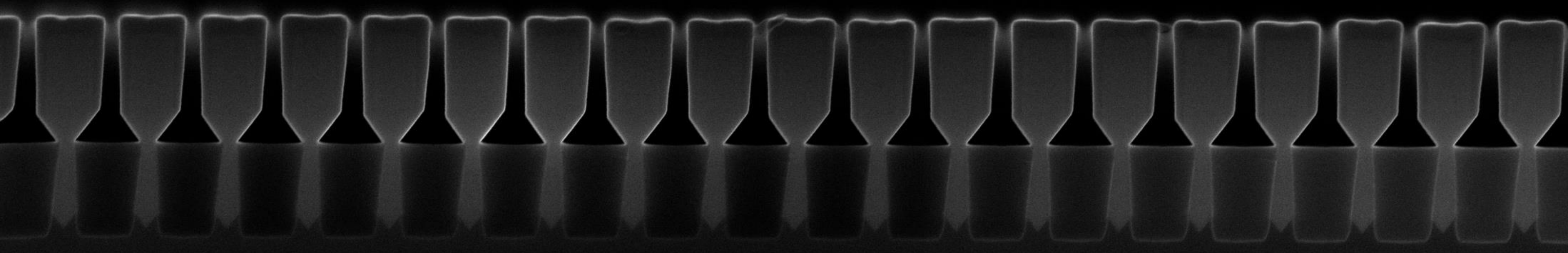

III-V Nano-Ridge Lasers Integrated on Silicon

Dries Van Thourhout

Main Contributors: D. Collucci, Z. Ouyang, A. Yiman, E. Fahmy, PY. Hsieh, P. Swekis
M. Demaeyer, G. Morthier, J. Van Campenhout, B. Kunert

Motivation

It's all about light, so we need a laser source !

- Main driver: interconnect for AI engines
- Different options
  - Off-chip, separate from the core optical interconnect
    - Option 1: high-power, stand alone
    - Option 2: multi-wavelength laser modules with additio
  - On-chip
    - Probably challenging when densily integrated with elect (temperature)
    - Relevant for other types of applications (e.g. cheap optical sensors)

NVIDIA and Coherent Announce Strategic Partnership to Develop Optics Technology to Scale Next-Generation Data Center Architecture

NVIDIA to Invest $2 Billion in Coherent to Expand Supply, Deepen R&D and Advance US-Based Manufacturing

NVIDIA Announces Strategic Partnership With Lumentum to Develop State-of-the-Art Optics Technology

March 2, 2026

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NVIDIA to Invest $2 Billion in Lumentum to Grow Capacity, Advance US-Based Manufacturing and Deepen R&D Collaboration in Data Center Optics

Related CLEO talks:

STU2G.1. [Invited Talk] Perspectives on Heterogeneous Laser Integration in Silicon Photonics *Roel Baets*

AM4B.1. [Invited Talk] Scaling Lasers to Support High Bandwidth Silicon Photonics *Jessie Rosenberg*

Integration

Silicon Photonics has no native laser source, so we need heterogeneous integration

- Many integration approaches based on layer transfer are being explored
  - Flip-chip, wafer-bonding, die-to-wafer bonding, microtransfer printing…
  - Allow for transfer of pristine layers, different materials (= different wavelengths), versatile
- Hetero-epitaxy is an alternative but challenging
  - **Lattice** mismatch, mismatch in **thermal** expansion coefficient, mismatch in **polarity**
  - Every material needs separate development
- So why ?
  - Ultimate scalability
  - Designer no longer has to worry about integration approach
  - Think Ge detector vs. III-V detector

Approaches for Hetero-Epitaxy

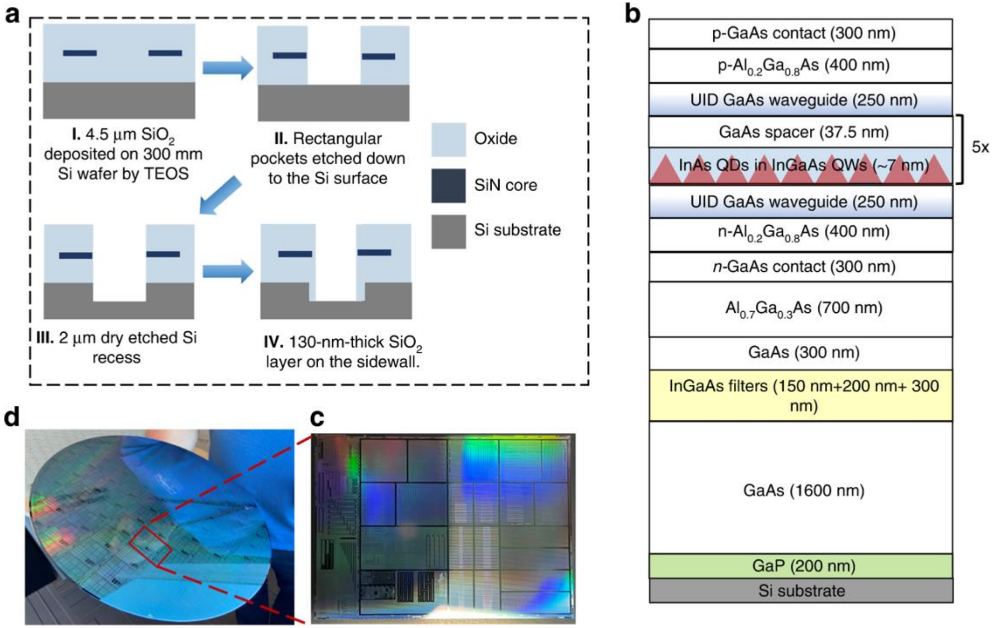
Planar growth vs. localised growth

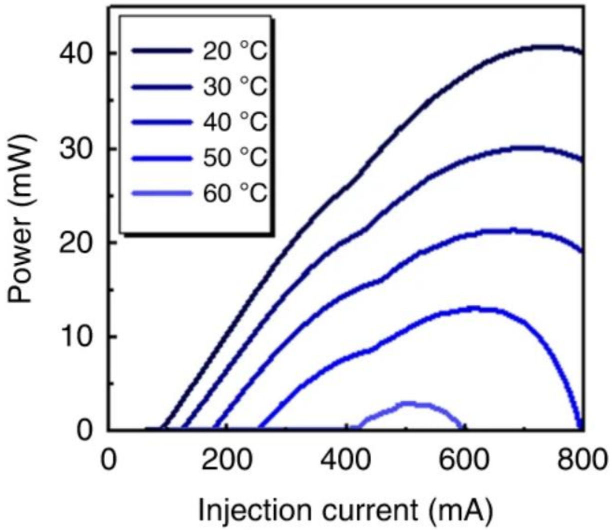
e.g. work UCSB, UCL, Shangai University

Approaches for Hetero-Epitaxy

Planar growth vs. localised growth

- A buffer layer grown on the silicon substrate accomodates for the mismatch in materials





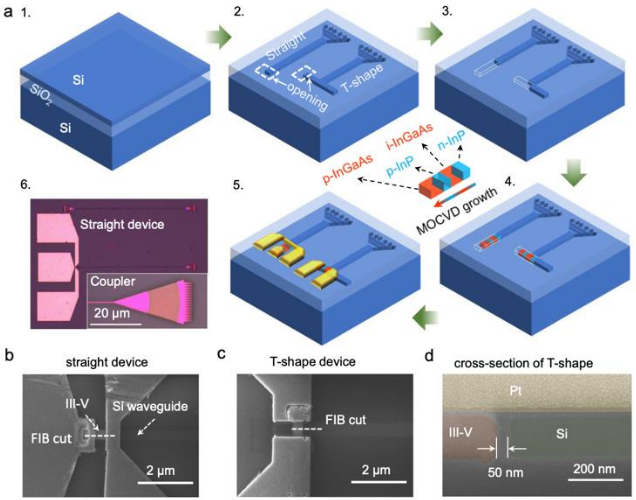
Shang, C., *et al.* Electrically pumped quantum-dot lasers grown on 300 mm patterned Si photonic wafers. *Light Sci Appl* 11, 299 (2022). https://doi.org/10.1038/s41377-022-00982-7

Approaches for Hetero-Epitaxy

Planar growth vs. **localised growth**

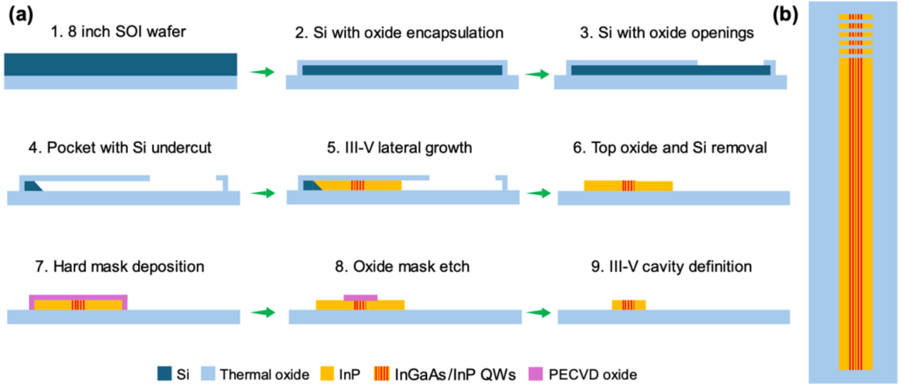
Growing in a confined space suppresses defects

IBM - Template Assisted Growth



Wen, P., Tiwari, P., Mauthe, S. *et al.* Waveguide coupled III-V photodiodes monolithically integrated on Si. *Nat Commun* **13**, 909 (2022). https://doi.org/10.1038/s41467-022-28502-6

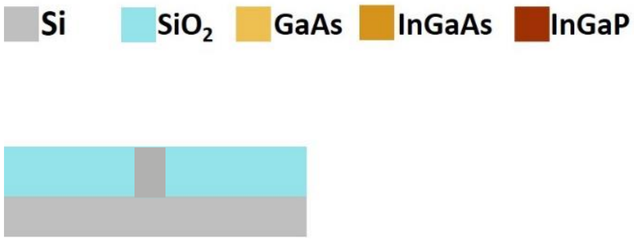
HKUST - Lateral MOCVD



Y.Xue, J.Li, Y.Wang, K.Xu, Z.Xing, K. S.Wong, H. K.Tsang, K. M.Lau, In-Plane 1.5 µm Distributed Feedback Lasers Selectively Grown on (001) SOI. Laser Photonics Rev2024, 18, 2300549. https://doi.org/10.1002/lpor.202300549

Our Approach

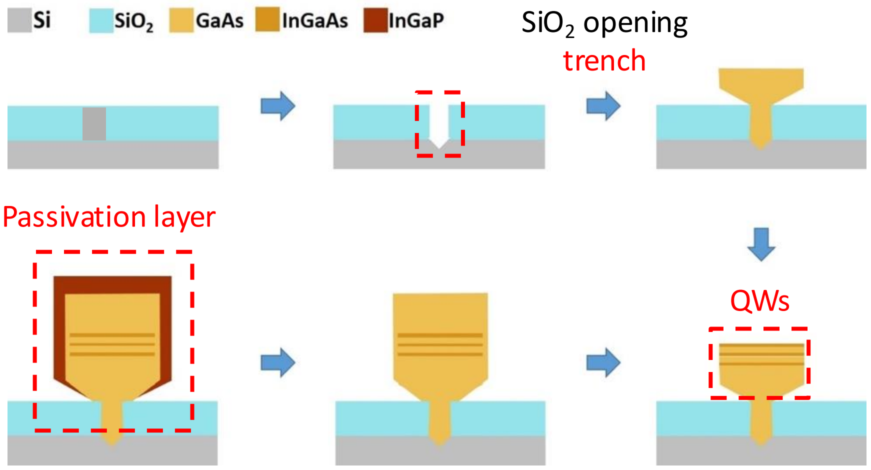
Aspect Ratio Trapping (ART) combined with Nano-Ridge Engineering (NRE)



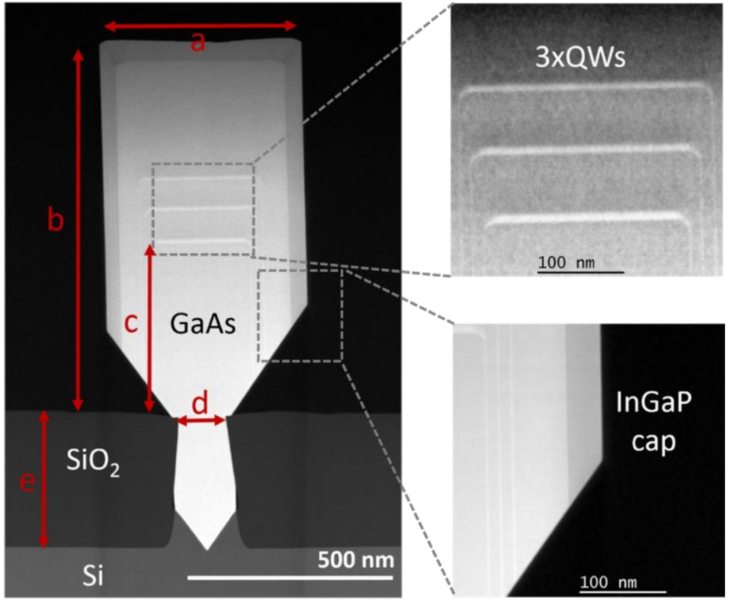
STI-process

Aspect-Ratio-Trapping (ART)

Basic processing scheme



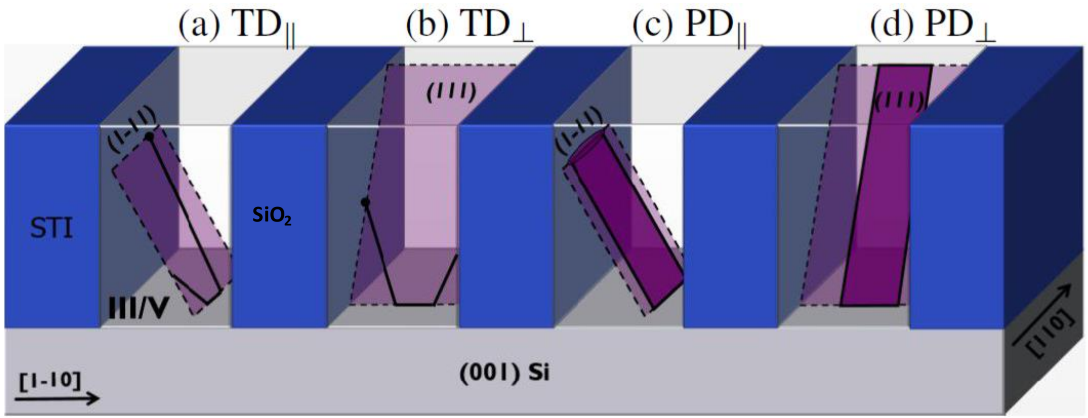
Reference sample



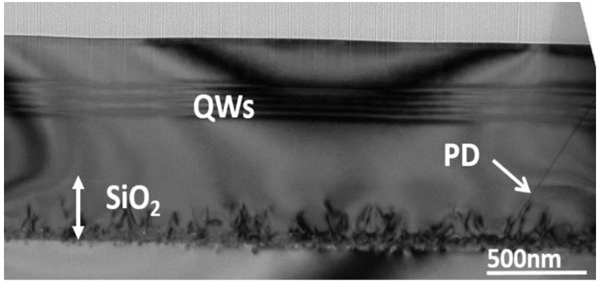
B. Kunert e.a. *Appl. Phys. Lett*. 29 August 2016; 109 (9): 091101. https://doi.org/10.1063/1.4961936

Aspect ratio trapping (ART)

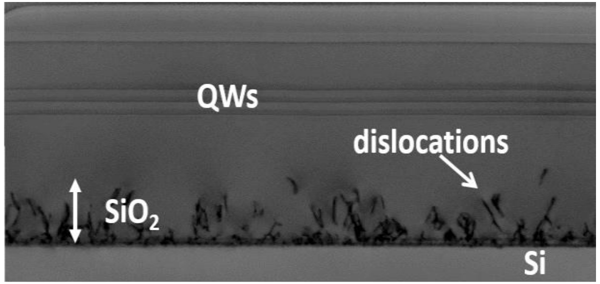
- High-AR SiO_2 trenches enable **trapping of threading dislocations.**



Longitudinal TEM-pictures



100nm trench



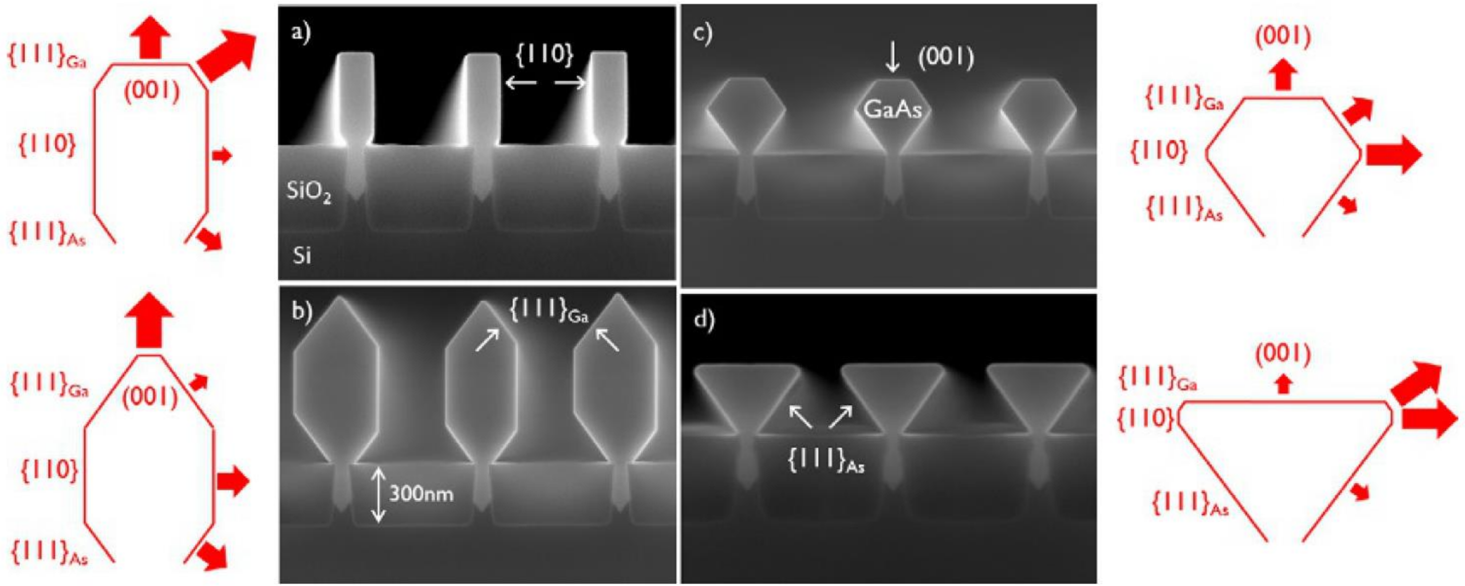
200nm trench

TD < $3 \times 10^6 cm^{-2}$
(limited by measurement)
PD < 0.14–0.45µm-1

Nano-ridge engineering (NRE)

Control growth rate on different crystal planes to obtain well-defined nano-ridge profile

Higher growth rate facets disappear, whereas facets with **lower growth rates define the nano-ridge profile**

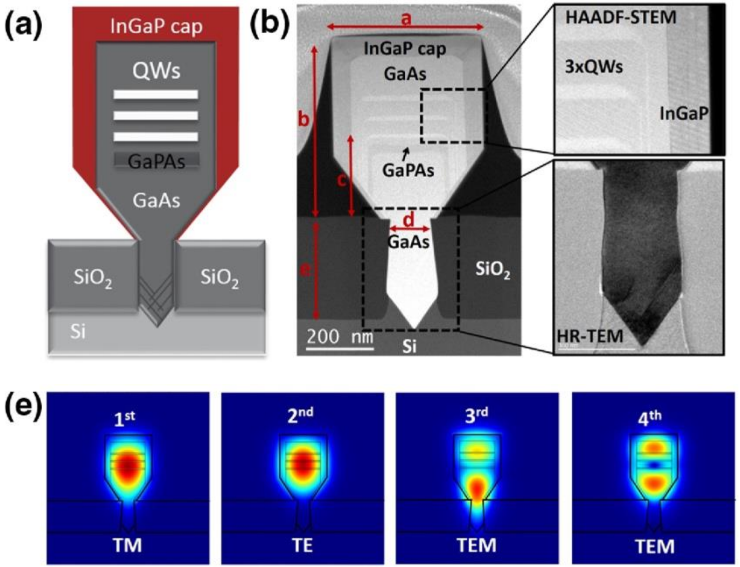


B. Kunert e.a. III/V nano ridge structures for optical applications on patterned 300 mm silicon substrate. *Appl. Phys. Lett*. 29 August 2016; 109 (9): 091101. https://doi.org/10.1063/1.4961936

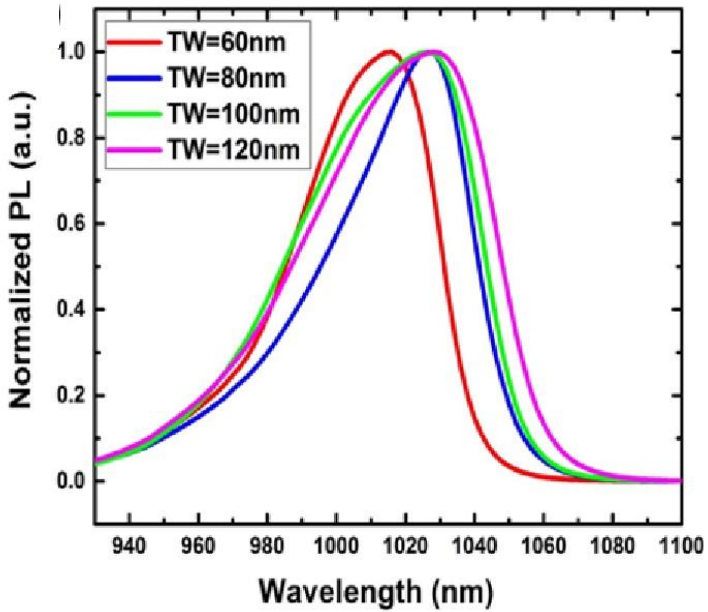
Optical Characterisation of InGaAs QWs

Photoluminescence Characteriation (PL)

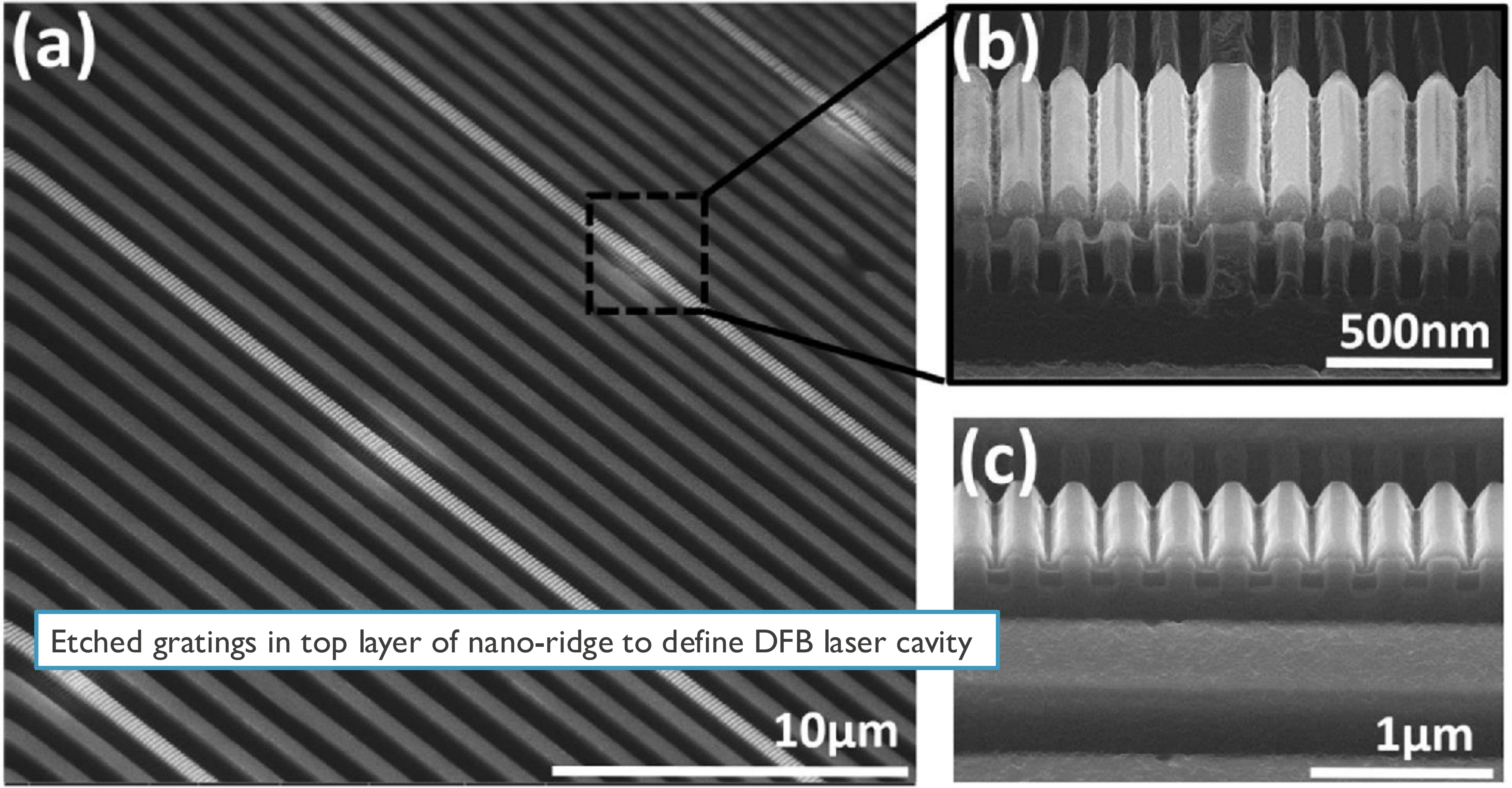
InGaP capping layer is essential



TE-mode (2nd) is strongly confined and has low substrate leakage



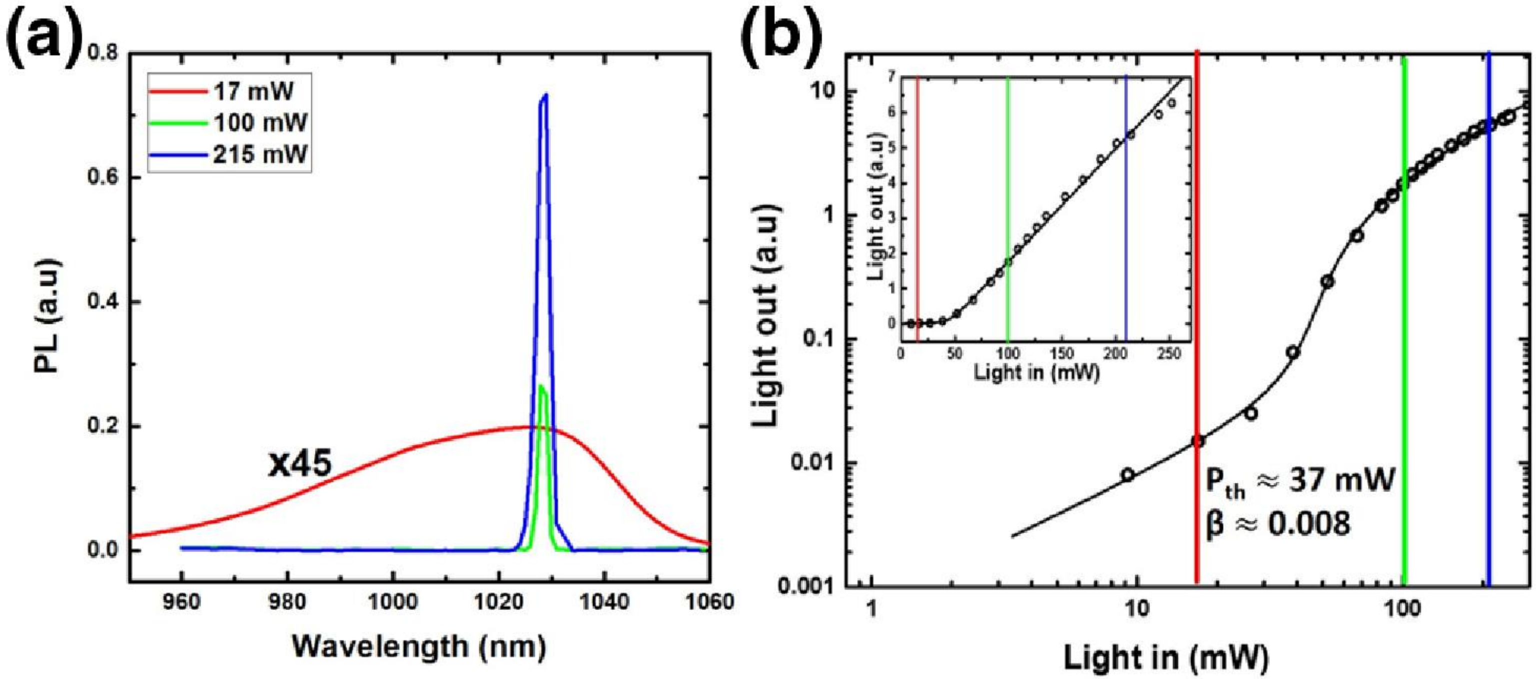
Yuting Shi e.a., "Optical pumped InGaAs/GaAs nano-ridge laser epitaxially grown on a standard 300-mm Si wafer," Optica 4, 1468-1473 (2017) https://doi.org/10.1364/OPTICA.4.001468



Etched gratings in top layer of nano-ridge to define DFB laser cavity

Optically Pumped Lasing (Etched Grating)

Succesful single mode lasing was demonstrated



Yuting Shi e.a., "Optical pumped InGaAs/GaAs nano-ridge laser epitaxially grown on a standard 300-mm Si wafer," Optica 4, 1468-1473 (2017) https://doi.org/10.1364/OPTICA.4.001468

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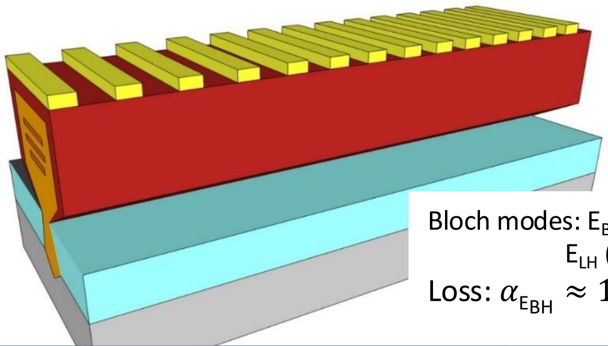
DFB-laser with Metal Grating

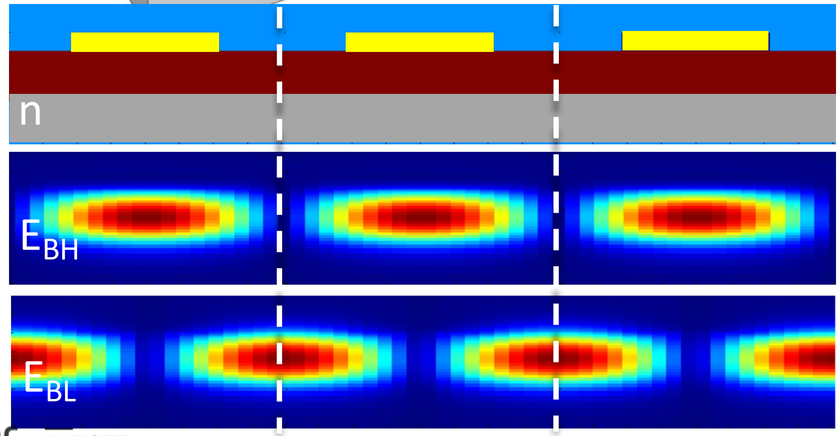
Continuous Au-contact: $\alpha_{TE} = 74\ cm^{-1}$

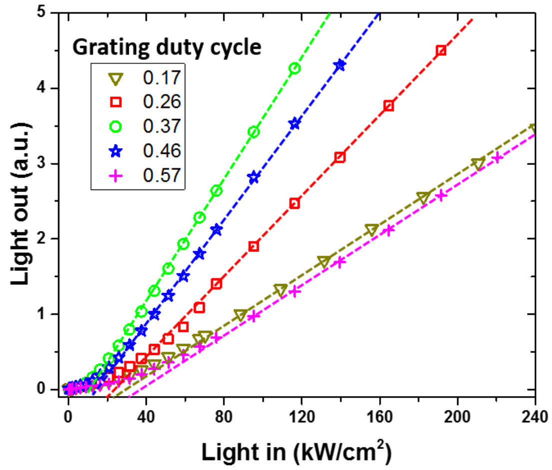
Grating with 40% duty cycle: $\alpha_{E_{BL}} = 7cm^{-1}$

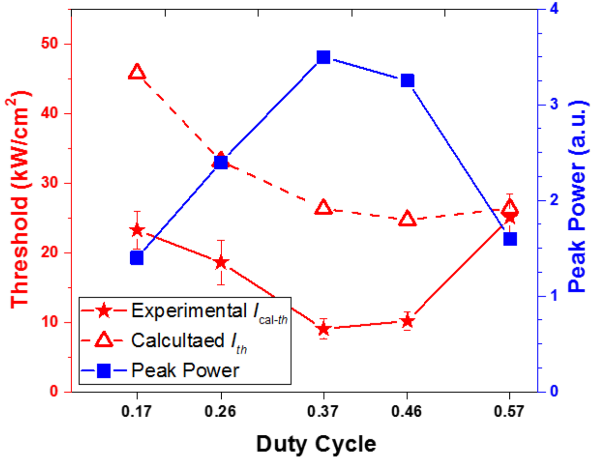


Bloch modes: E_{BH} (high overlap)
E_{LH} (low overlap)

Loss: $\alpha_{E_{BH}} \approx 10 \times \alpha_{E_{BL}}$

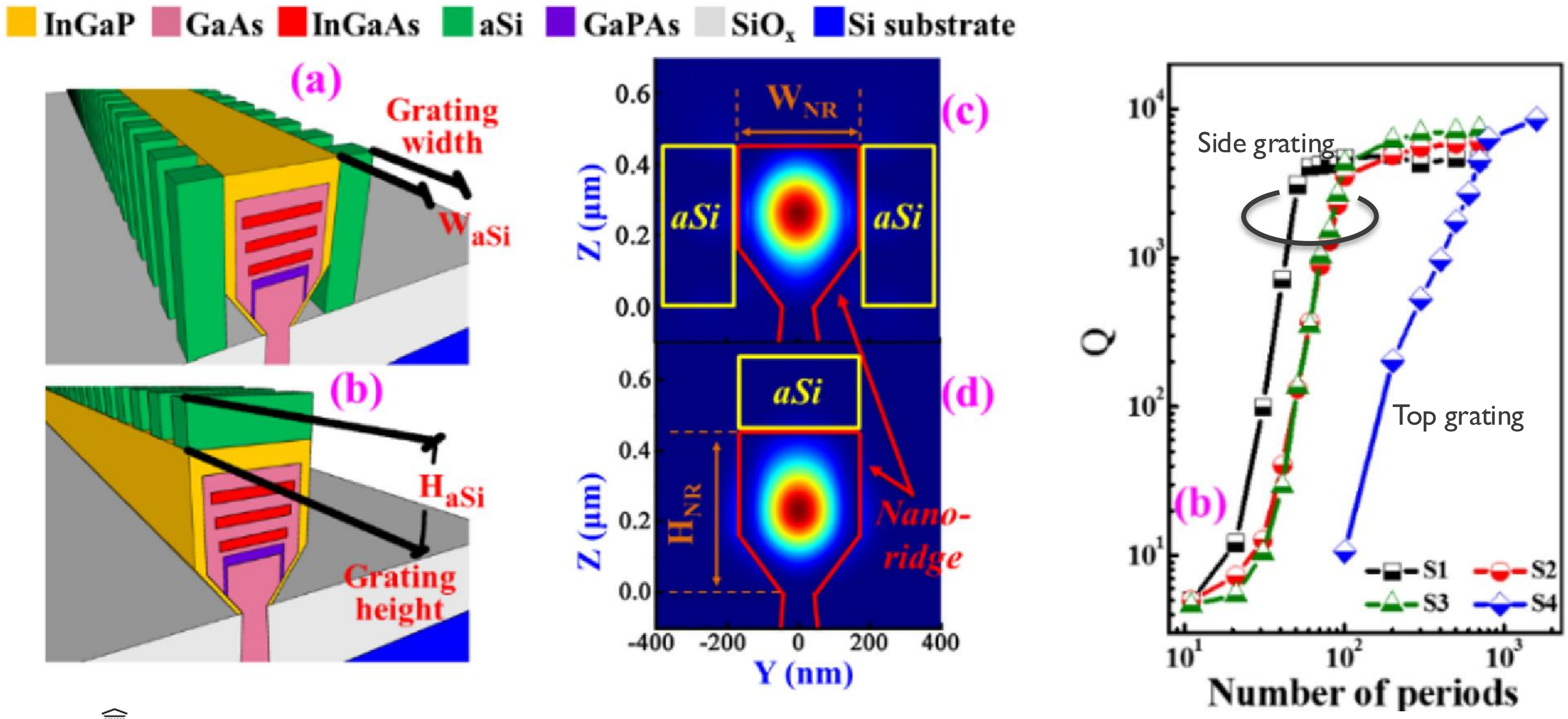






Amorphous Silicon Grating

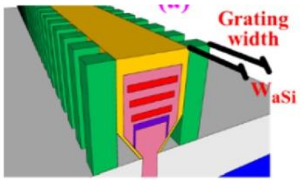
Grating deposited on sides of nano-ridge alllows for strong feedback



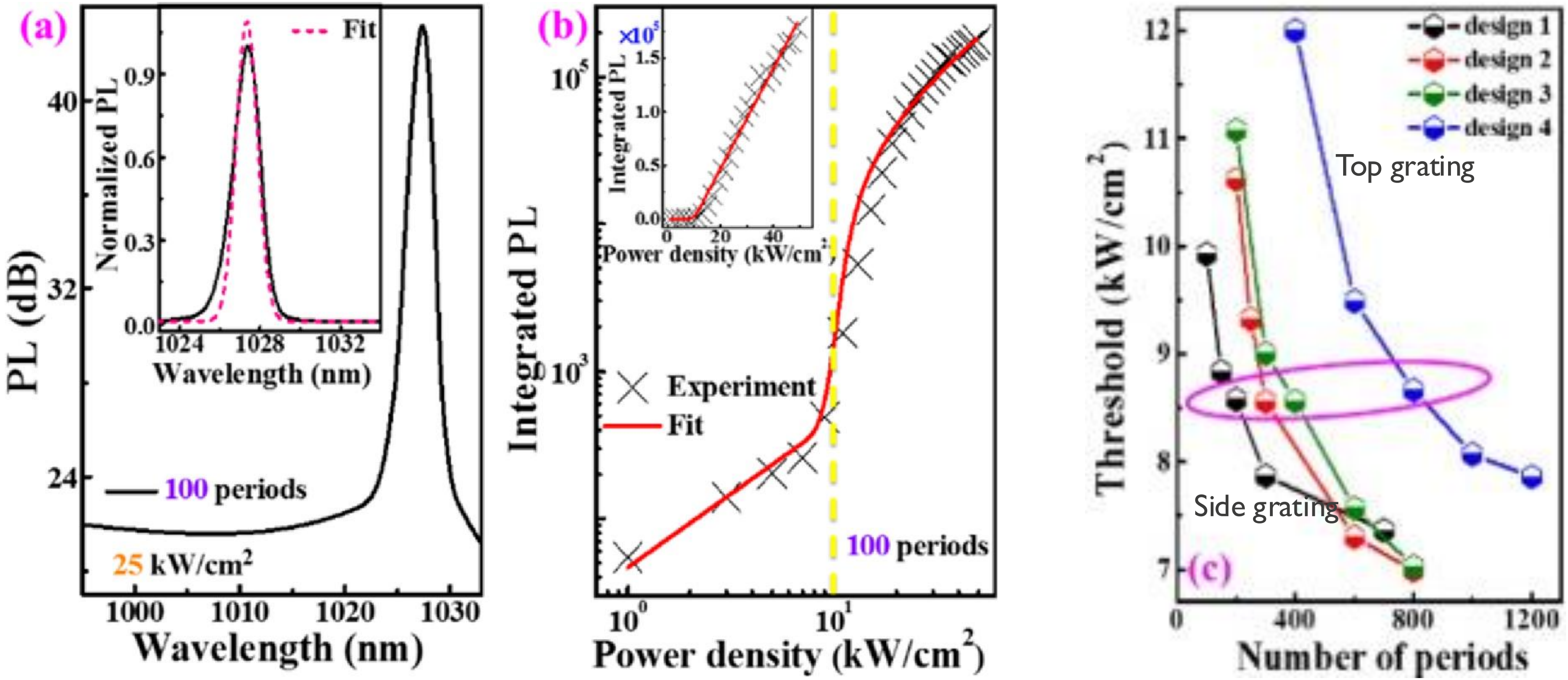
Z. Ouyang e.a.," Opt. Lett. 50, 2358-2361 (2025), https://doi.org/10.1364/OL.555718

Lasing from 16µm laser !

Grating deposited on sides of nano-ridge alllow for strong feedback



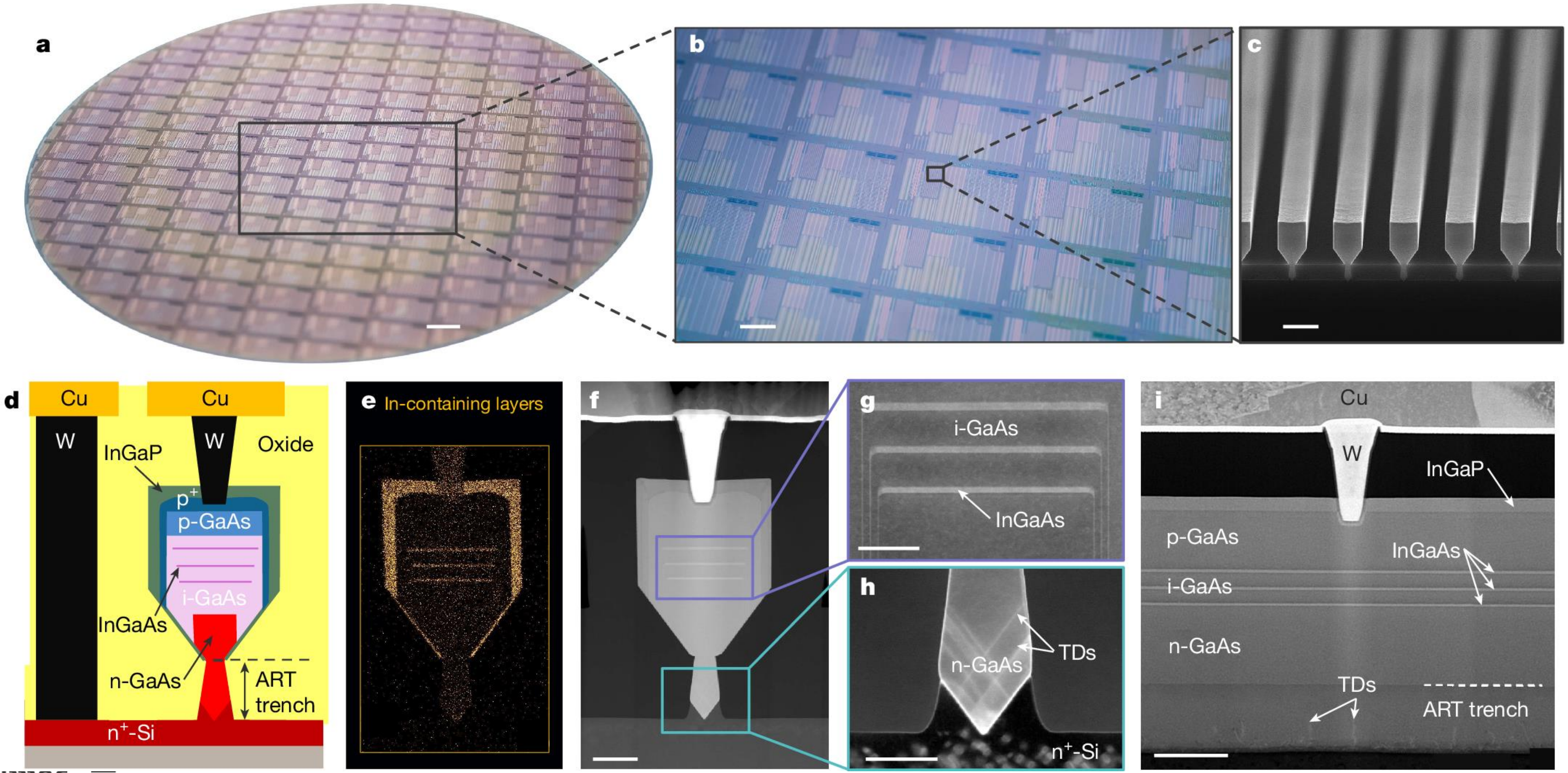
100 periods = 16µm



Z. Ouyang e.a.," Opt. Lett. 50, 2358-2361 (2025), https://doi.org/10.1364/OL.555718

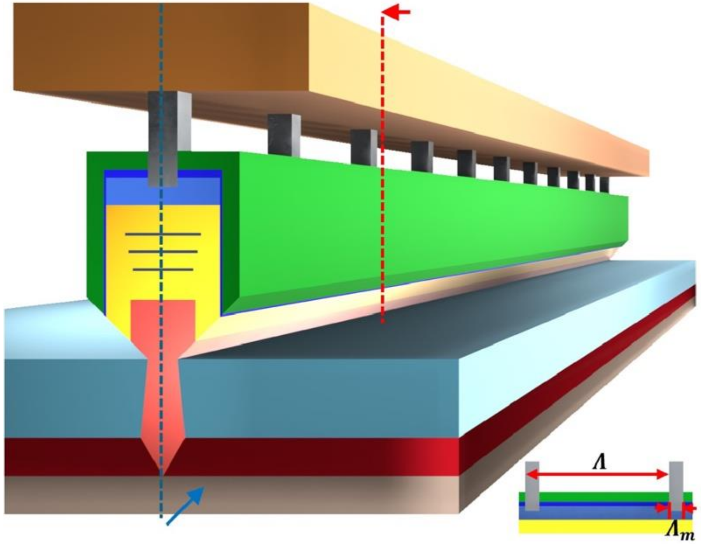
Electrically Injected Devices

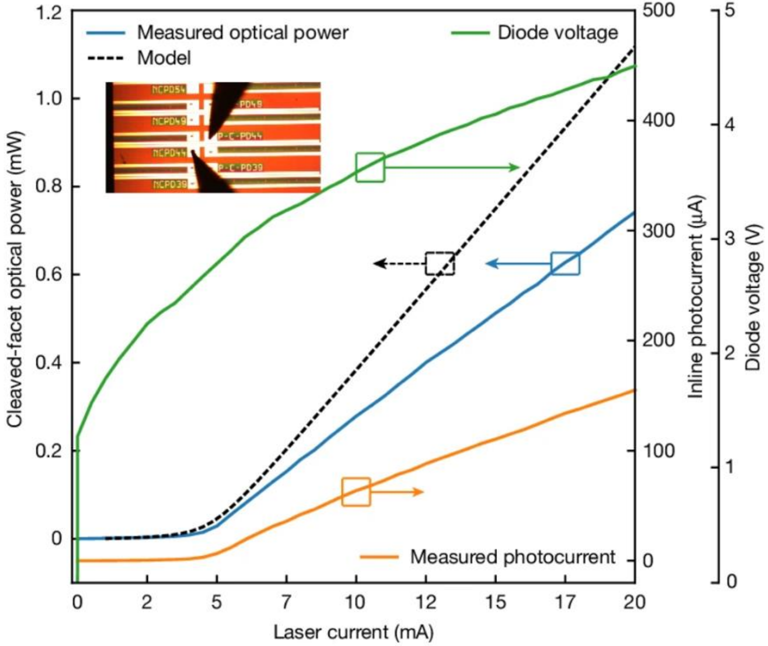
Challenge: Electrical Contact Strongly Affects Optical Mode



Metal Contacts Expected to Result in High Loss

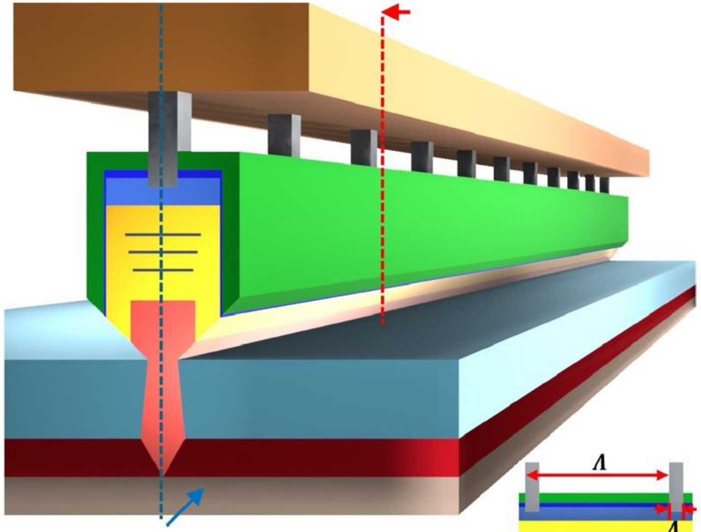
Nevertheless: low threshold lasing observed !



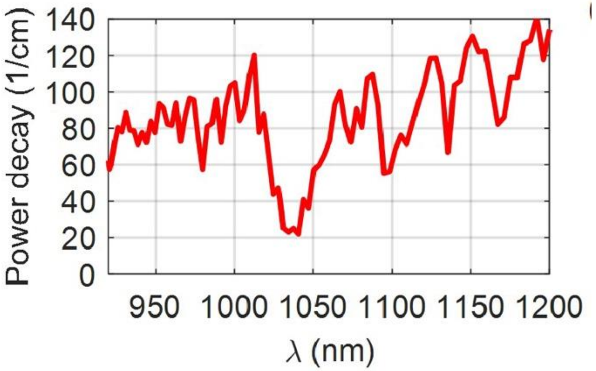


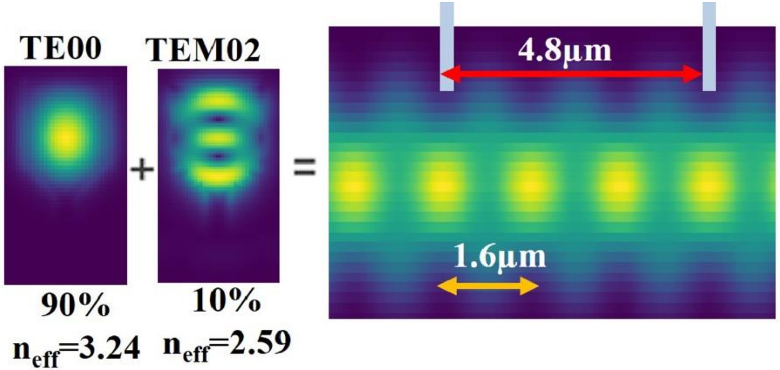
Metal Contacts Expected to Result in High Loss

But: Mode beating suppresses loss in metal contacts



Simulation of transmitted power (FDTD)



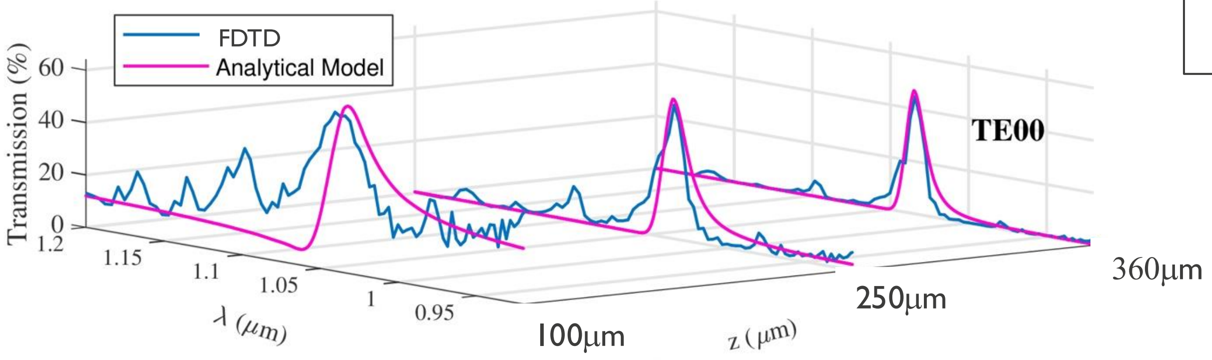


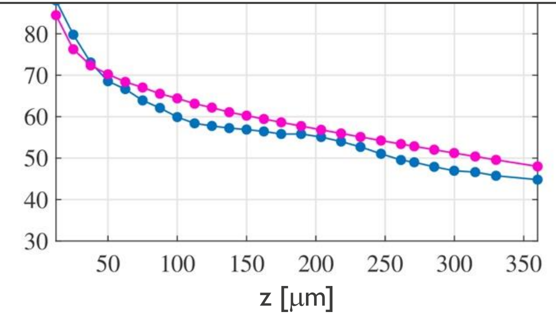
Analytical Model Confirms FDTD Simulations

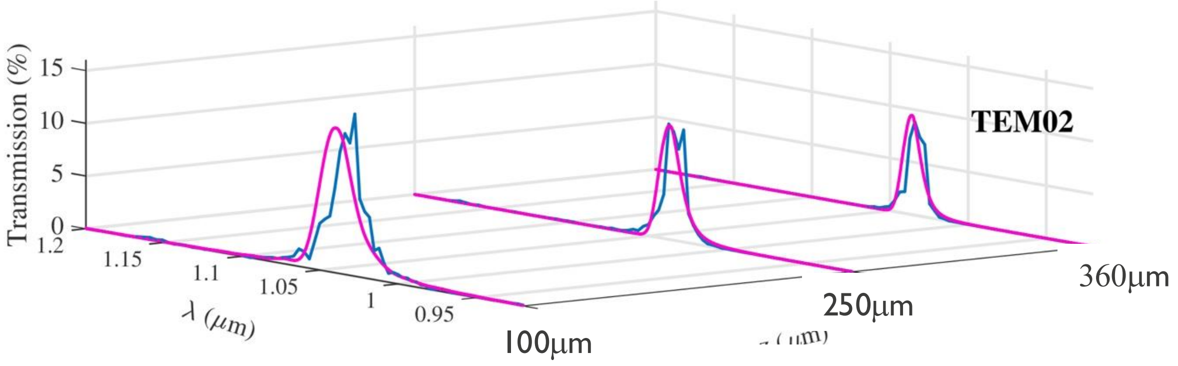
Waveguide excited by mode 1, at z=0μm

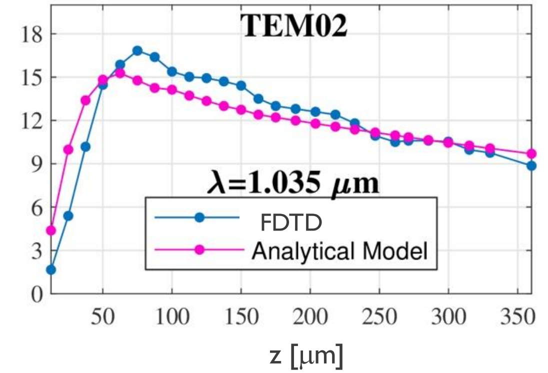
$$\frac{dE_1(z)}{dz} = -j\frac{\varkappa_0^2}{2\beta_1}E_1\frac{\int \Delta\epsilon U_1^2\,dA}{\int U_1^2\,dA} - j\frac{\varkappa_0^2}{2\beta_1}e^{-j(\beta_2-\beta_1)}E_2\frac{\int \Delta\epsilon U_1 U_2\,dA}{\int U_1^2\,dA}$$

$$\frac{dE_2(z)}{dz} = -j\frac{\varkappa_0^2}{2\beta_2}E_2\frac{\int \Delta\epsilon U_2^2\,dA}{\int U_2^2\,dA} - j\frac{\varkappa_0^2}{2\beta_2}e^{-j(\beta_1-\beta_2)}E_1\frac{\int \Delta\epsilon U_1 U_2\,dA}{\int U_2^2\,dA}$$





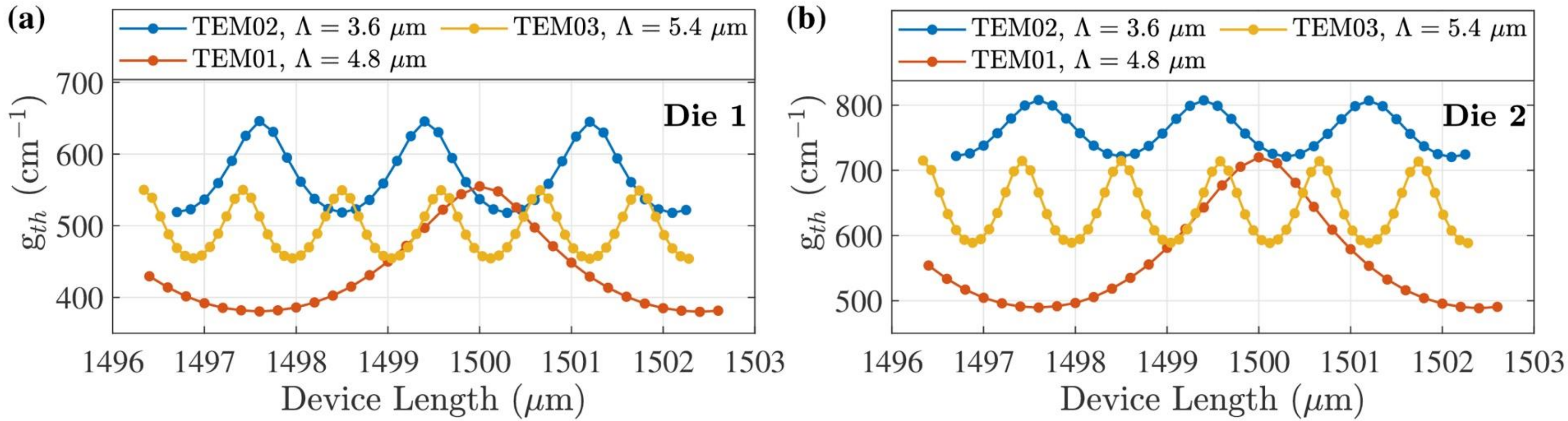




Andualem Ali Yimam e.a., Opt. Express 33, 2101-2114 (2025), https://doi.org/10.1364/OE.543613

Analytical model: threshold gain prediction

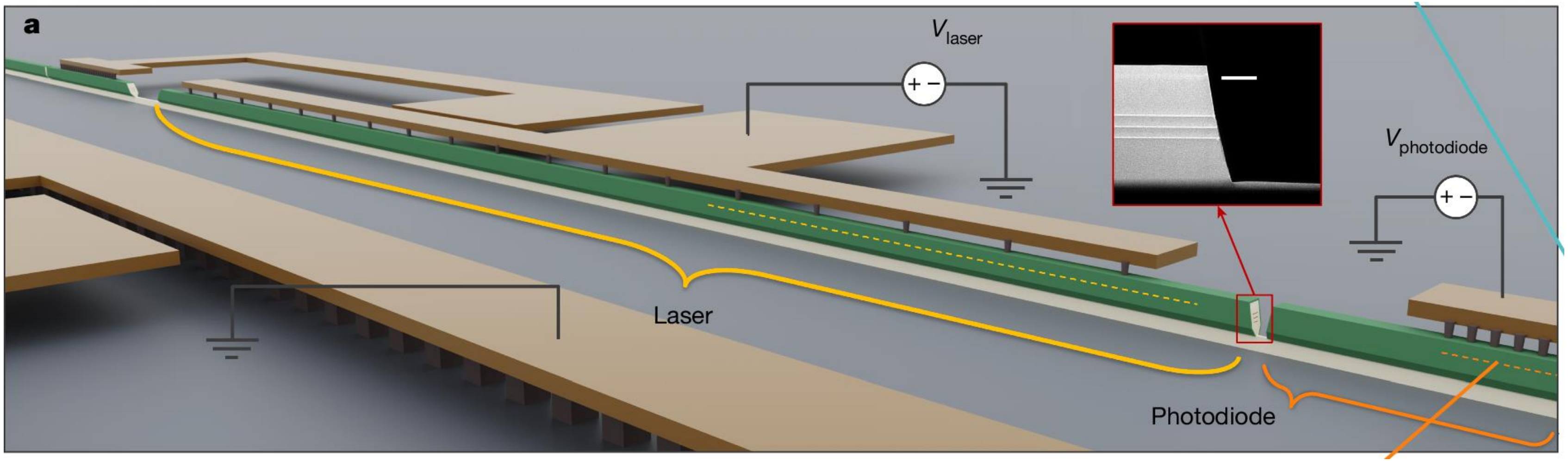
Different modes result in different beating length and different lasing wavelenth



Exact cavity length impacts laser threshold

Laser Layout

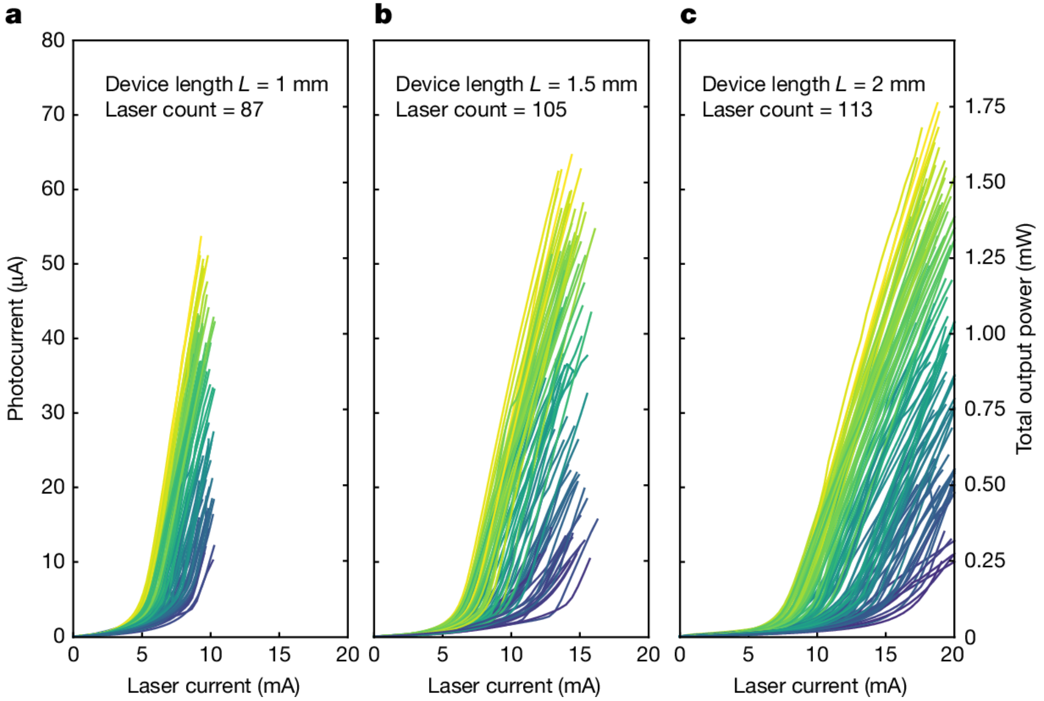
Integrated photodiode allows waferlevel characterisation

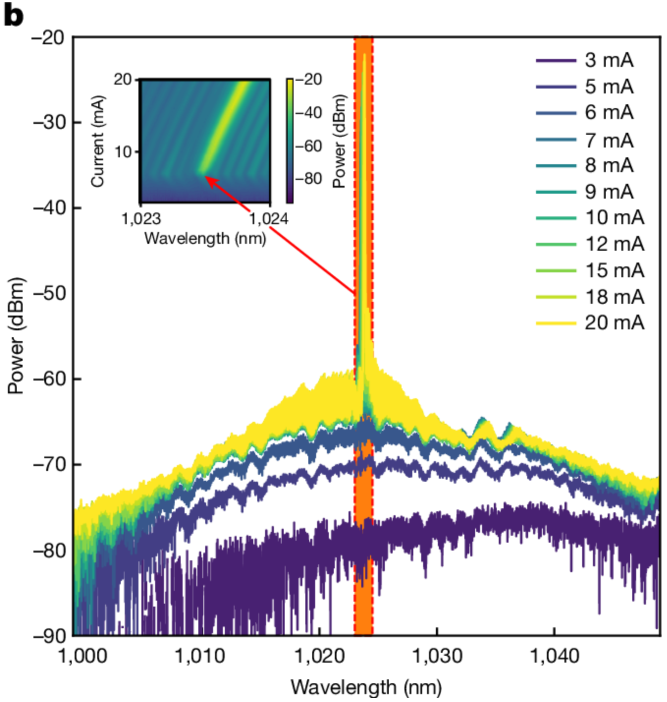


De Koninck, Y., *et al*. GaAs nano-ridge laser diodes fully fabricated in a 300-mm CMOS pilot line. *Nature* **637**, 63–69 (2025). https://doi.org/10.1038/s41586-024-08364-2

Waferscale Characterisation of Nano-Ridge Laser

Low threshold and single mode lasing





De Koninck, Y., *et al*. GaAs nano-ridge laser diodes fully fabricated in a 300-mm CMOS pilot line. *Nature* **637**, 63–69 (2025). https://doi.org/10.1038/s41586-024-08364-2

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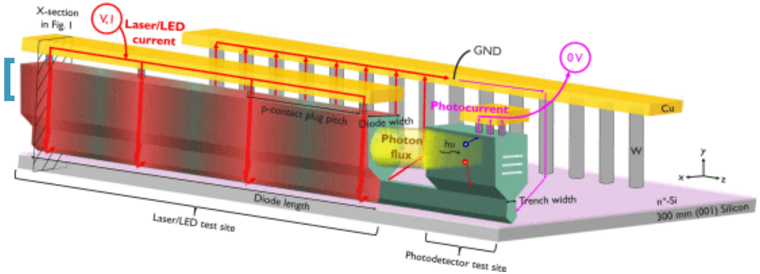
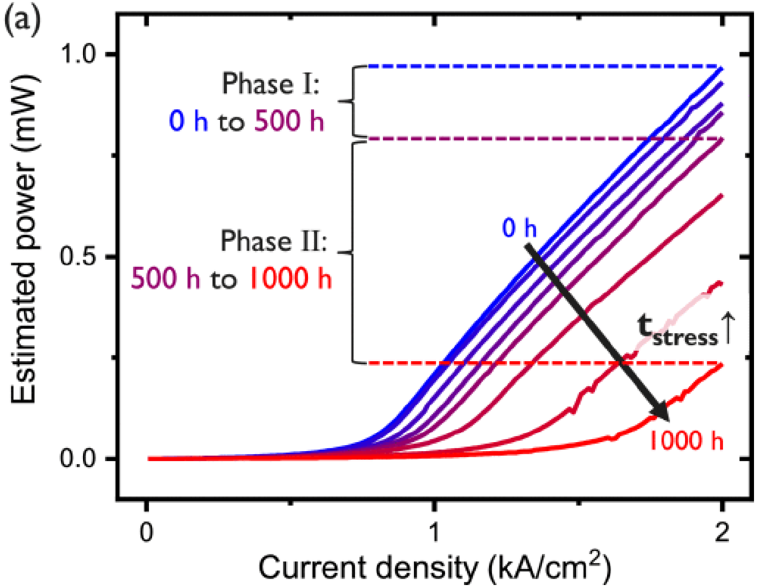
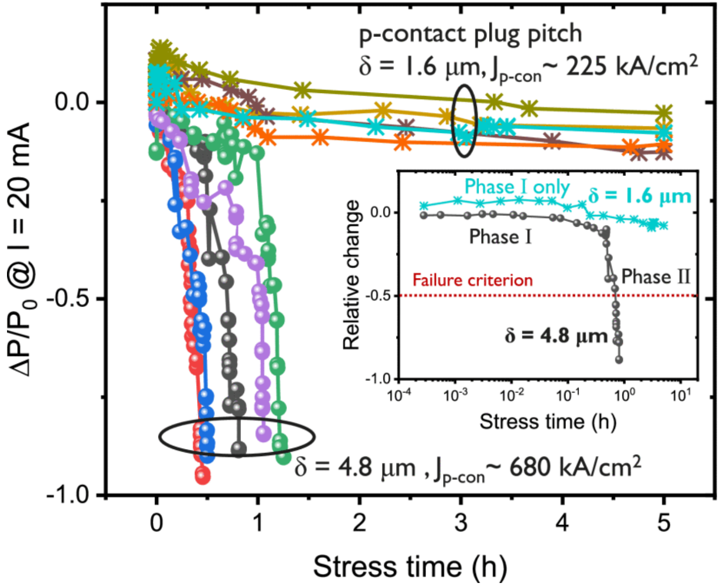
Degradation Mechanisms in Nano-Ridge

Sparce Contact Plugs Result in Limited Lifetime



Lasers devices with 4.8 μm plug pitch

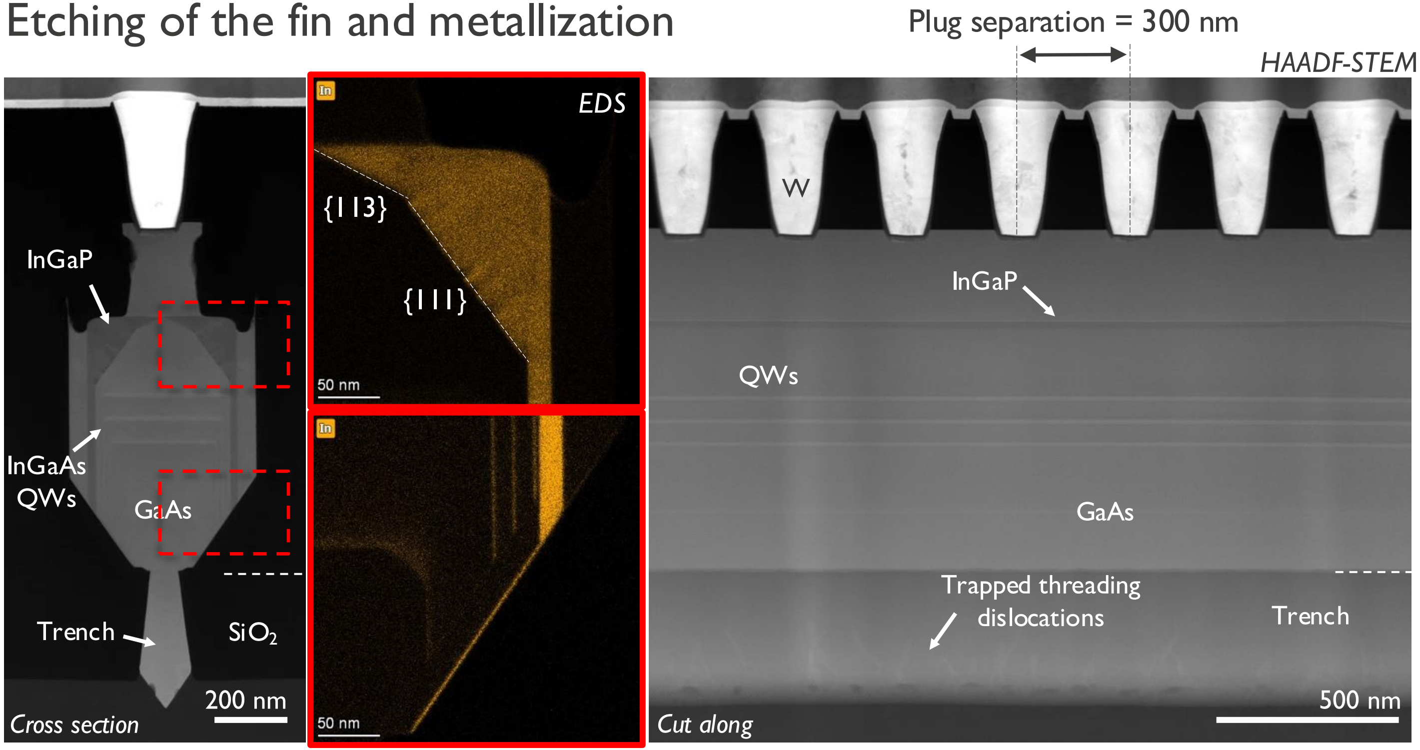




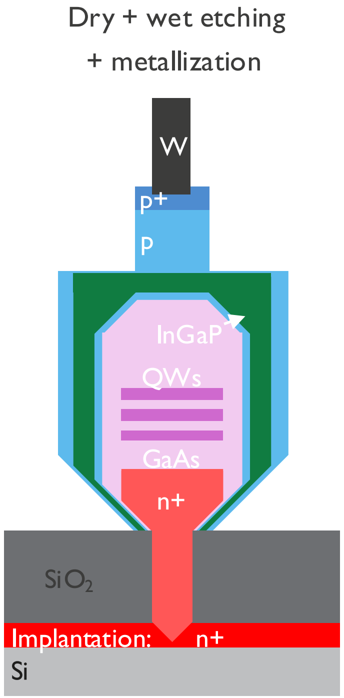
P. -Y. Hsieh *et al.*, "Degradation Mechanisms of Monolithic GaAs-on-Si Nano-Ridge Quantum Well Lasers," in *Journal of Lightwave Technology*, vol. 43, no. 12, pp. 5811-5819, 15 June15, 2025, doi: 10.1109/JLT.2025.3557373

NR2.0: Etched fin separates optical mode from contact plugs

Etching of the fin and metallization



HAADF-STEM



- **InGaP (001) < 10 nm**
- **Full InGaP passivation of the active region**

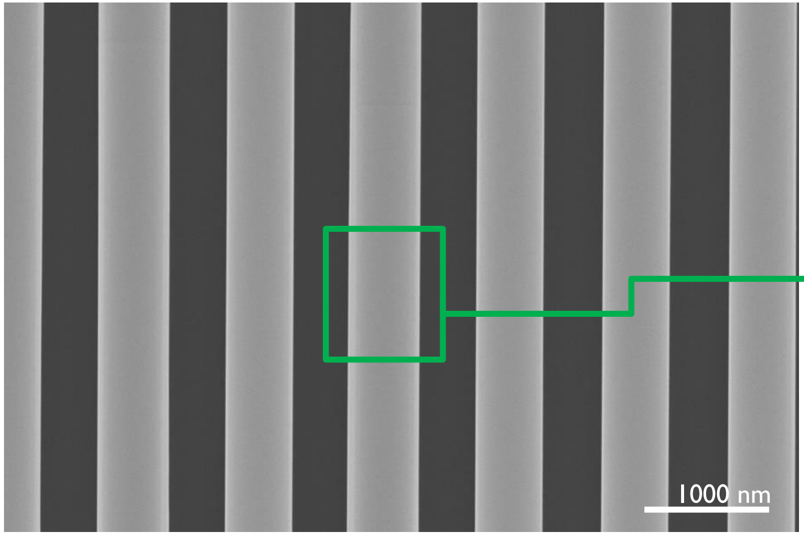
HAADF-STEM: High-angle annular dark-field scanning transmission electron microscopy, EDS: energy dispersive X-ray spectroscopy

NR2.0: device processing

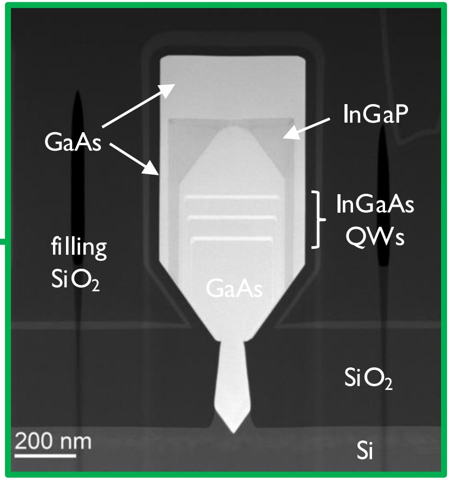
Developed by Peter Swekis

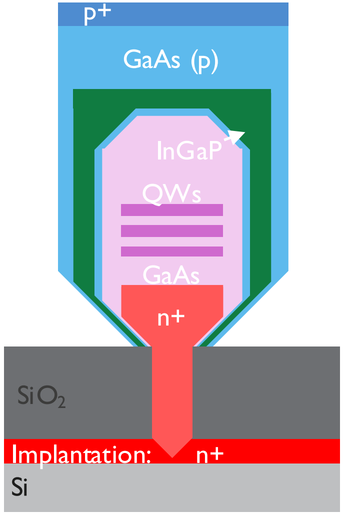
Epitaxial growth

Top view SEM



HAADF-STEM





Uniform nano-ridges with all layers successfully developed

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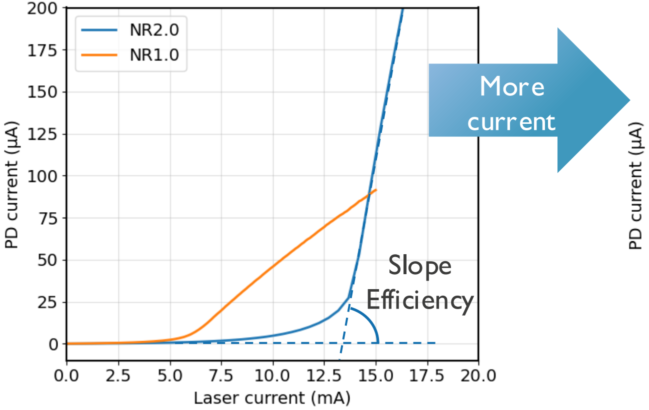
HAADF-STEM: High-angle annular dark-field scanning transmission electron microscopy, SEM: scanning electron microscopy

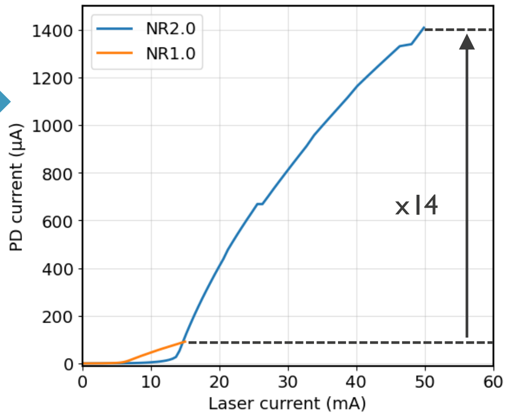
Wafer-scale laser characterization – Preliminary results

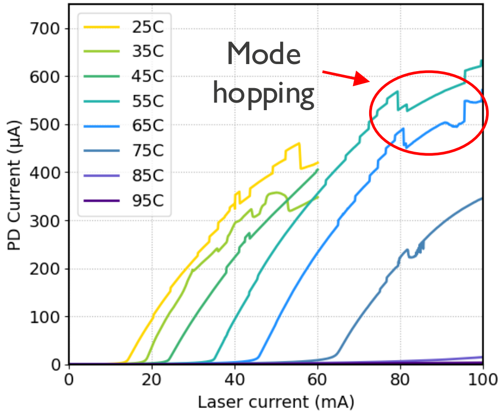
Read-out of the inline nano-ridge photodiodes

Key results

- Higher threshold current than NR1.0 (13 mA vs 5 mA)
- 4x max slope efficiency
- Up to 14x in output power (assuming comparable photodiode responsivity)
- Lasing operation at higher temperature than NR1.0 (75 °C vs 55 °C)





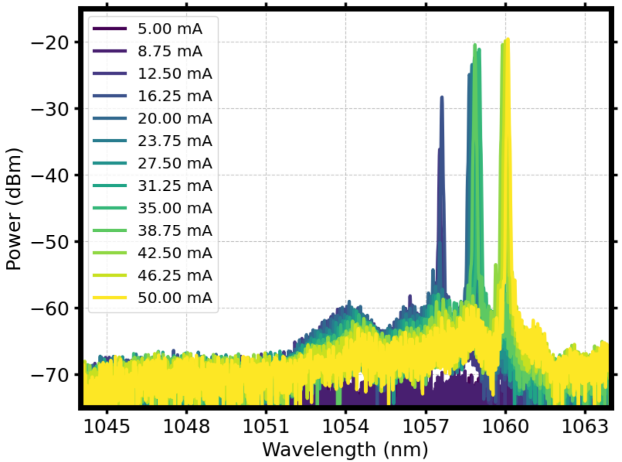


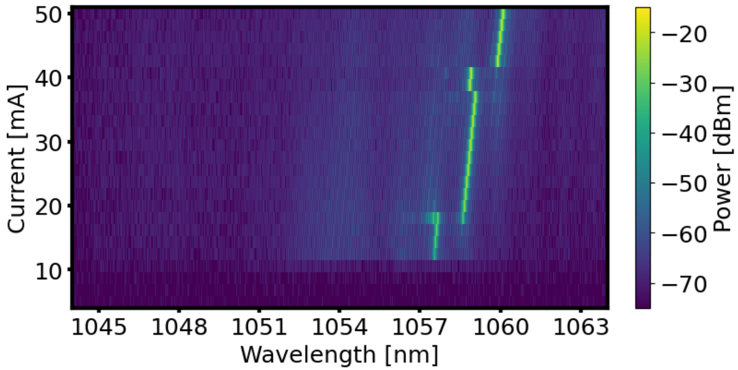
Laser spectrum analysis – Preliminary results

Detection at a cleaved laser facet

Key results

- Higher threshold current than NR1.0 (13 mA vs 5 mA)
- 4x max slope efficiency
- Up to 14x in output power (assuming comparable photodiode responsivity)
- Lasing operation at higher temperature than NR1.0 (75 °C vs 55 °C)
- Multimode emission centred around 1050 nm

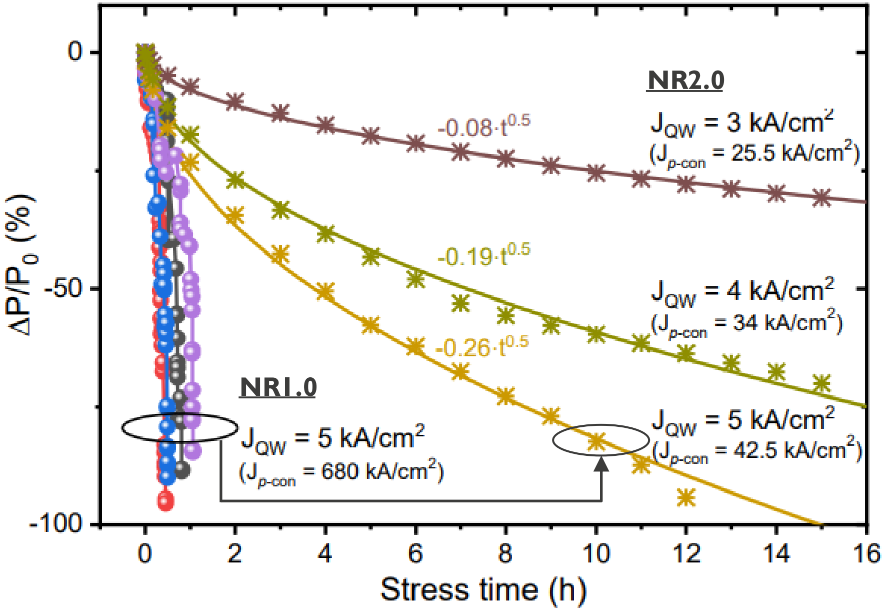




Wafer-scale reliability tests – Preliminary results

P-contact-breakdown failure mode solved

- x10 lifetime improvement at $J_{QW} = 5\ kA/cm^2$
- Gradual degradation in the output power likely linked to an impurity diffusion process

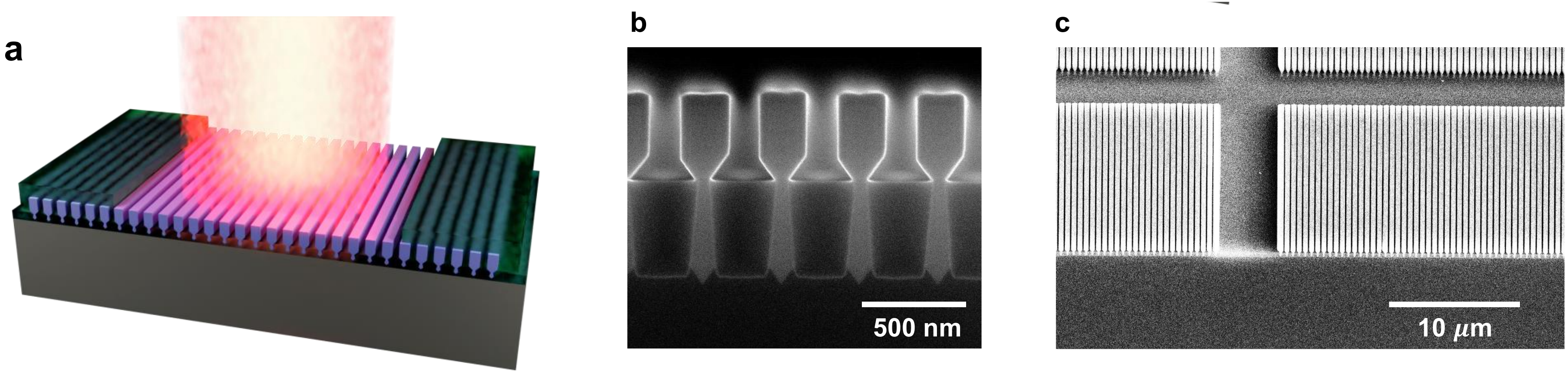


P.-Y. Hsieh et al., OFC2026 Poster Session, 2026, W2A.10

New Directions

Nano-Ridge Surface Emitting Lasers

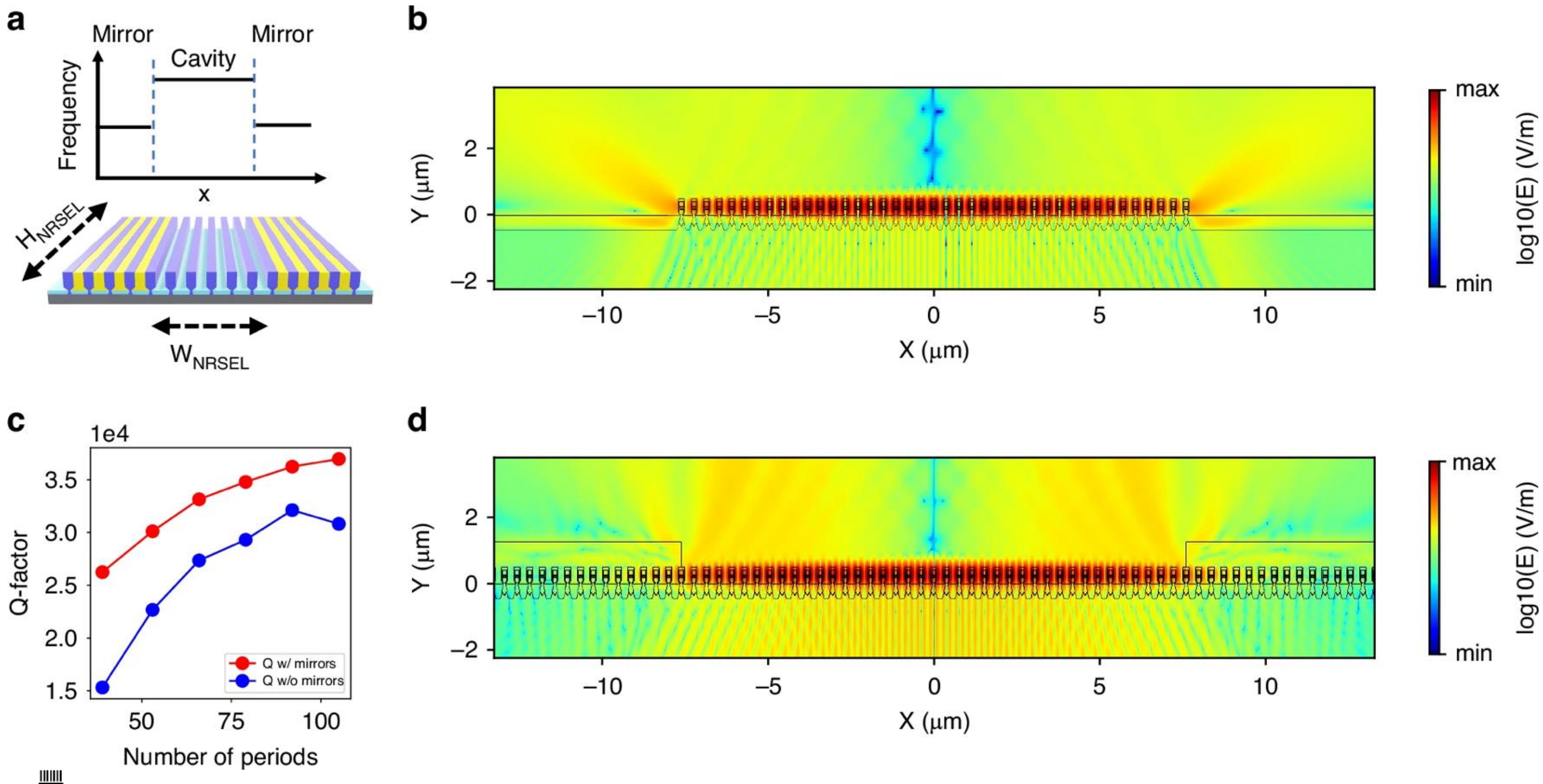
Cam we exploit 1D periodic arrays of nano-ridges to realize more complex devices ?



Fahmy, E.M.B., e.a.. *Light Sci Appl* **15**, 120 (2026).
https://doi.org/10.1038/s41377-025-02061-z

Nano-Ridge Surface Emitting Lasers

Cam we exploit 1D periodic arrays of nano-ridges to realize more complex devices ?



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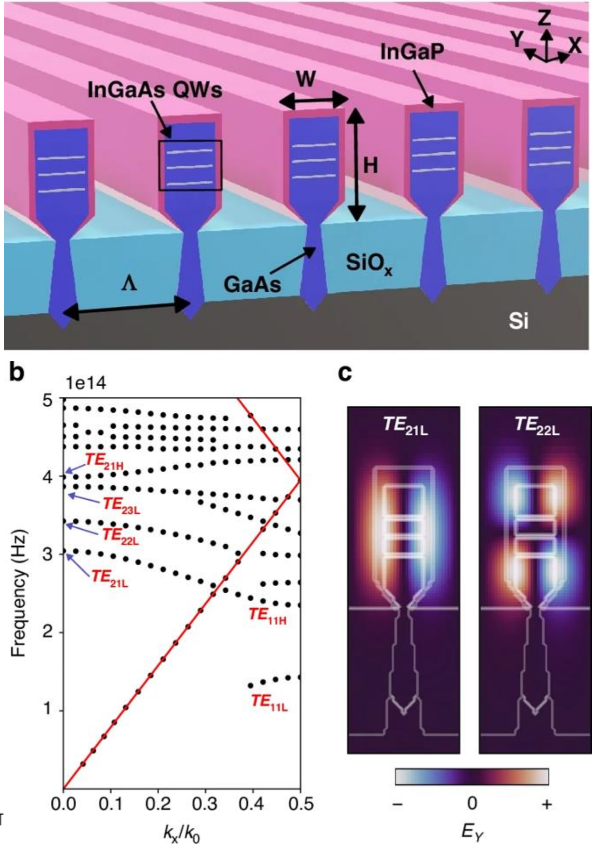
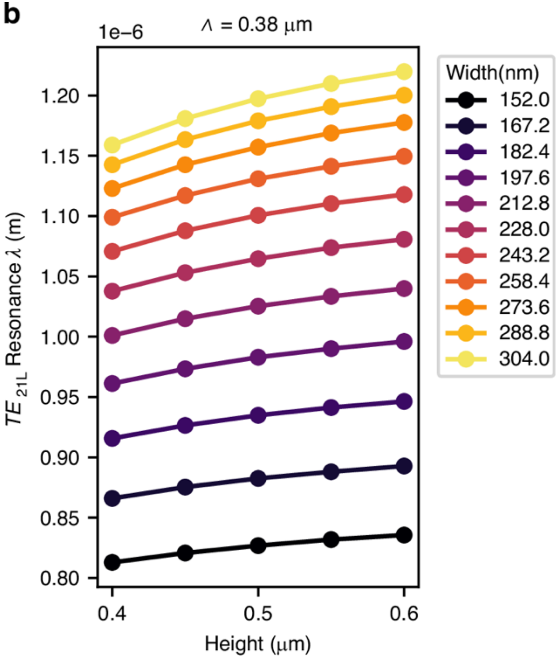
Fahmy, E.M.B., e.a.. *Light Sci Appl* **15**, 120 (2026).
https://doi.org/10.1038/s41377-025-02061-z

Nano-Ridge Surface Emitting Lasers

Matching the device parameters to gain bandwidth (~1050nm)

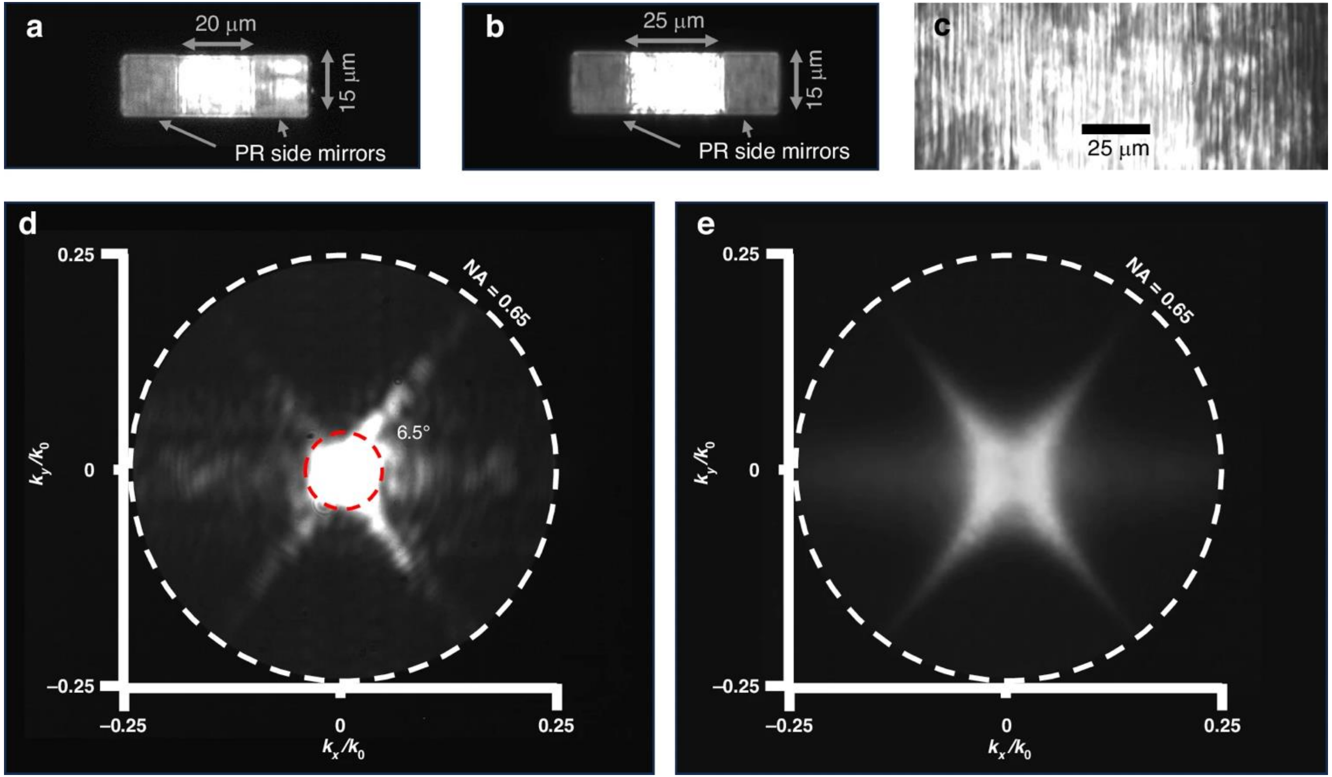




Challenge: mask fixed upfront - no room to vary period

Nano-Ridge Surface Emitting Lasers

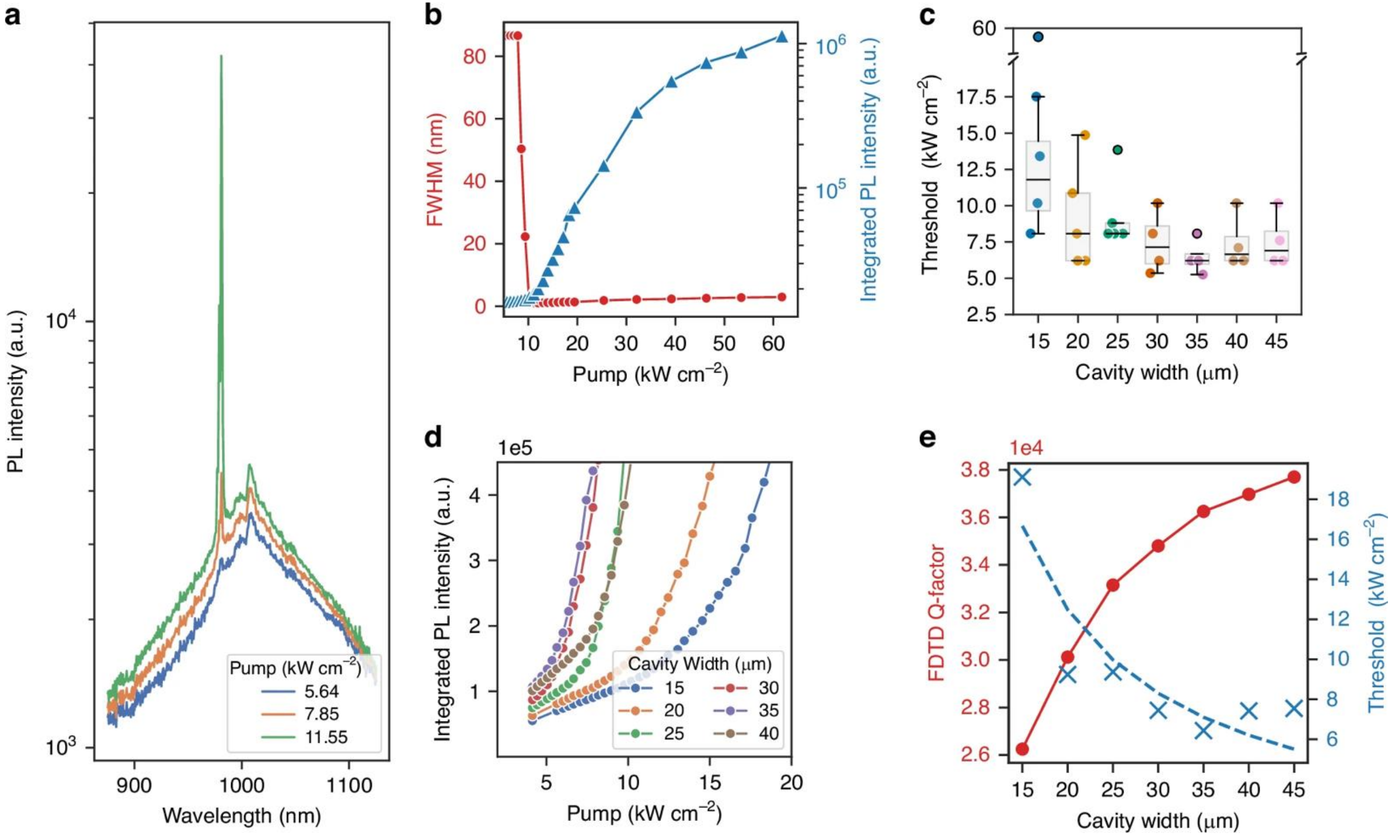
Far- and near-field images



Fahmy, E.M.B., e.a.. *Light Sci Appl* **15**, 120 (2026).
https://doi.org/10.1038/s41377-025-02061-z

Nano-Ridge Surface Emitting Lasers

Clear single mode lasing observed under optical pumping (7 ns pulses)



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Fahmy, E.M.B., e.a.. *Light Sci Appl* **15**, 120 (2026).
https://doi.org/10.1038/s41377-025-02061-z

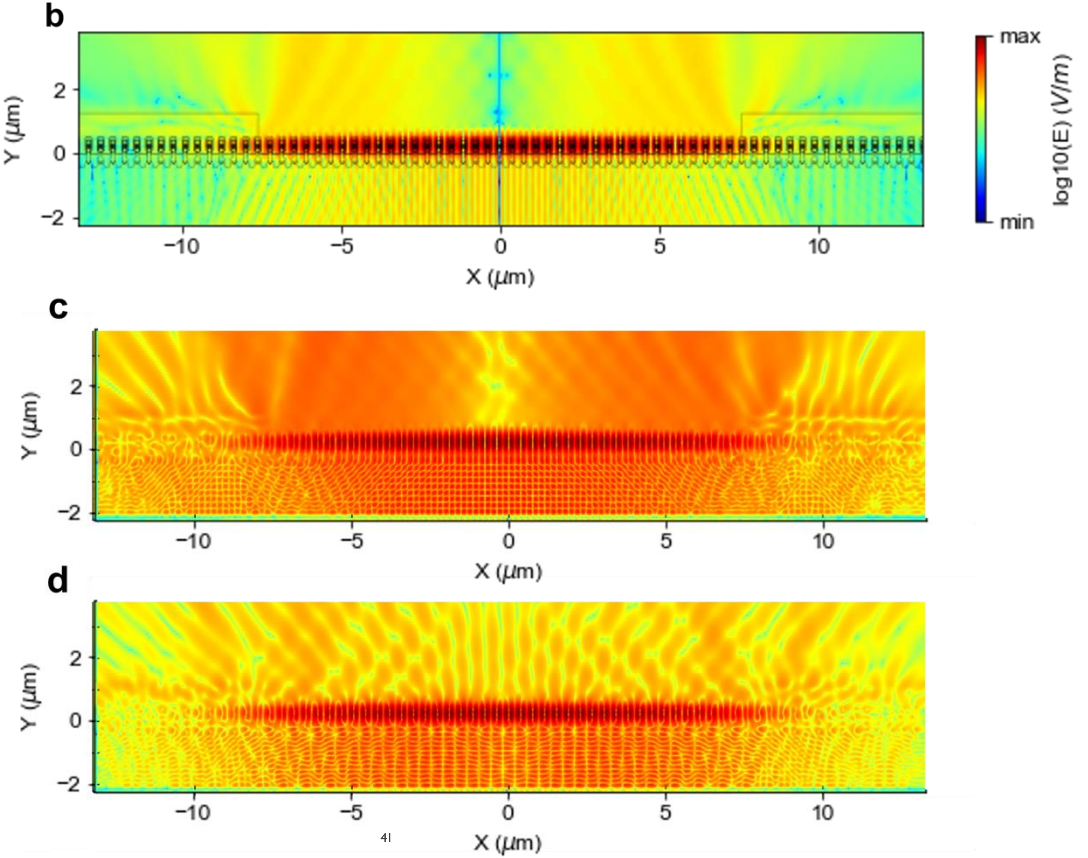
Nano-Ridge Surface Emitting Lasers

Room for further improvement: Effect of bottom mirror

No mirror
Q=20k

Mirror in phase
Q=28k

Mirror out of phase
Q=319k



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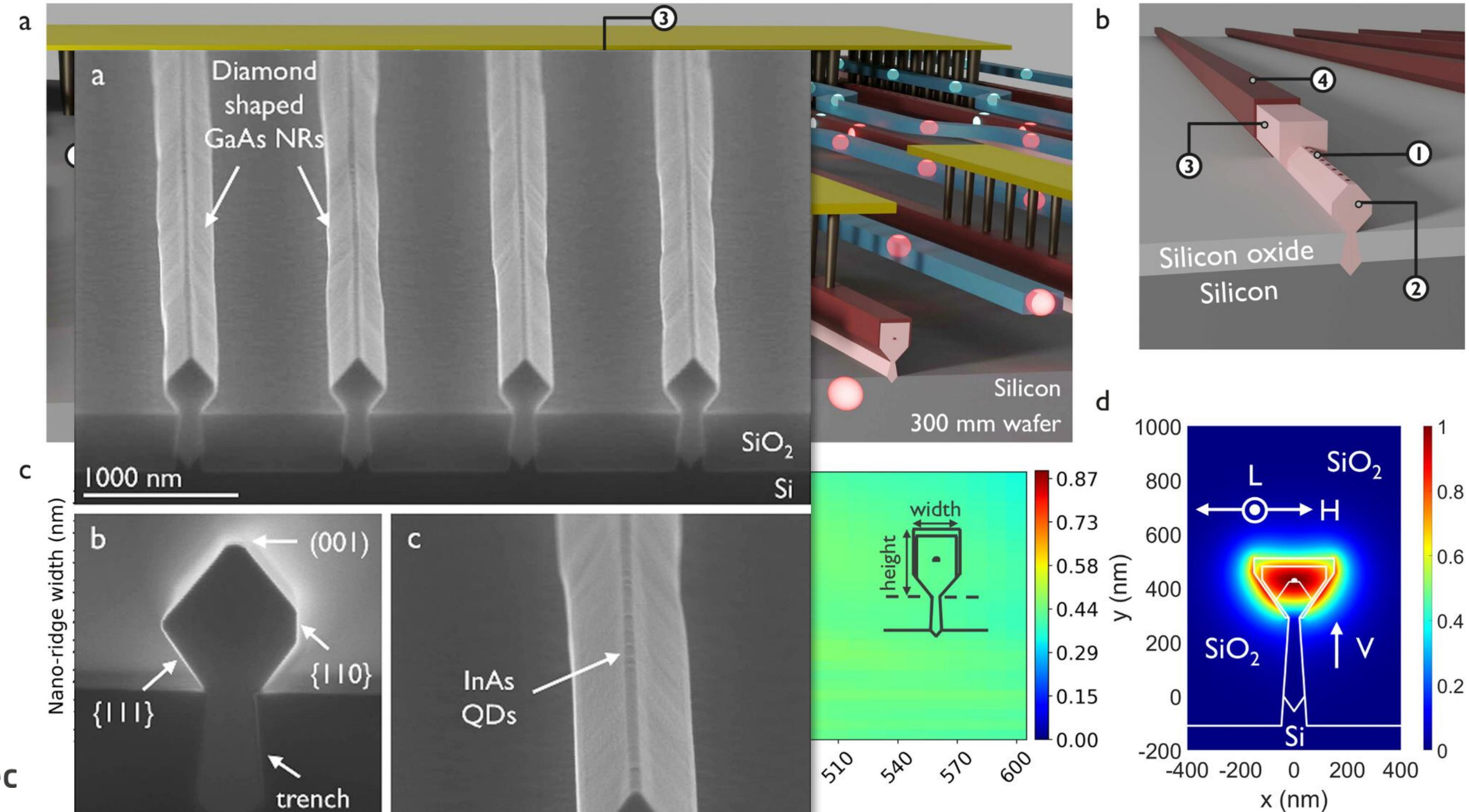
InAs QDs on 300mm Wafers

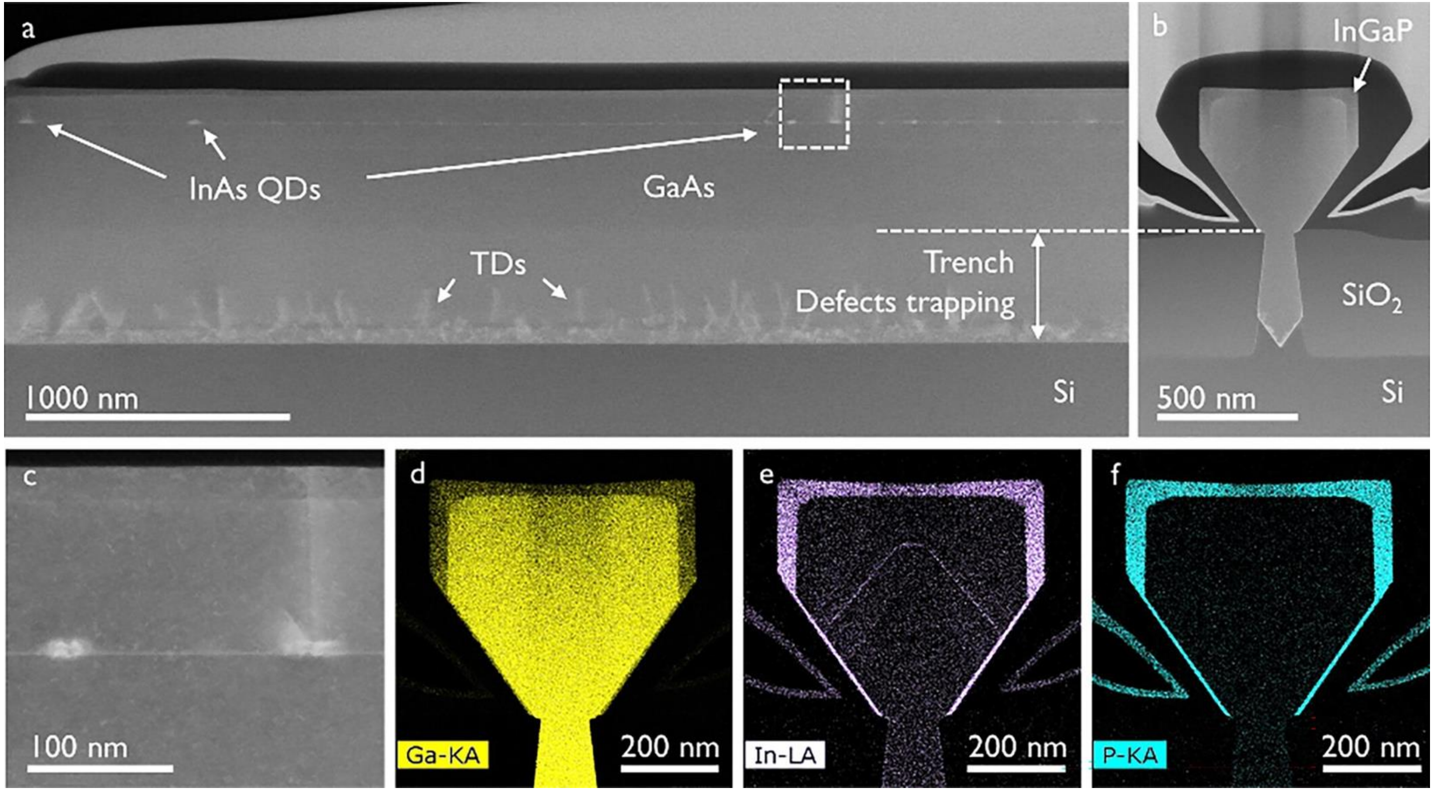
Nano-Ridge for Quantum Dot Site Control

Dimensional control allows for coupling factor (β) above 85%



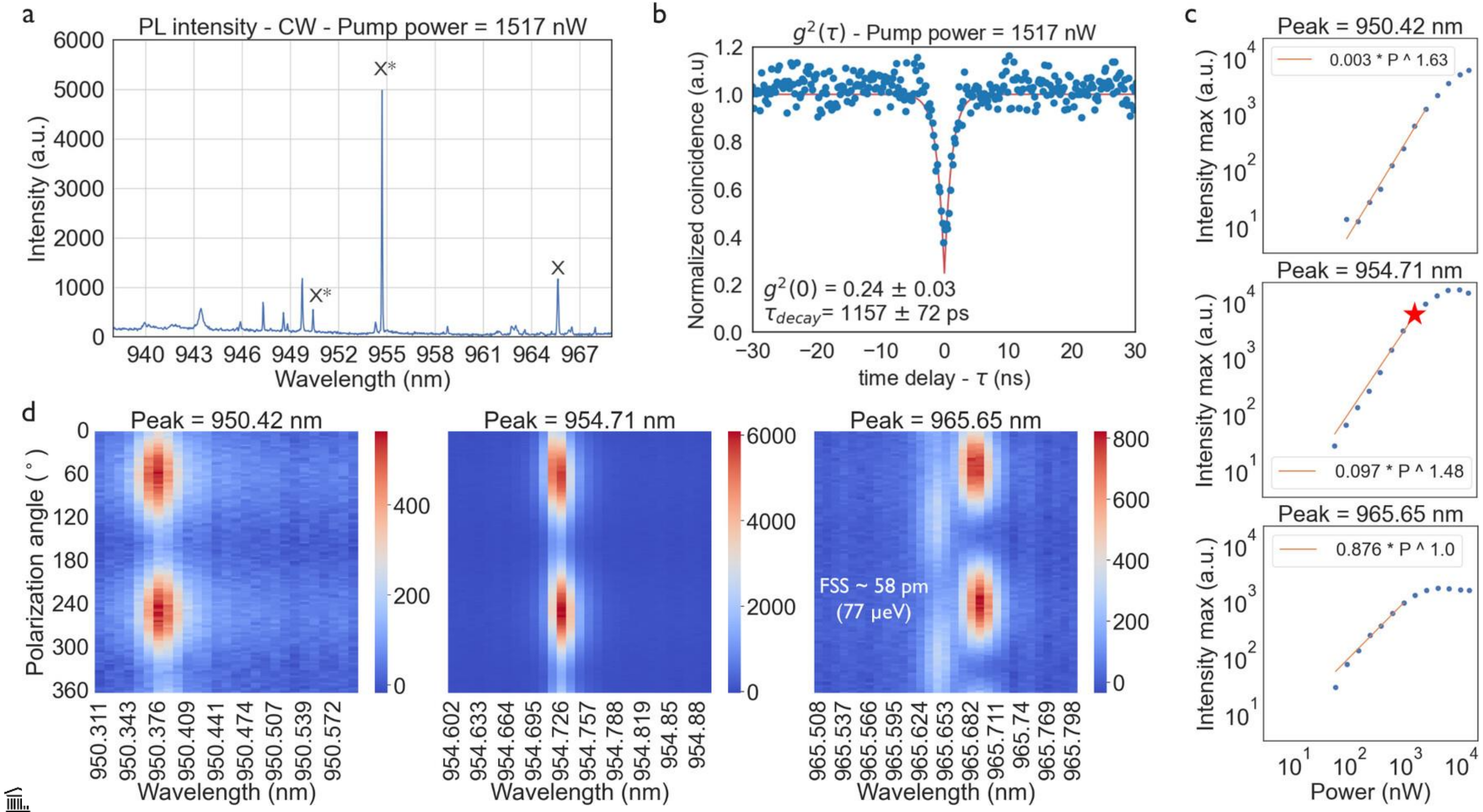
InAs QDs on 300mm Wafers

Structural analysis



InAs QDs on 300mm Wafers

Spectral Analysis



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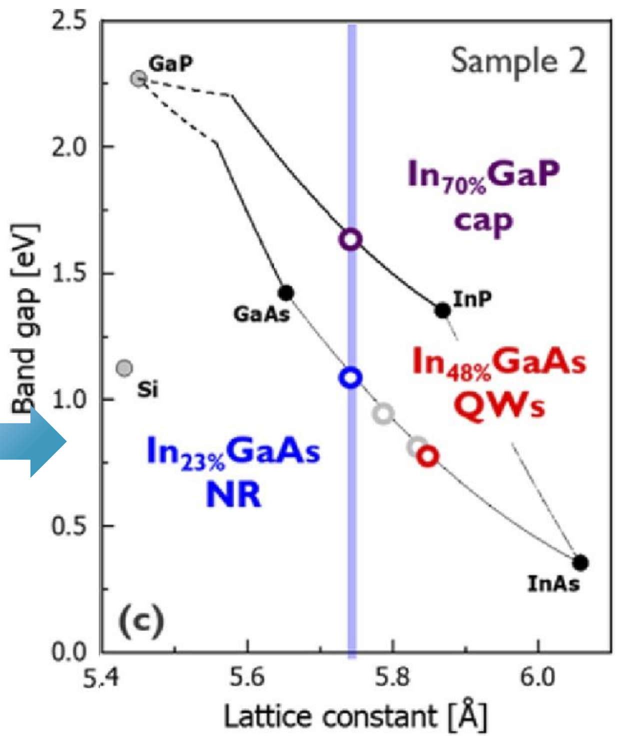
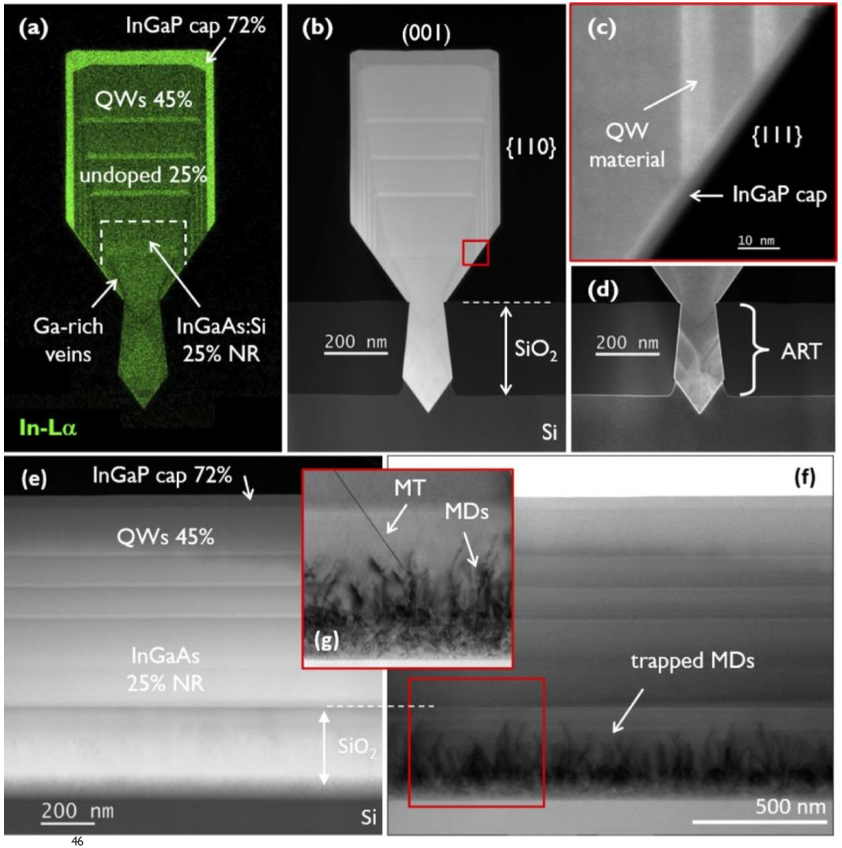
Towards O-Band Lasing

In$_{25}$Ga$_{75}$As matrix allows higher QWs with higher Indium content

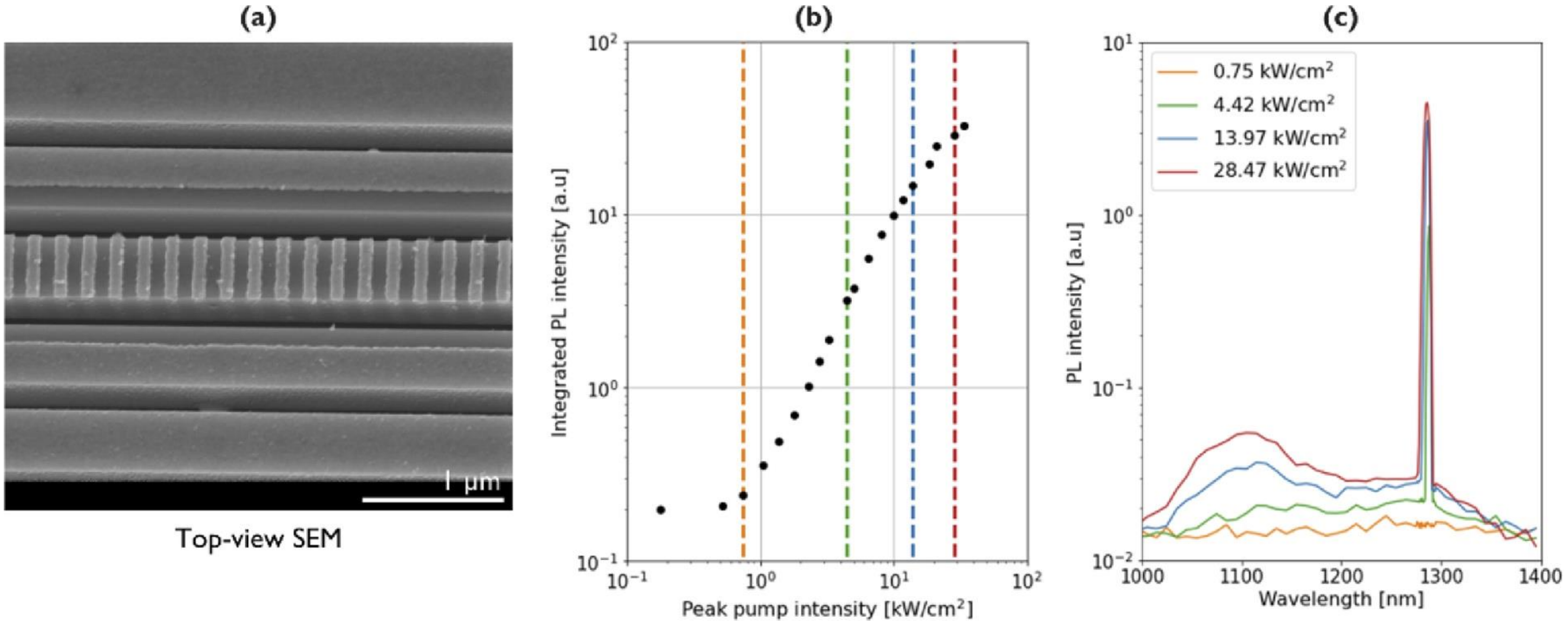


Target bandgap



Towards O-Band Lasing

Lasing at 1280nm demonstrated

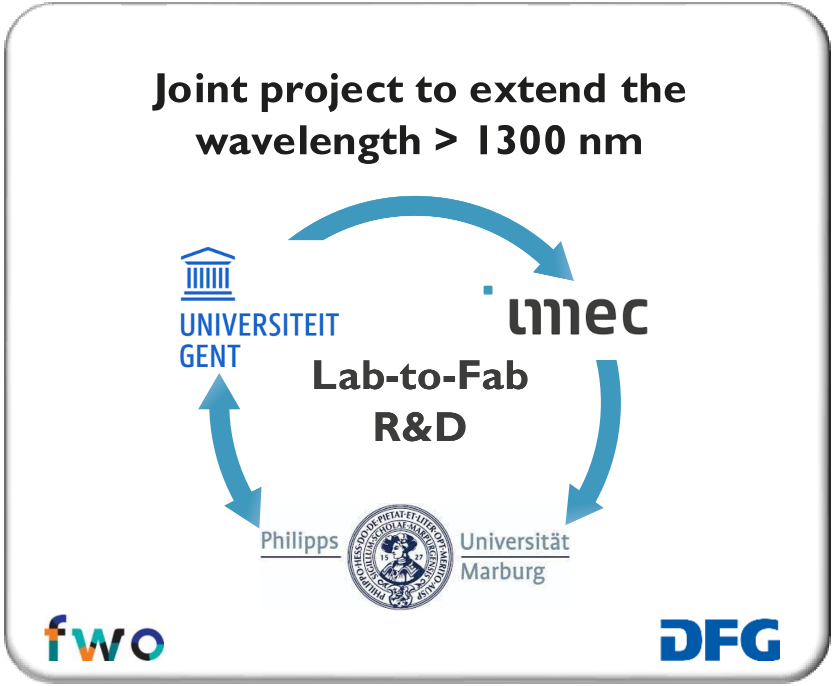


Top-view SEM

Towards O-Band Lasing

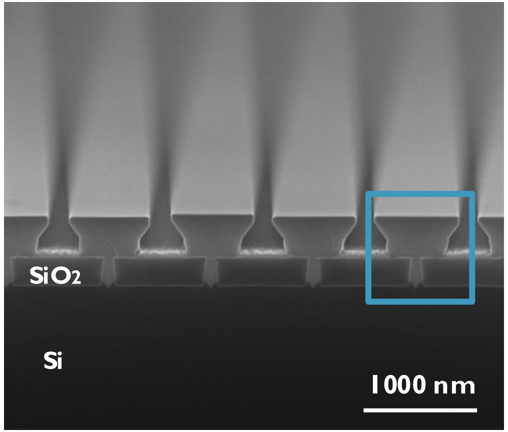
Next steps

- Control of matrix composition
  - Flexible approach but challenging epitaxy
- Alternative approaches
  - Quantum dot lasers
  - W-band gain structure
  - …

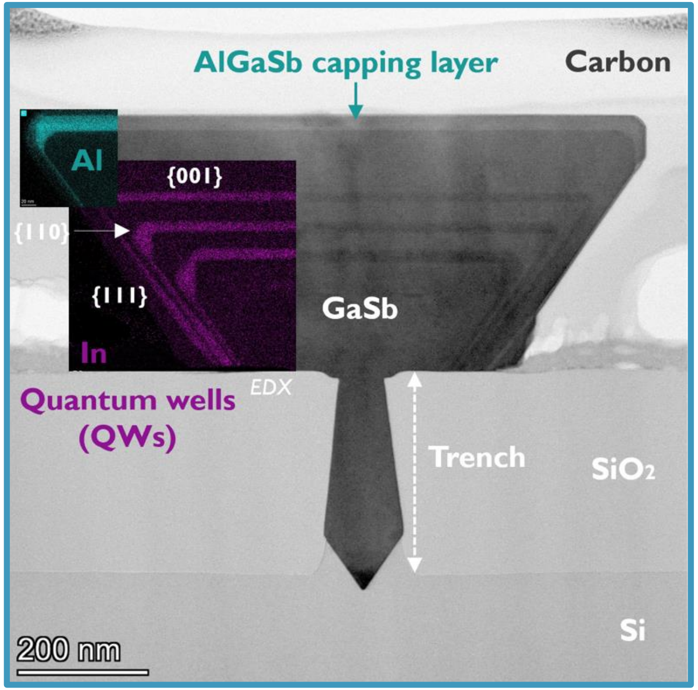


GaSb NRs with InGa(As)Sb MQWs and AlGaSb capping layer

Extend emission to the **SWIR (1.5 – 3 μm)**

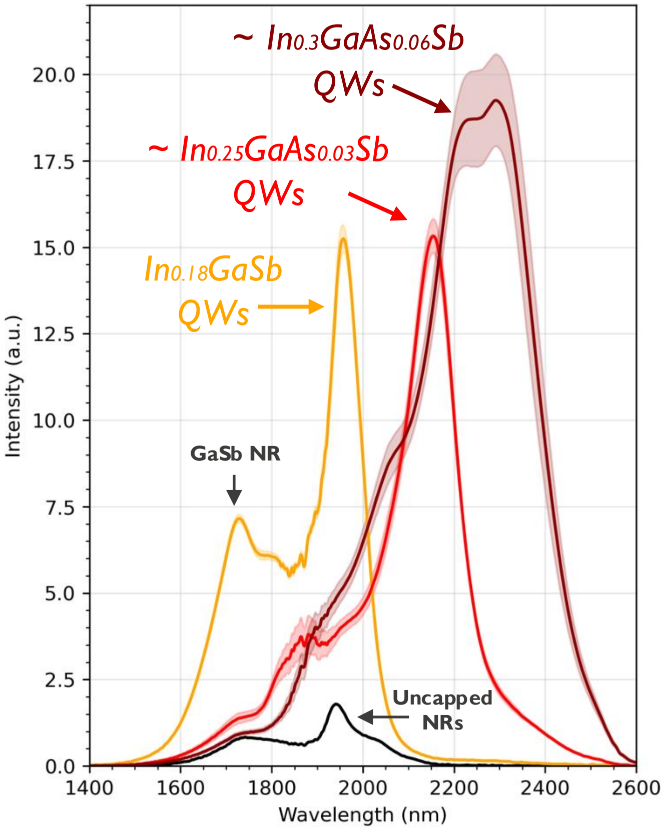


Tilted-view SEM



ABF-STEM

RT photoluminescence

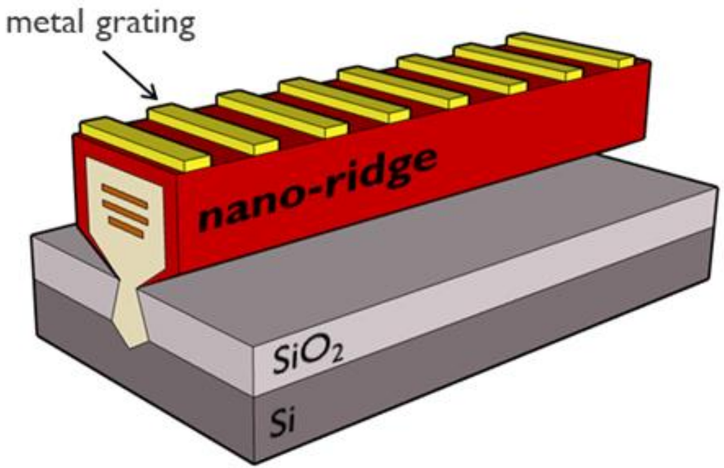


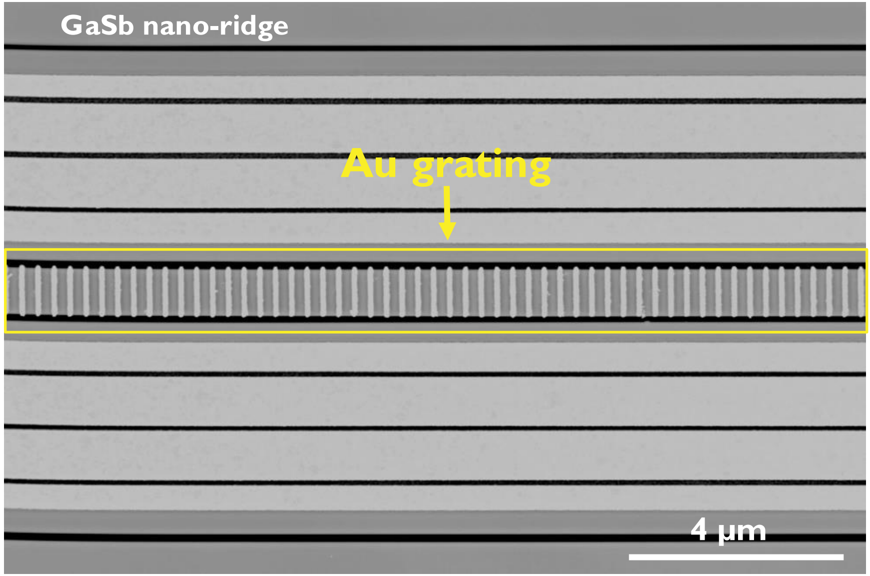
ABF-STEM = Angular Bright Field Scanning Transmission Electron Microscopy *SEM = Scanning Electron Microscopy* *RT = Room temperature*

Outlook

Realize lasing using **Distributed Feedback Grating (DFB)**

DFB grating for optical feedback





Top-view SEM

Colucci, et al (2022). Unique design approach to realize an O-band laser monolithically integrated on 300 mm Si substrate by nano-ridge engineering. *Optics Express*, *30*(8), 13510-13521.

SEM = cross section Scanning Electron Microscopy

Summary & Conclusion

Related PhD Theses

Supported by ERC Adv Grant NARIOS Grant agreement ID: 884963

- Y. Shi, "GaAs nano-ridge lasers epitaxially grown on silicon," Universiteit Gent. Faculteit Ingenieurswetenschappen en Architectuur, 2020.
- D. Colucci, "Development of a quantum dot single photon source on silicon for next generation integrated quantum circuits," Ghent University. Faculty of Engineering and Architecture, Ghent, Belgium, 2025.
- Z. Ouyang, "Ultra-compact and low-threshold nano-ridge lasers epitaxially grown on silicon," Ghent University. Faculty of Engineering and Architecture, Ghent, Belgium, 2025.
- A. Yiman, "Modelling and Characterization of Electrically Pumped InGaAs/GaAs Nano -Ridge Lasers Monolithically Grown on Silicon", Ghent University. Faculty of Engineering and Architecture, Ghent, Belgium, 2026
- E. Fahmy, "Nano-Ridge Surface Emitting Lasers", Ghent University. Faculty of Engineering and Architecture, Ghent, Belgium, 2026
- C. I. Özdemir, "III-V photodetectors monolithically integrated on silicon for interconnect applications," Ghent University. Faculty of Engineering and Architecture, Ghent, Belgium, 2024
- Hsieh, Ping-Yi, "Reliability of Monolithic GaAs-on-Si Photonic Devices for Data Communication" KULeuven, 2026 (DVT not involved)

NR2.0:
Processing and preliminary device characterization

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