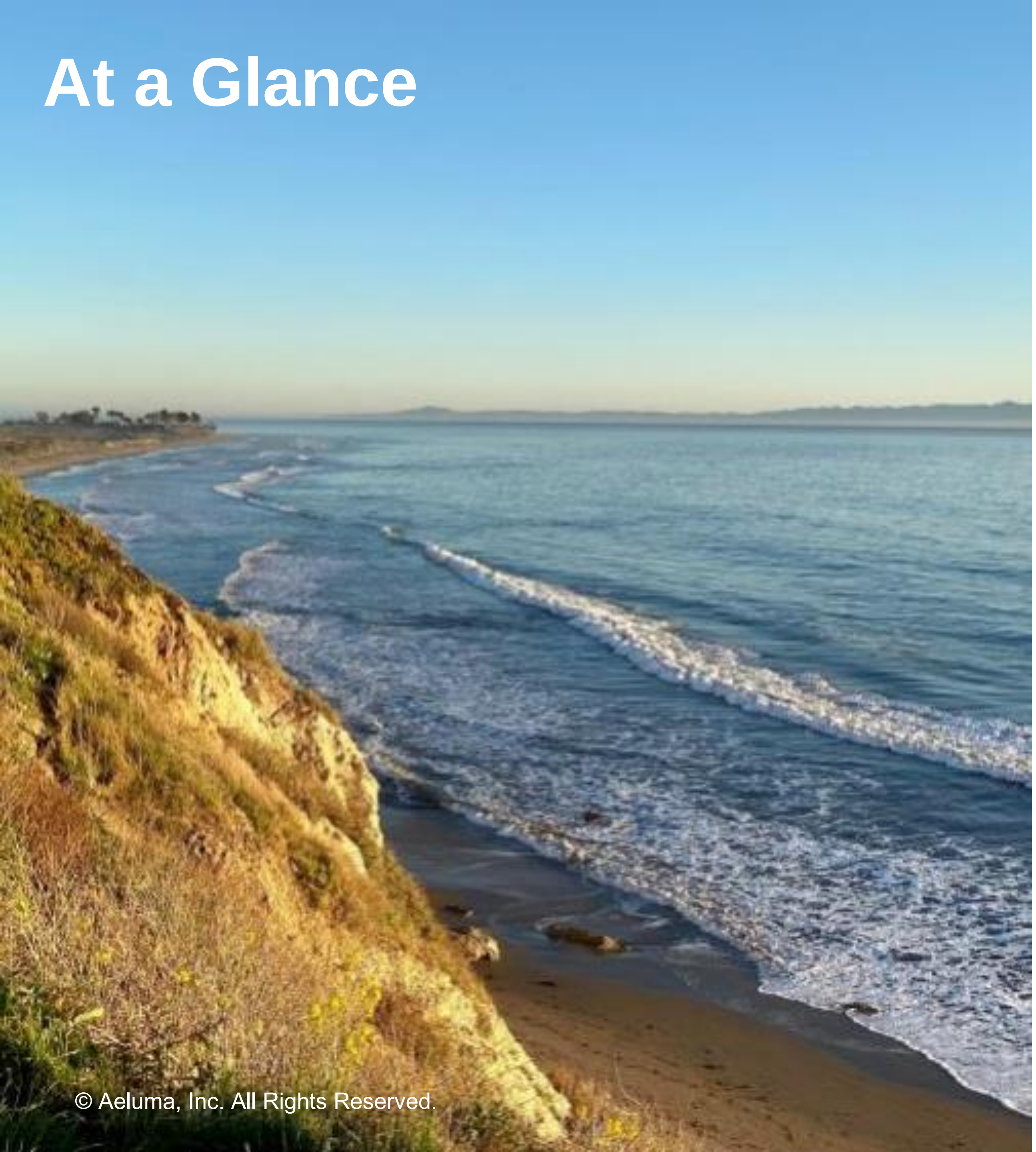
Scaling and Commercialization Opportunities

At a Glance



Aeluma, Inc. (OTCQB: ALMU)

A transformative semiconductor chip company

High Performance Semiconductors that Scale

Headquarters: Goleta/Santa Barbara, California

Markets: Automotive LiDAR, Mobile, AR/VR, Communication, Defense & Aerospace, AI

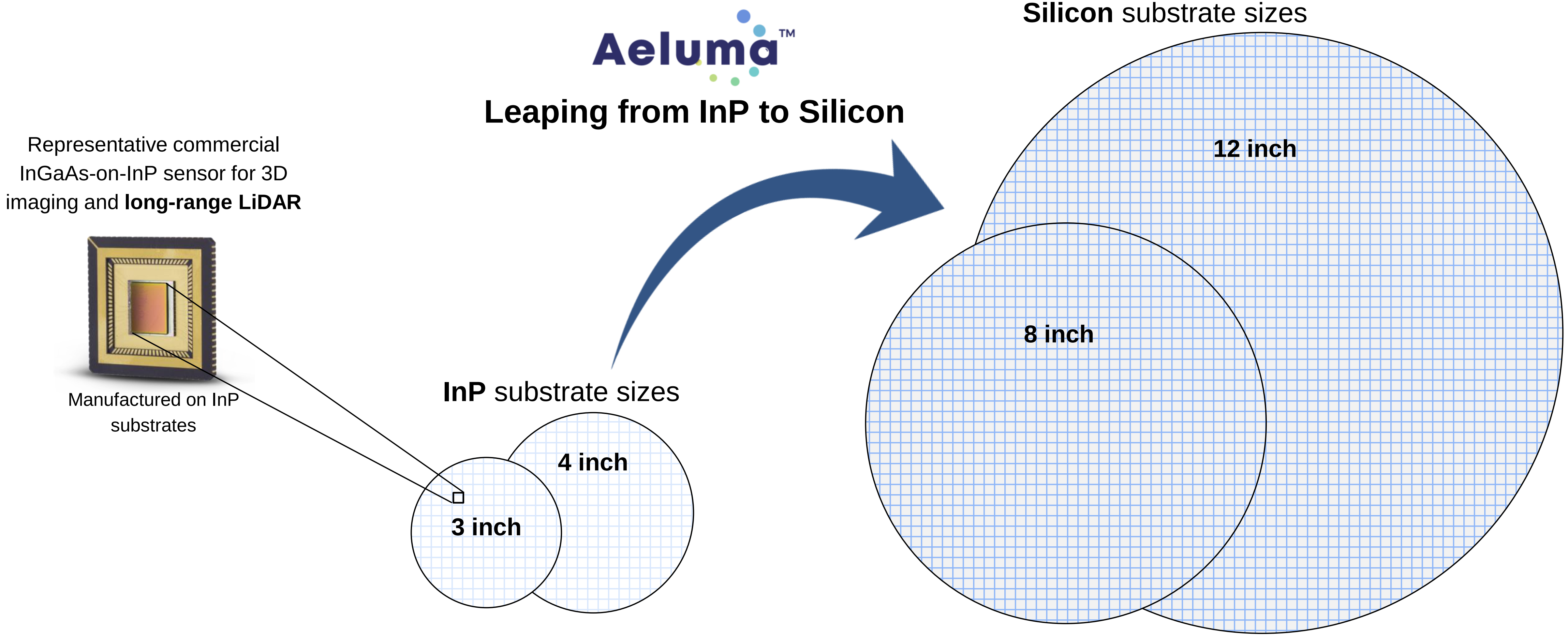
Team: ~15 people

Expertise: Compound semiconductors, heteroepitaxy, photonic integrated circuits, silicon photonics, lasers, detectors, volume manufacturing

Intellectual Property: ~25 issued and pending patents, trade secrets

The Aeluma Approach to Sensor Manufacturing

High-Performance Technology with Large-Diameter Substrate Manufacturing



InGaAs: Indium Gallium Arsenide; InP: Indium Phosphide; LiDAR: Light detection and ranging; FPA: Focal plane array
Source of image: https://www.flir.com/support/products/swir-ingaas-fpa/; Note: Outcomes cannot be guaranteed.

Aeluma's Technology Breakthrough

Scalable, Cost-Effective Manufacturing Enabled by Cutting-Edge Intellectual Property

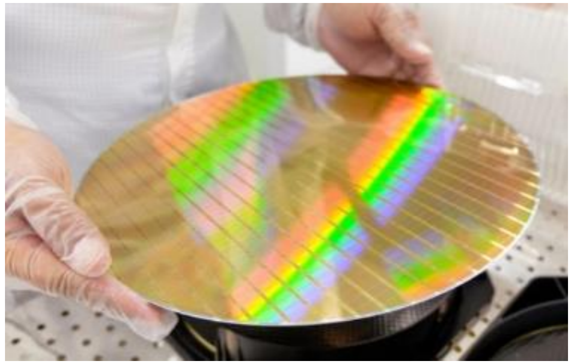
Conventional manufacturing of InGaAs photodetector arrays

Non-scalable, manual and low throughput

16X wafer area

Moving from 3-inch to 12-inch wafers

Aeluma high-performance InGaAs photodetector arrays with Silicon manufacturing



- ✔ Highly automated and ability to produce many arrays per wafer
- ✔ 10X lower manufacturing cost for mass market applications

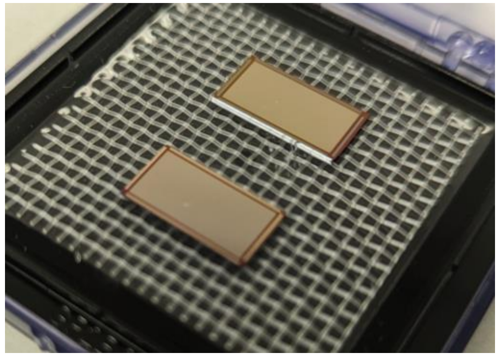
Note: Outcomes cannot be guaranteed.

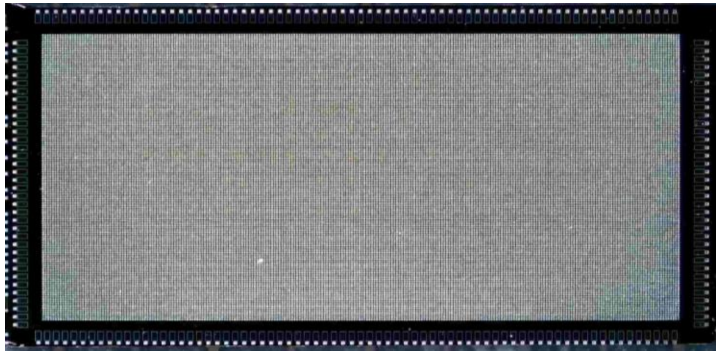
Summary of Product/Technology Offerings

Detector Arrays

Custom Detector Arrays

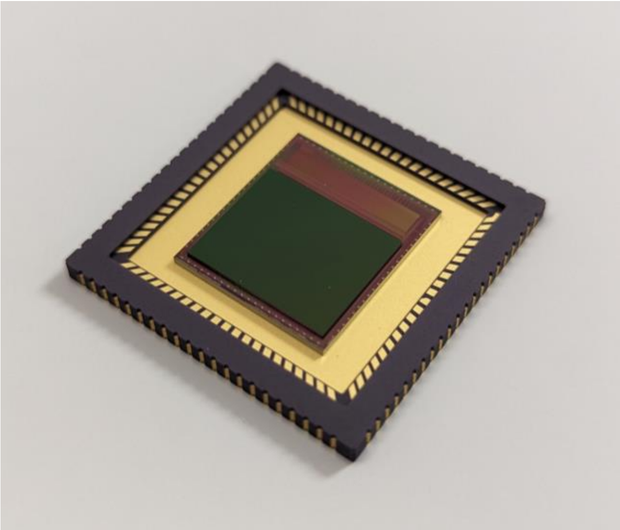
- Low dark current photodetector arrays manufactured with large-diameter substrate platform
- Pixel and array size customizable
- Typical array sizes: 128 X 32, 256 X 128, 640 X 512
- Delivered as PDA chips or with ROICs
- FPA assembly available
- Small test arrays (ex. 8 X 8) available for eval./qual.





Examples shown are 256 X 128 arrays

Focal Plane Array Assembly



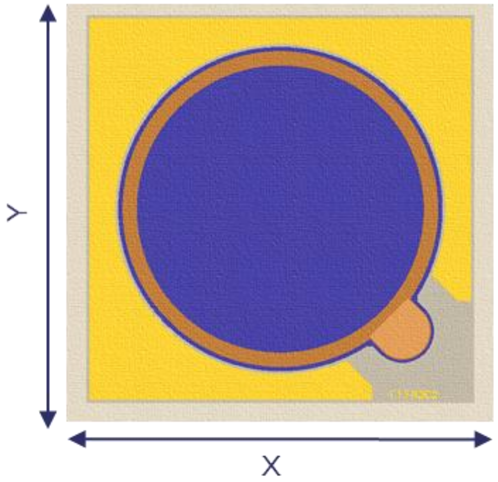
Applicable markets include automotive, mobile, AR/VR, defense & aerospace, industrial and logistics, and security

Summary of Product/Technology Offerings

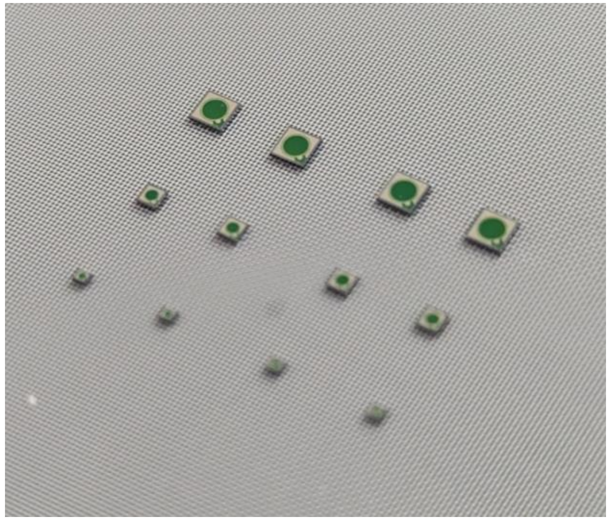
Large-Area InGaAs Detectors

High sensitivity, low dark current and high speed detectors for SWIR and XSWIR

- Typical Photosensitive Diameter (D): 0.25 to 5.0mm
- Typical Operating Wavelength (λ): 0.95 to 1.55μm)
- Device: PIN, APD or SPAD
- Format: Bare die or mounted in TO package



Bare Die

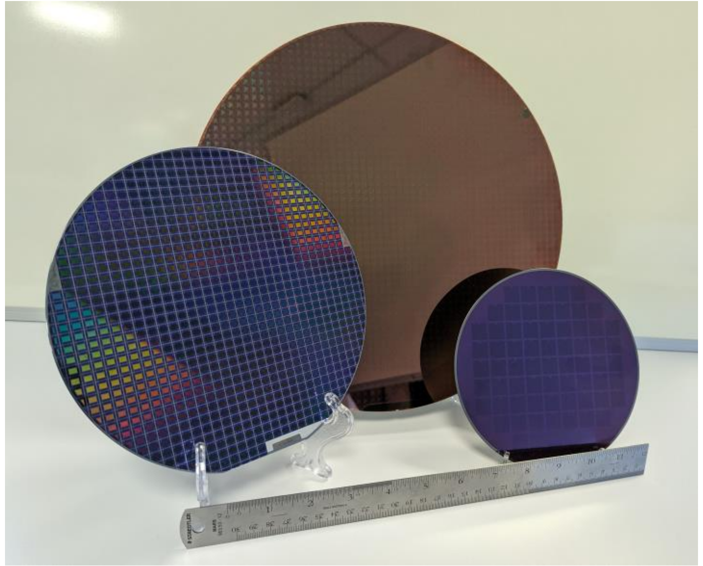


TO Package

Applicable markets include automotive, mobile, AR/VR, defense & aerospace, industrial and logistics, gas sensing, instrumentation, and security

Summary of Product/Technology Offerings

Heterogeneous Integration Platform

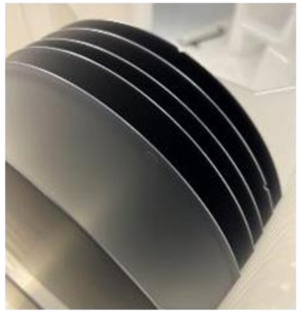


Aeluma's proprietary heterogeneous integration platform integrates high-performance compound semiconductors (ex. GaAs, InP, GaSb) on large-diameter substrates including up to 12-inch Silicon.

This technology has the potential to scale, reduce cost, and increase yield, all of which are critical for emerging and mass-market applications.

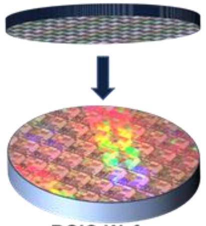
Summary of Offerings

High Quality Templates



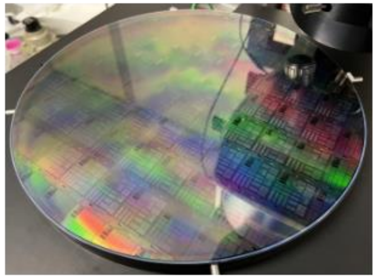
High-quality GaAs, InP, and GaSb templates grown on up to 12-inch Silicon substrates for scaling high-performance technologies to larger wafer sizes.

Large-Scale Detectors for Wafer-Scale Integration



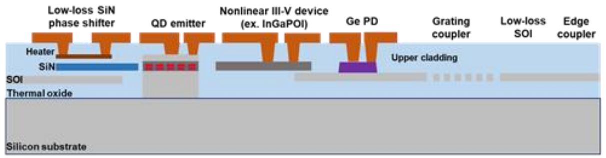
Manufacturing detectors on the same substrate size as read-out ICs enables wafer-scale integration to improve performance, increase functionality, and reduce cost.

Monolithic Integration by Selective Growth



Selective growth enables CMOS process integration and may be applied to Silicon Photonics, III-V electronics integrated with Silicon CMOS, integration of InGaAs detectors with CMOS read-out ICs, and more.

Lasers for Silicon Photonics



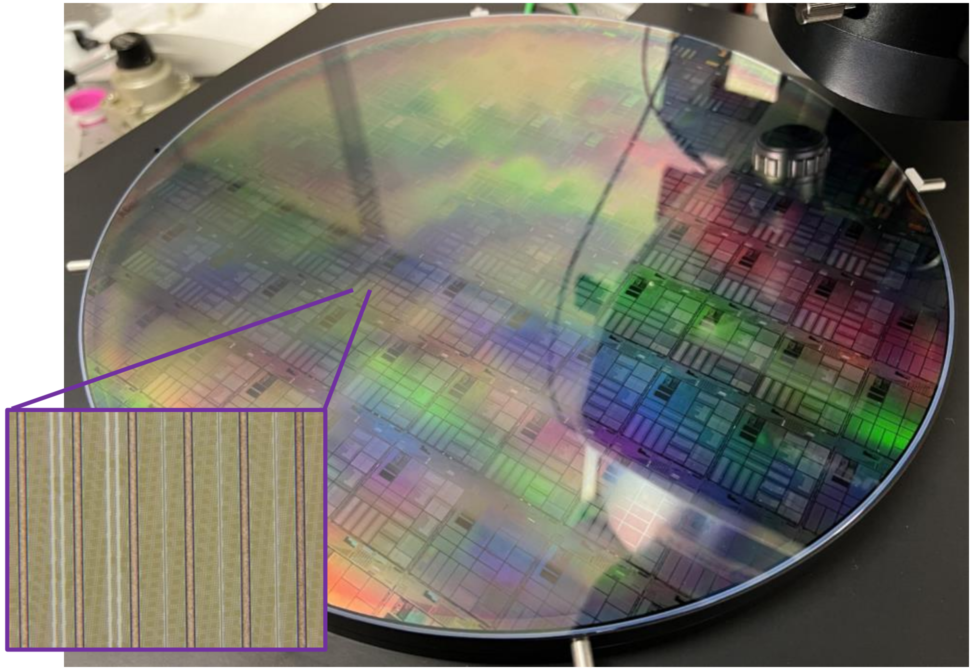
Integration of quantum dot lasers and other group III-V active devices in Silicon Photonics

Applicable markets include automotive, mobile, AR/VR, defense & aerospace, quantum computing, AI, and communication

Silicon Photonics and Laser Integration

Aeluma's Technology Can Enable Process Integration

12-inch Silicon Photonics Wafer with Aeluma Materials



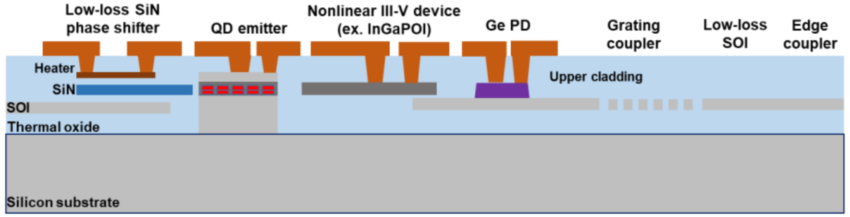
[Aeluma, Inc. Enters into Agreement with RFSUNY to Support AIM Photonics]

Silicon Photonics Applications

High-Performance Computing and Data Centers

AI and Photonic Computing

Lasers for Silicon Photonics



Integration of quantum dot lasers and other group III-V active devices in Silicon Photonics

Outcomes cannot be guaranteed.
Sources of images: https://venturebeat.com; https://spie.org/news/photonics-focus

Aiming to Service a Broad Market

High-Performance Semiconductors for Sensing and Communications

Automotive LiDAR

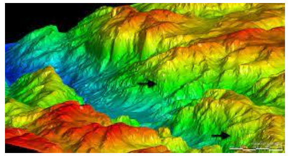


- Consumer vehicles
- Robotaxis
- Trucking

Industrial and Logistics


- Robotics
- Delivery robots
- Factory automation
- Logistics
- Security

Defense & Aerospace

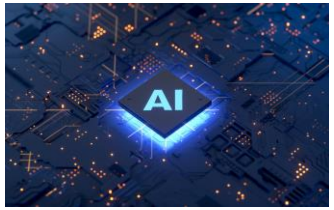
- Imaging and LiDAR
- Security
- Autonomous systems
- Atmospheric sensing
- Topography

Mobile and AR/VR



- Mobile phone, tablet
- Face ID
- LiDAR scanner
- Proximity sensors
- AR/VR glasses

Communications, Quantum and AI

- Telecommunications
- Data centers
- Quantum computing
- 5G/6G
- AI communications

Summary and Outlook on QDs and Heterogeneous Integration

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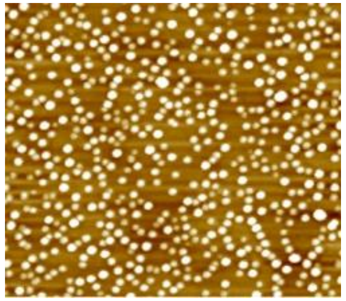
- Hybrid approach (MOCVD+MBE) interim solution for demonstration and low volumes
- (MO)CVD is required for growth on standard CMOS Si substrates and for process integration (i.e. selective growth)
- All-MOCVD approach preferred for scaling and process integration

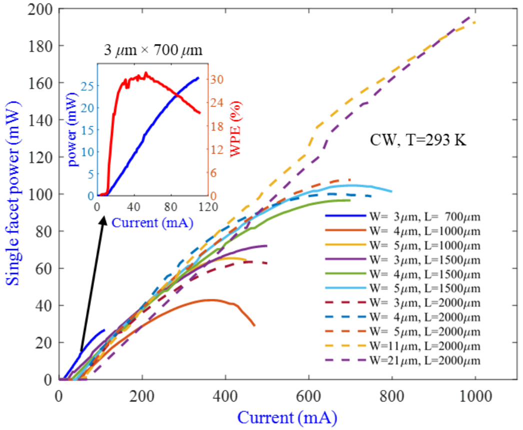
MOCVD Quantum Dot Lasers



Perspectives on MOCVD and Quantum Dot Lasers

- ~15 years ago: "You cannot grow VCSELs by MOCVD, you have to use MBE"
- Today: All large-volume commercial VCSELs grown by MOCVD

- There are many other examples of transition to MOCVD for commercialization
  - III-V HEMTs, Visible LEDs/Lasers, etc.



- Recently: "You cannot grow Quantum Dots by MOCVD, you have to use MBE"
- <u>Prediction: "As demand for Quantum Dot lasers and integration with Silicon Photonics grows, all commercial Quantum Dot lasers will be grown by MOCVD"</u>

Acknowledgements: Support from DARPA (LUMOS), SRC (CogniSense), CHIPS Act (MEC)