GHENT UNIVERSITY

DEPARTMENT OF INFORMATION TECHNOLOGY (INTEC) – **PHOTONICS RESEARCH GROUP**

20th August 2025

Ultra-compact and Low-threshold Nano-ridge Lasers Epitaxially Grown on Silicon

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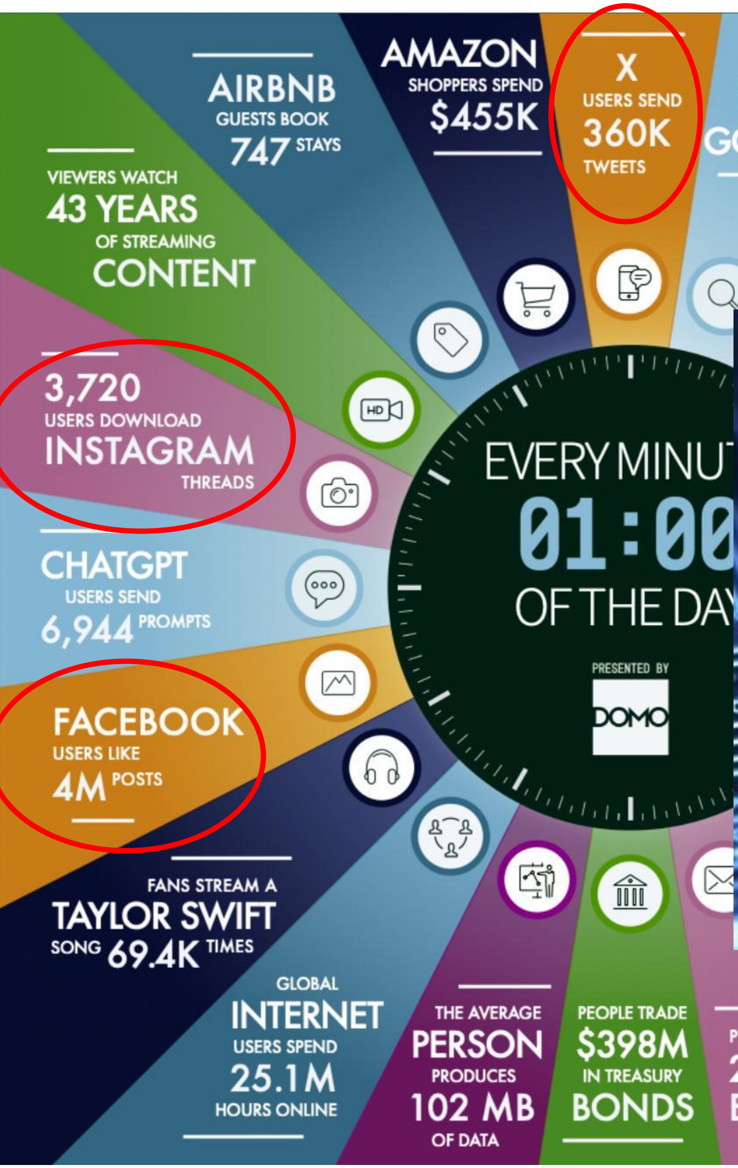
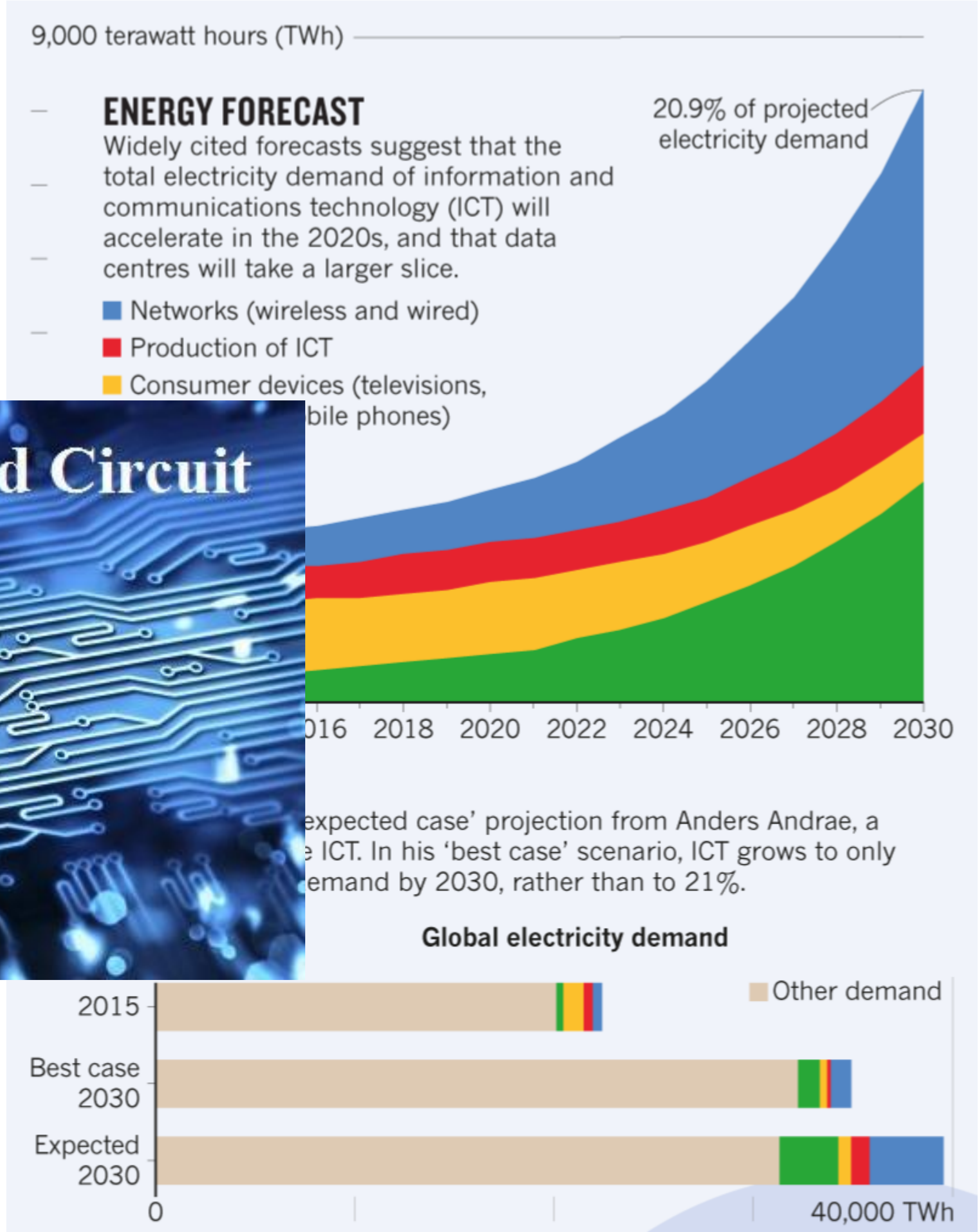
Supervisors: Dries Van Thourhout, Geert Morthier

imec

PHOTONICS RESEARCH GROUP

The explosion of social media



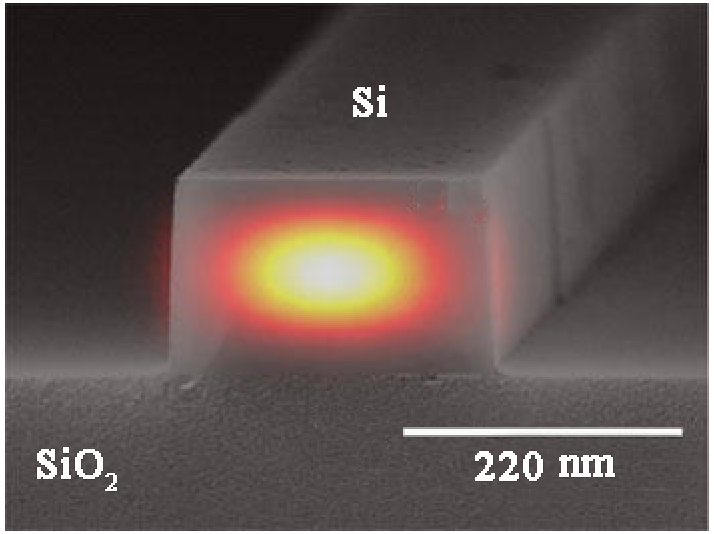


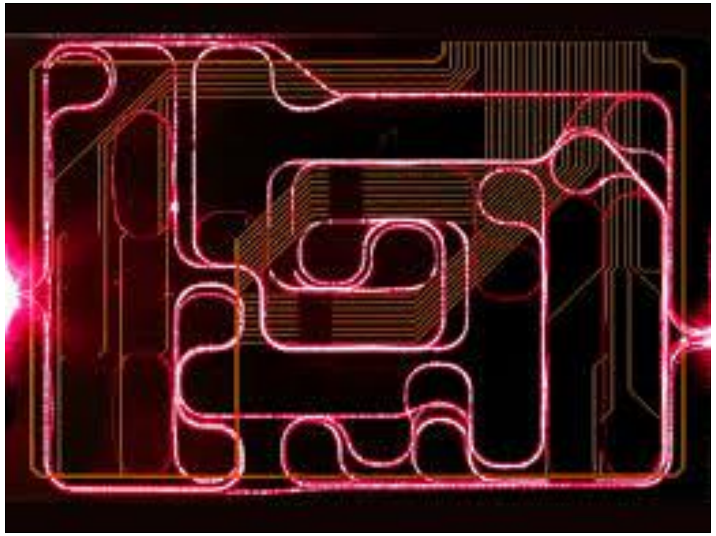
What are Silicon Photonic Integrated Circuits?

Waveguide: confine light tightly

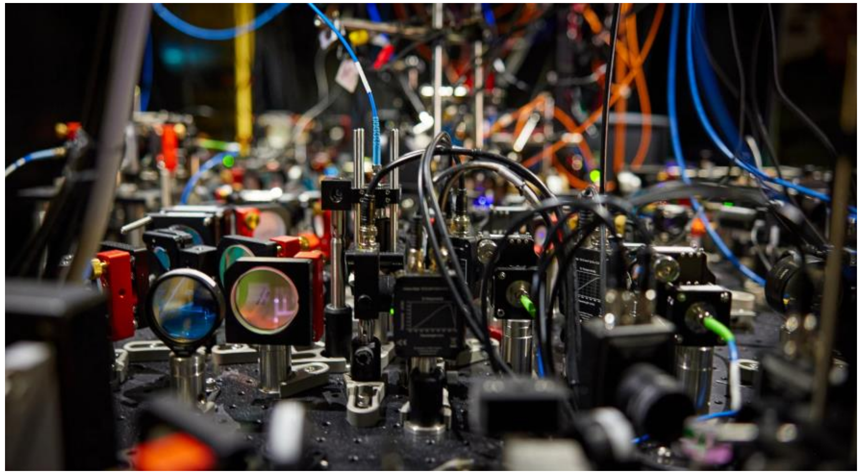
Guide and manipulate light on chip

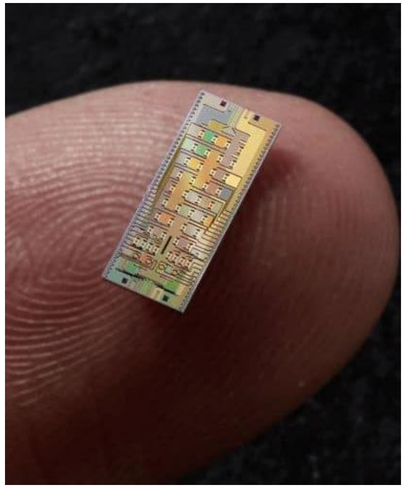
Silicon photonic





Photonic integrated circuits





Noteworthy commercial products

Mobileye, Intel subsidiary

Silicon photonic lidar system-on-chip

Sicoya

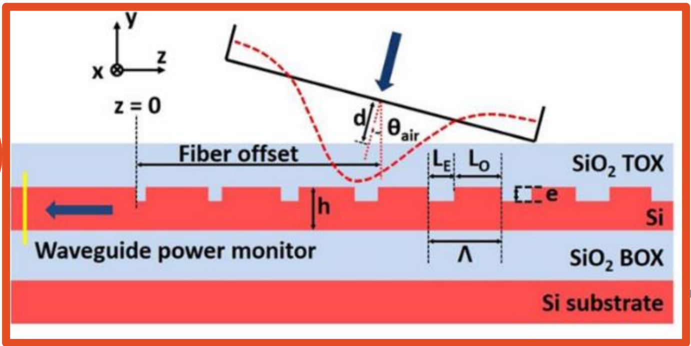
Optical transceivers

Key silicon photonic components

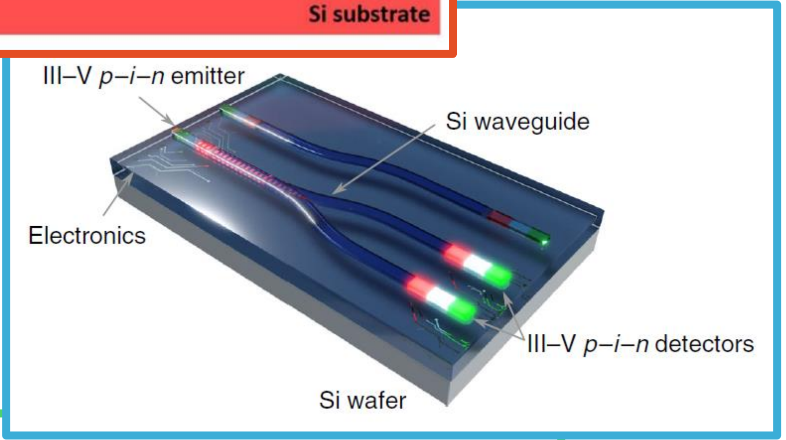
Silicon photonic technology

High-performance signal processing

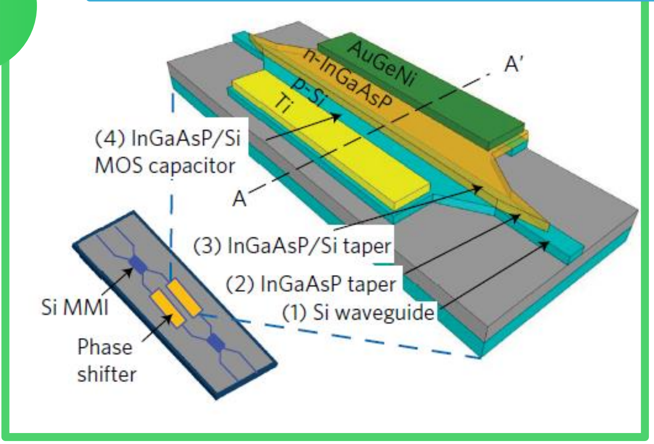
01 High-efficient grating couplers



02 High-response-speed photodetector



03 High-speed modulator



04 ***Missing practical laser***

On-chip light sources beyond III-Vs

Bulk silicon light source

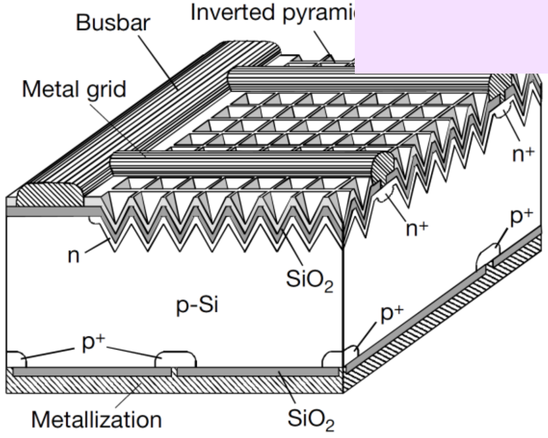
Ge-on-Si laser

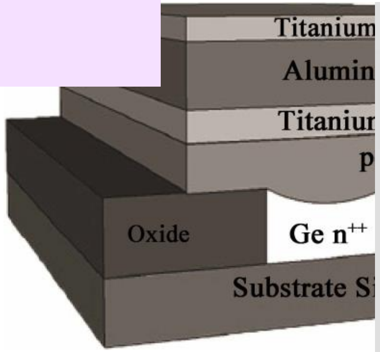
Er^{3+} doped light s

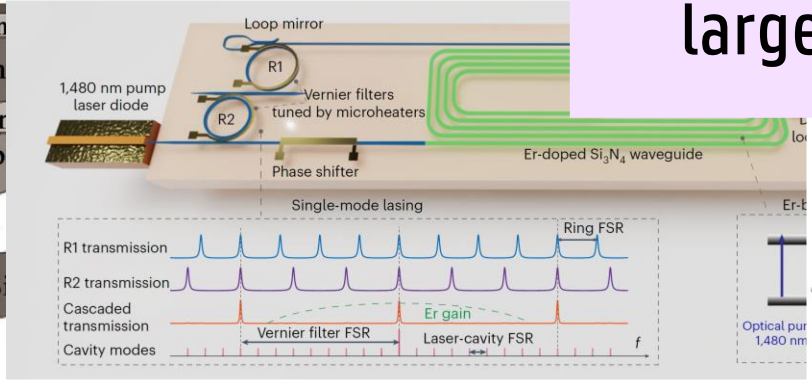
Ti:Sa laser

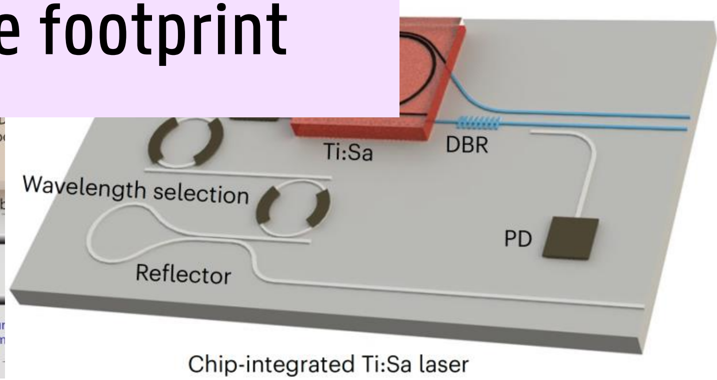
inefficient

Novel, optically pumped and large footprint

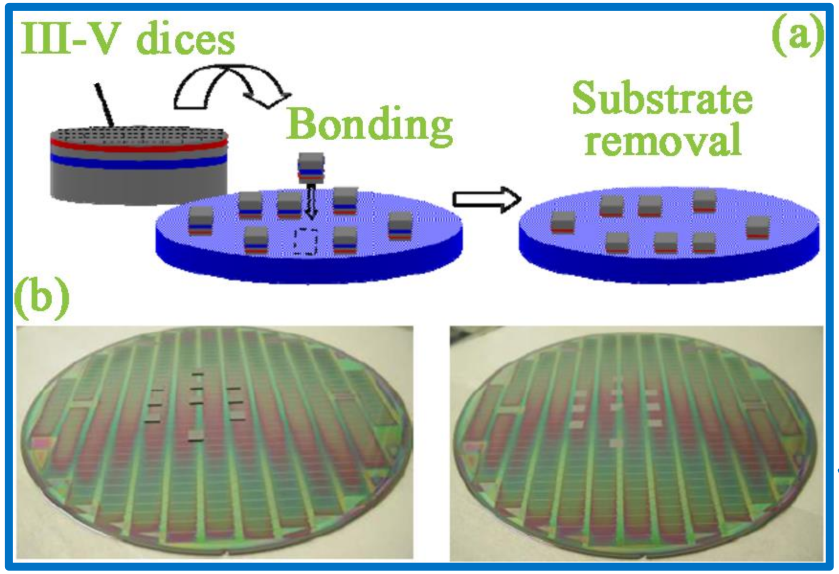


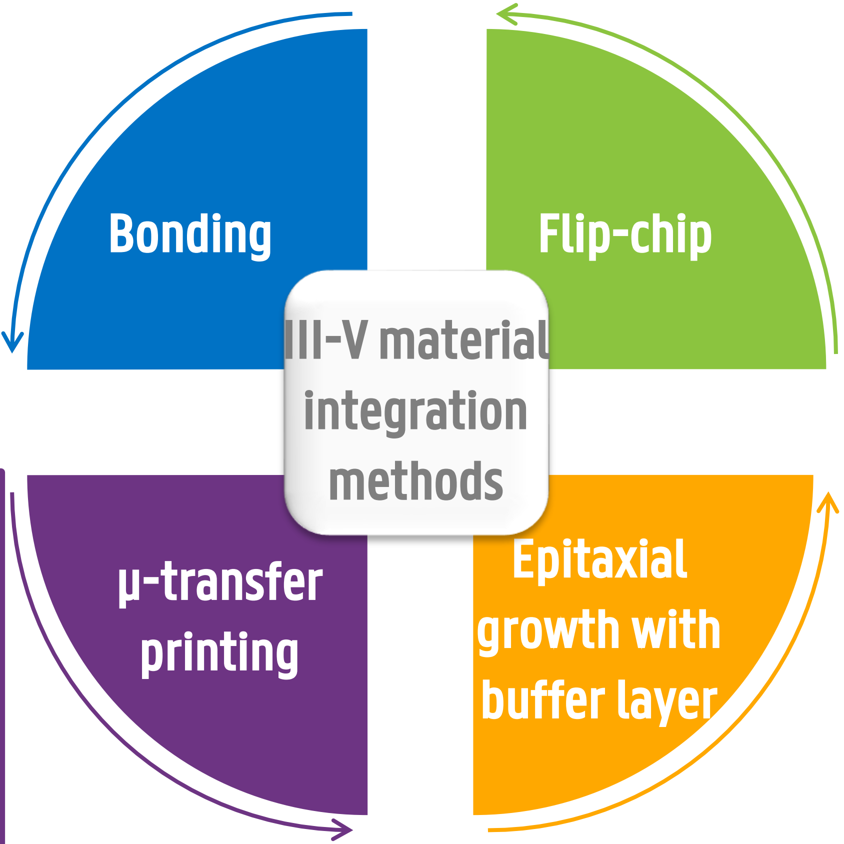


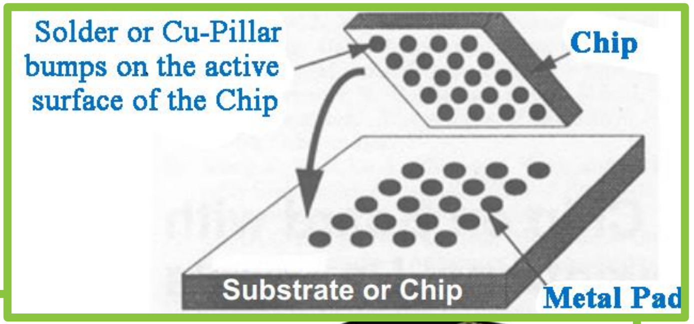


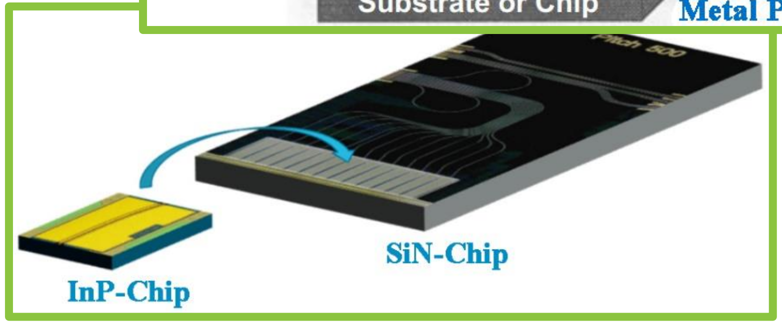


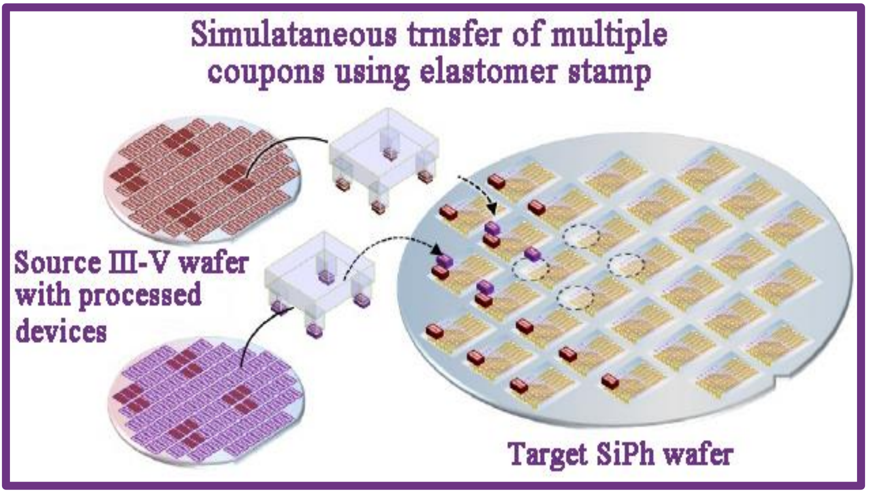
III-V Hybrid integration techniques

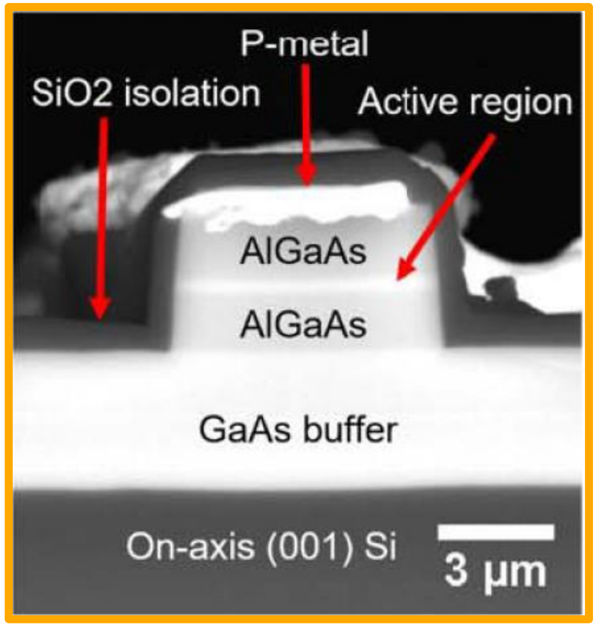












1. J. H. Lau, et al, Flip Chip Technology Versus FOWLP, chapter 2, 2018.
2. M. Theurer, et al, J. Light. Technol., 38(9), 2020.
3. J. Ben Bakir, et al, Opt. Express, 19, 10317-10325, 2011.
4. J. Marchetti, et al, Opt. Express, 18, 21275-21285, 2020.
5. J. C. Norman, et al, IEEE JOURNAL OF QUANTUM ELECTRONICS, 55(2), 2000511, 2019.

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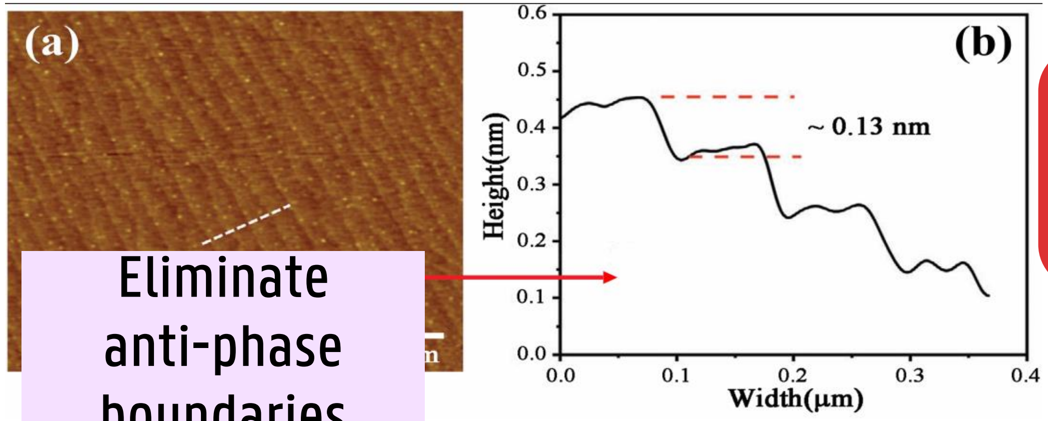
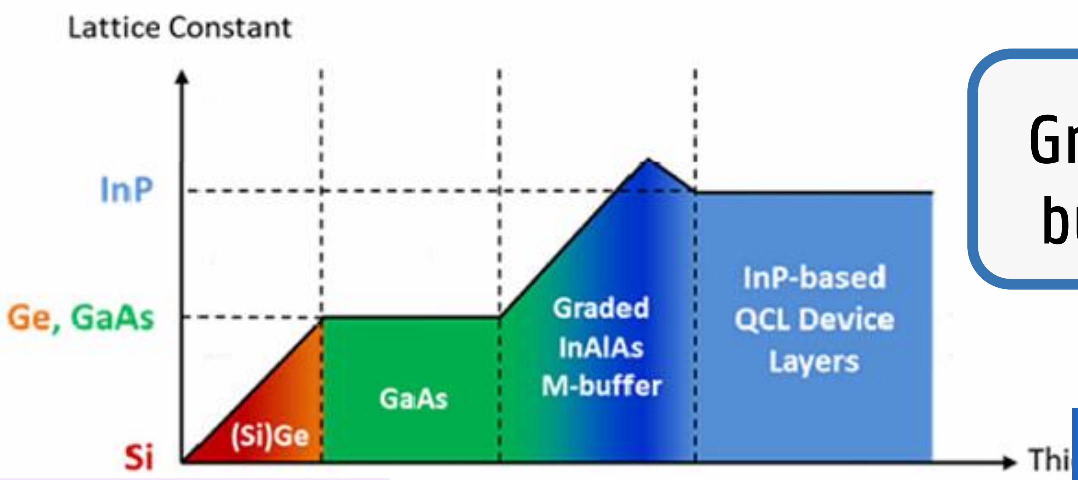
Epitaxial growth technology



Eliminate anti-phase boundaries



Lattice mismatch transitions

Double atomic step

Defect filter layer (DFL)

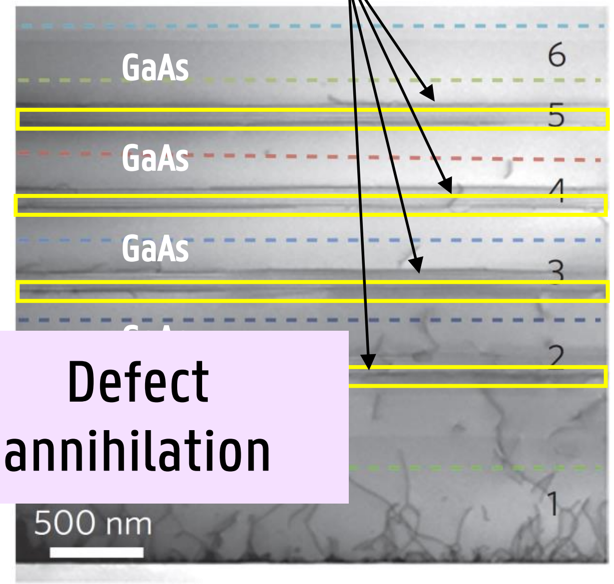
III-V on blank Si

Graded buffer

Quantum dots (QDs)

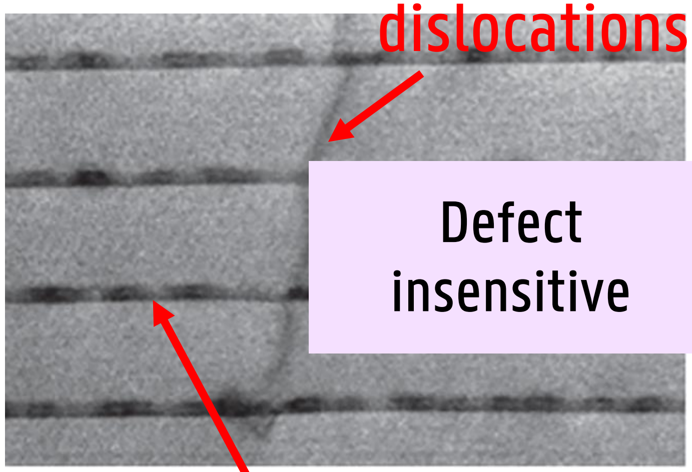
Harsh conditions or thick buffer layer

Dislocation filter layers



Defect annihilation

Thread dislocations

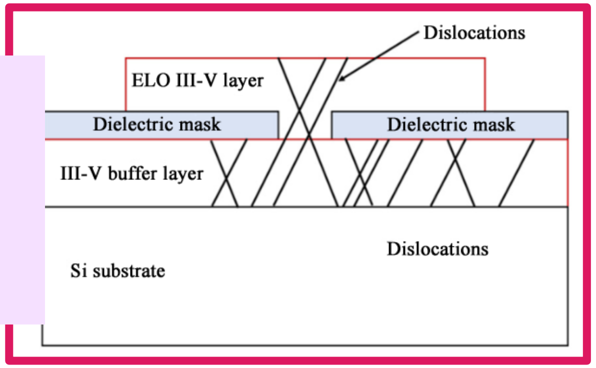


Defect insensitive

QDs

Epitaxial growth technology

Epitaxial lateral overgrowth (ELO)



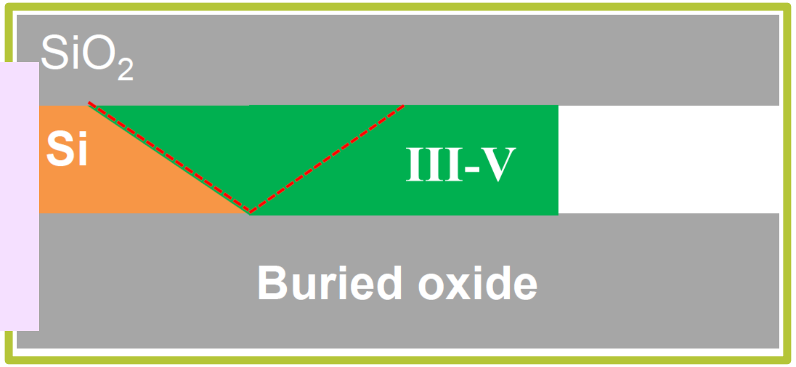
restricted defect-free regions, mechanical weakness

Template assisted selective epitaxy (TASE)

mechanical stability issue with template mask

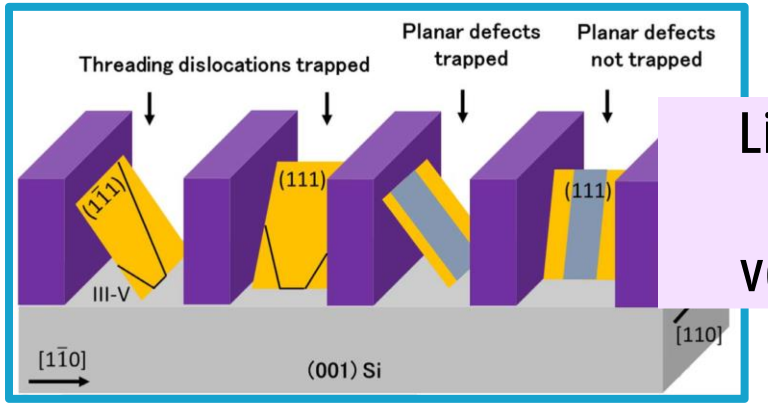
Selective area growth

Lateral aspect ratio trapping (LART)



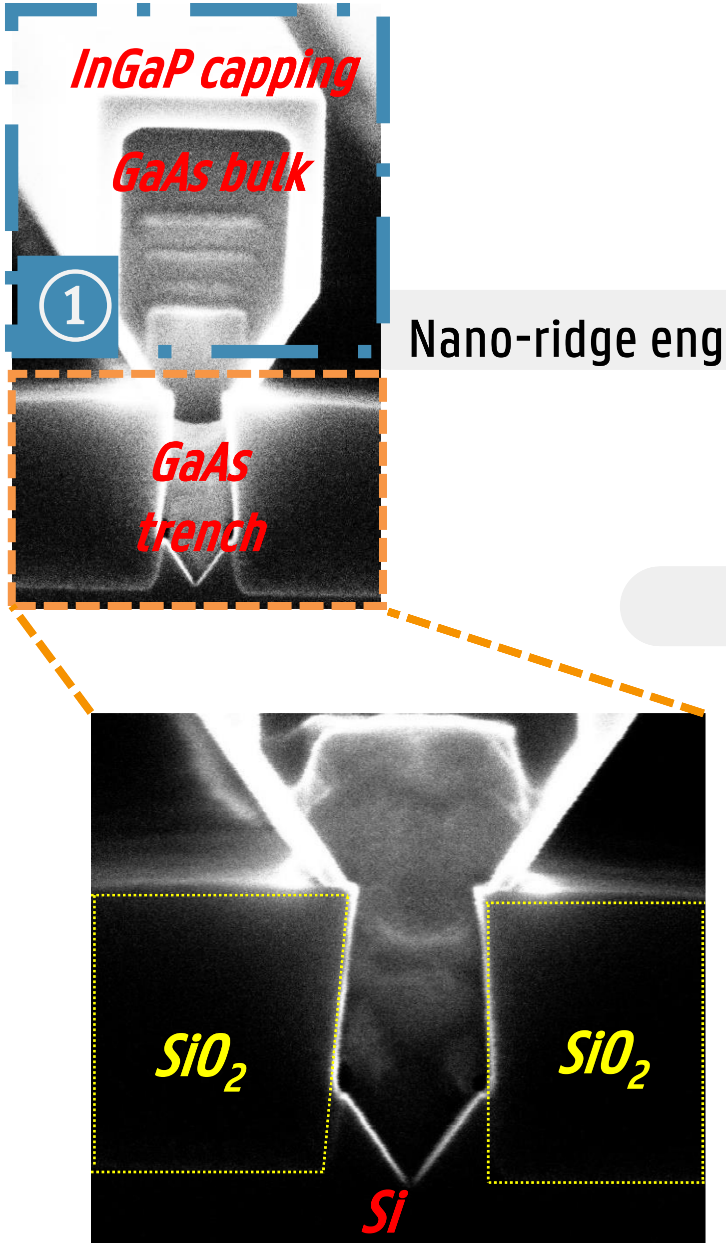
Exposure of III-V gain material to air

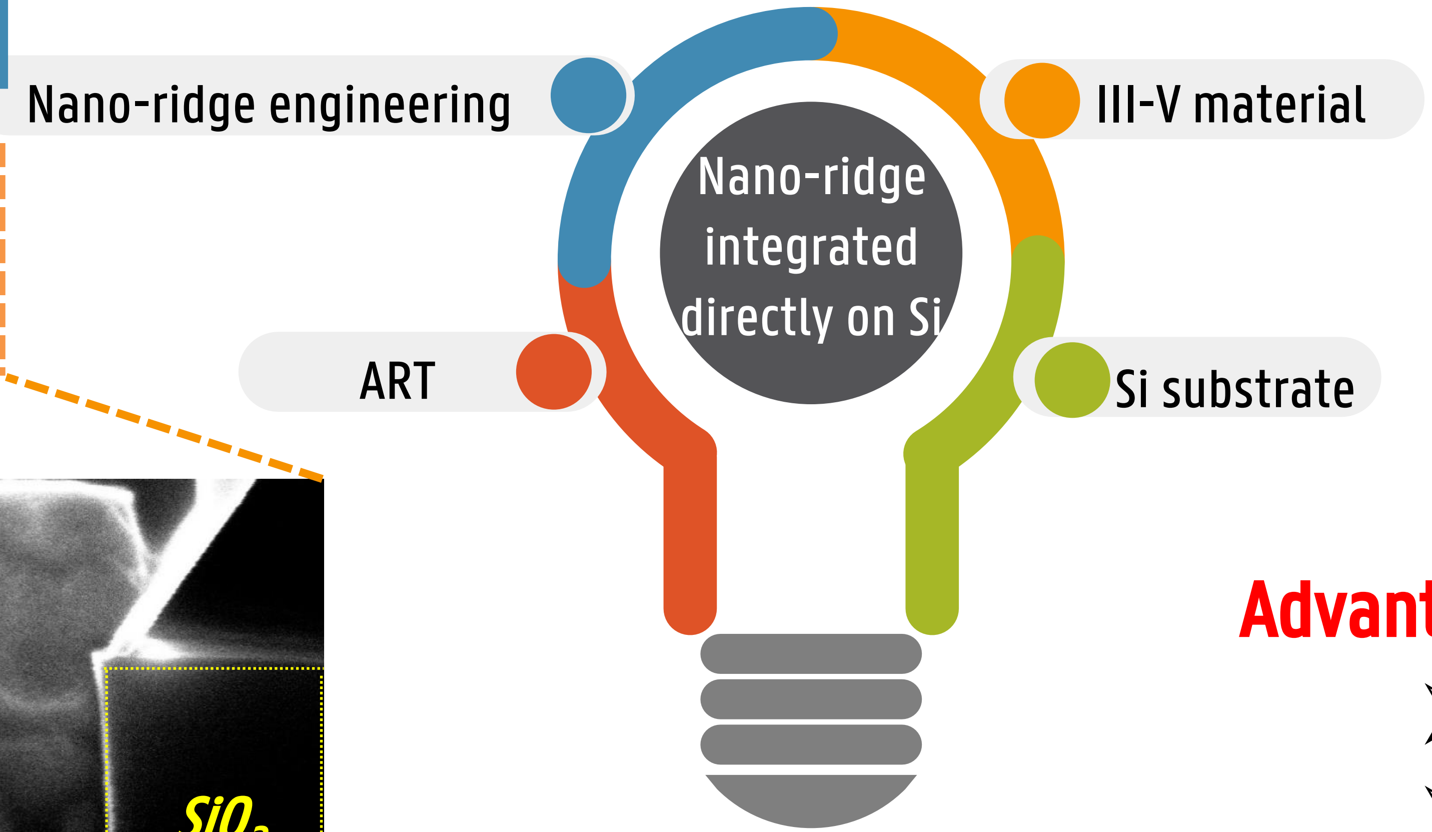
Aspect ratio trapping (ART)

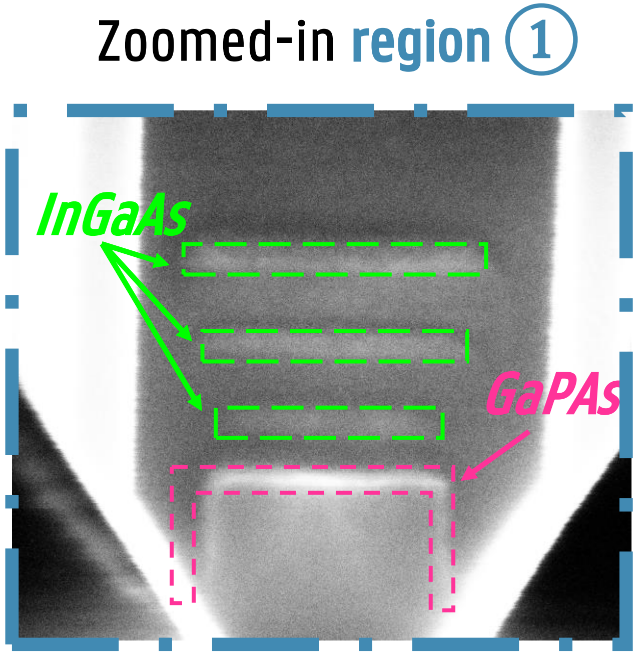


Limited III-V volume

III-V nano-ridge integrated on Silicon







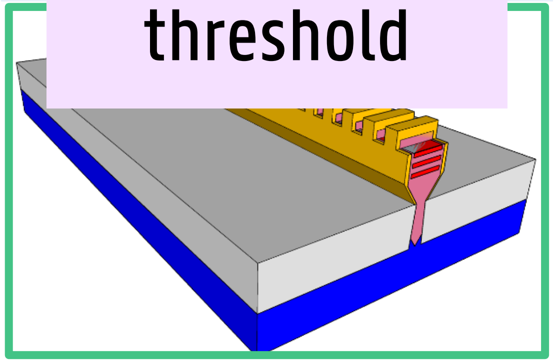
Advantages

- ➢Device scalability
- ➢Integration density
- ➢Fabrication cost

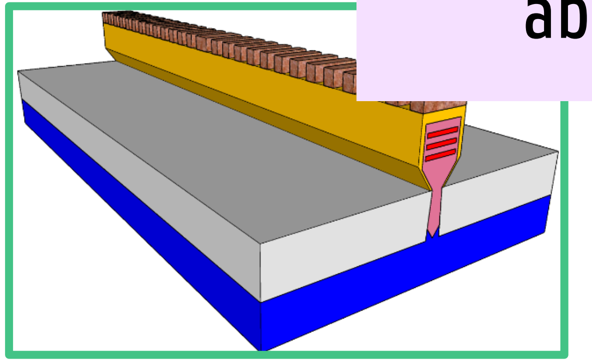
Demonstrated nano-ridges

Nano-ridge with an etched grating inside

High threshold



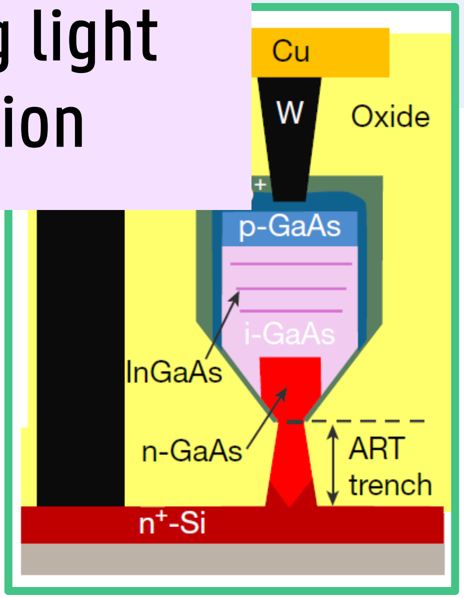
Nano-ridge with metal grating o



Large footprint and strong light absorption

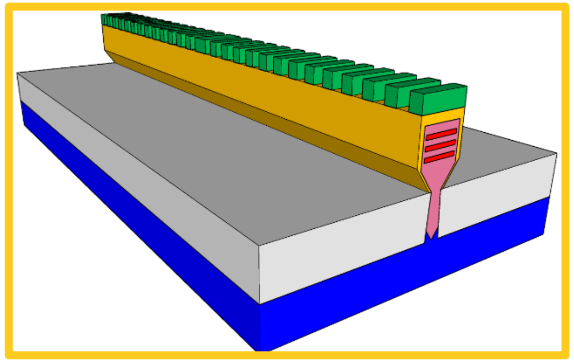
GaAs-based nano-rdge

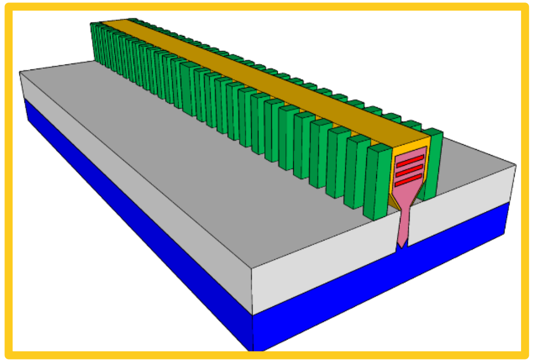
iobe

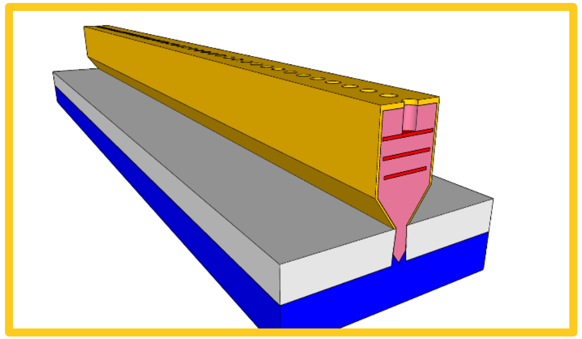


Thesis objective

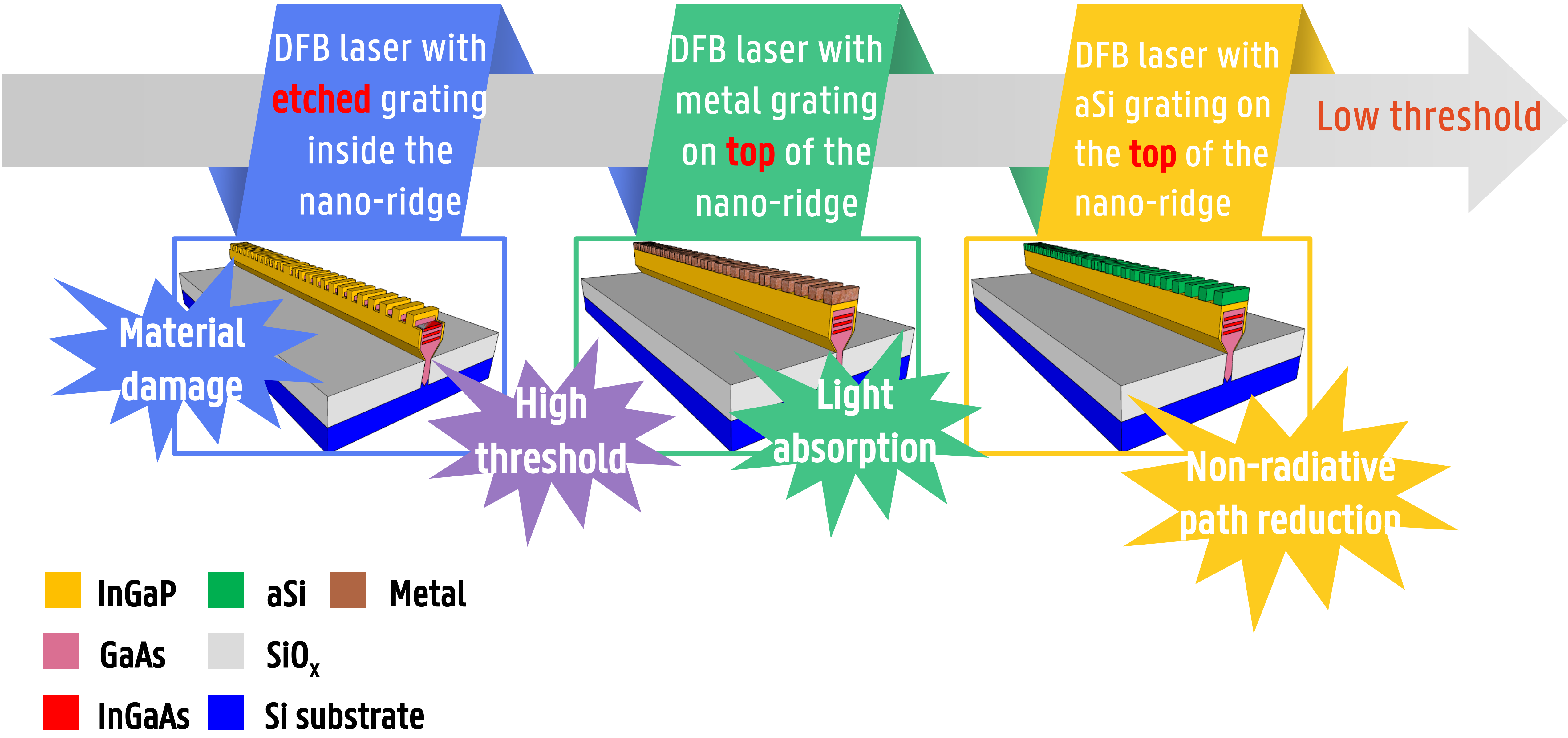
- To optimize nano-ridge lasers design to lower thresholds, as compared to earlier devices with an etching grating.
- To demonstrate nano-ridge lasers with low thresholds and small footprints.
- Three potential lasers are explored to realize these targets, including lasers with aSi graing on top, sides and photonic crystal defined inside.







Motivation-Why amorphous Si grating on top of nano-ridge?

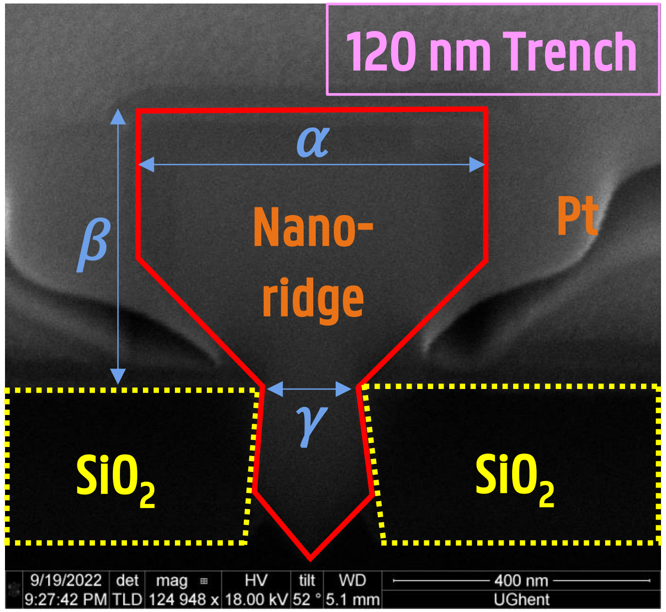


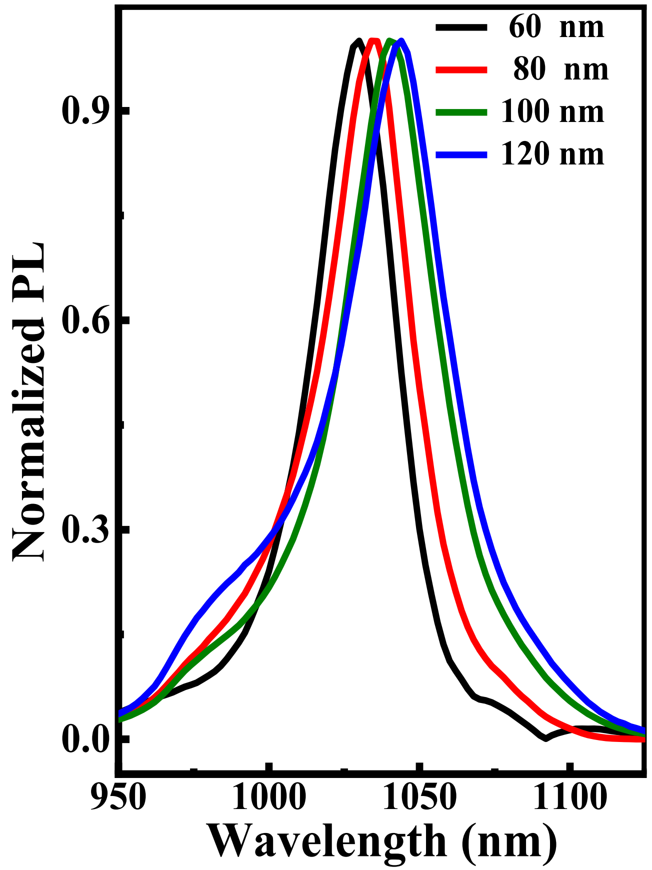
Nano-ridge dimension and emission wavelength

- Which structure and wavelength range?

➢ Dimensions in design are taken from the wafer

➢ Target design wavelength: 1030-1050 nm

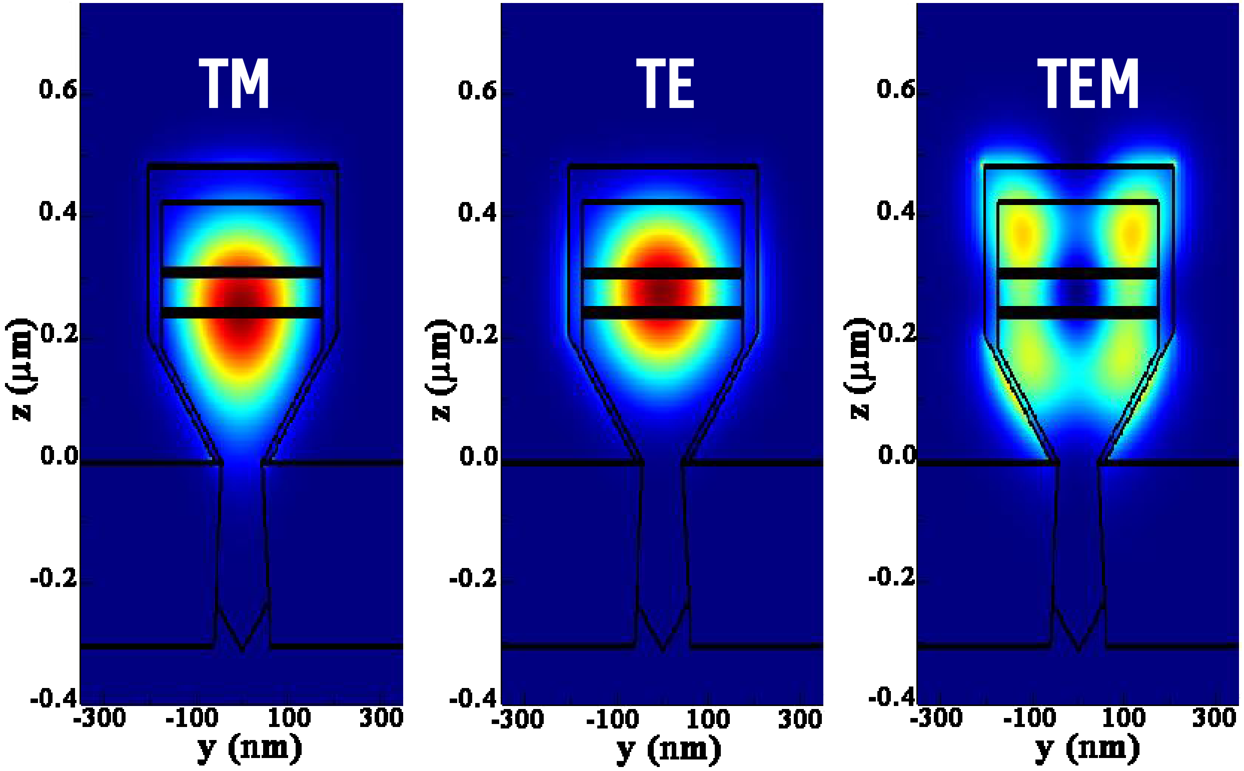


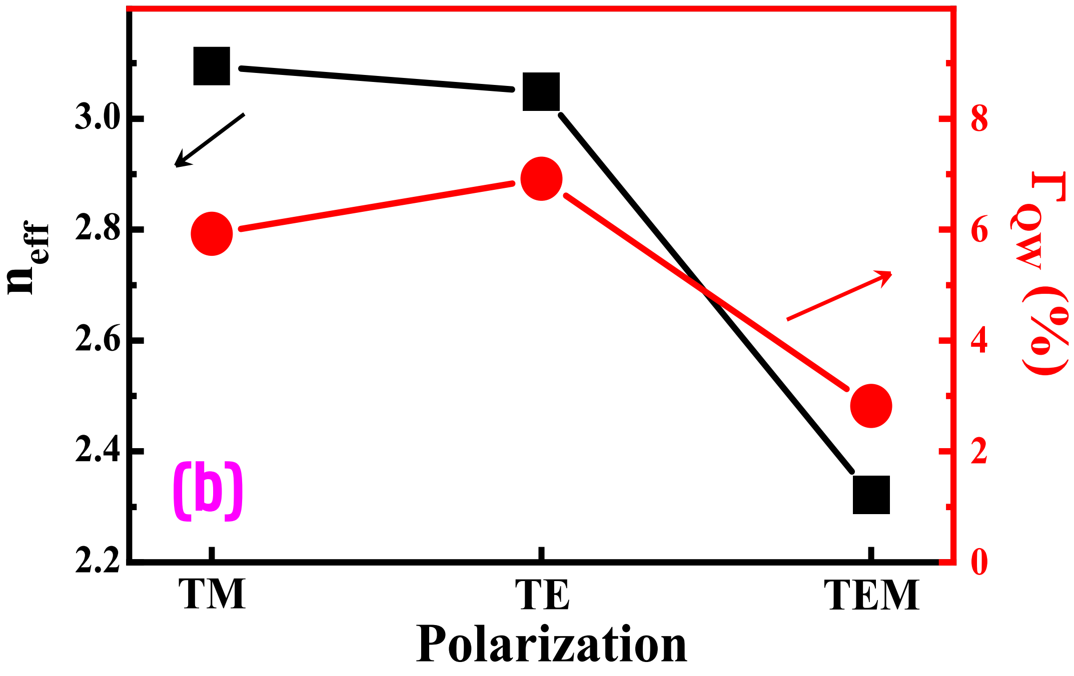


Electric field distributions and mode confinements

Electric field distributions

(a)

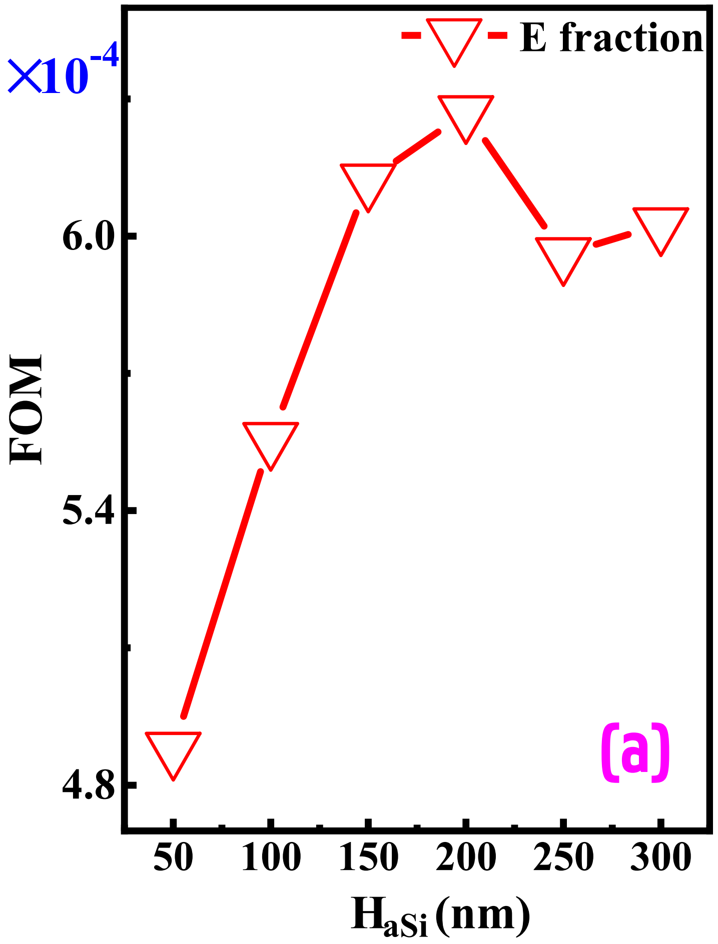


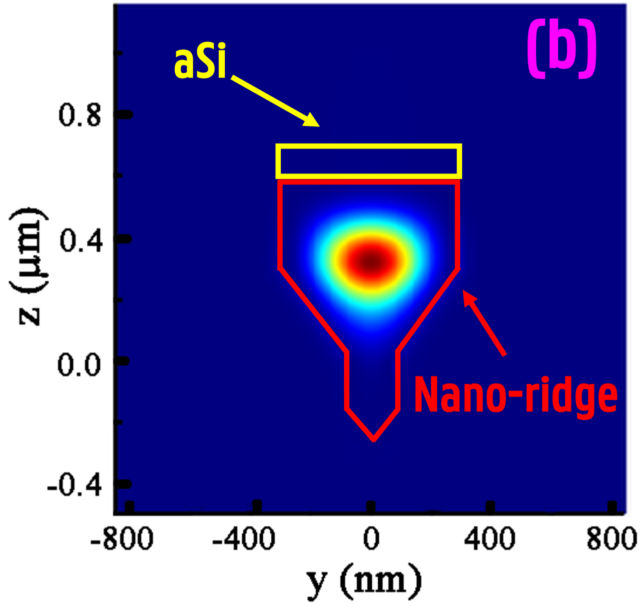


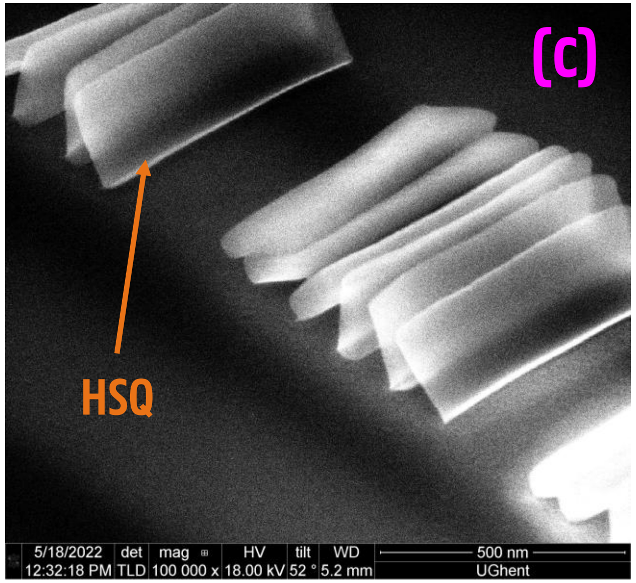
TE-like mode is the best option for laser designs.

Laser designs with various heights of the aSi grating

$$FOM = \Gamma_{aSi}\Gamma_{QWs}$$

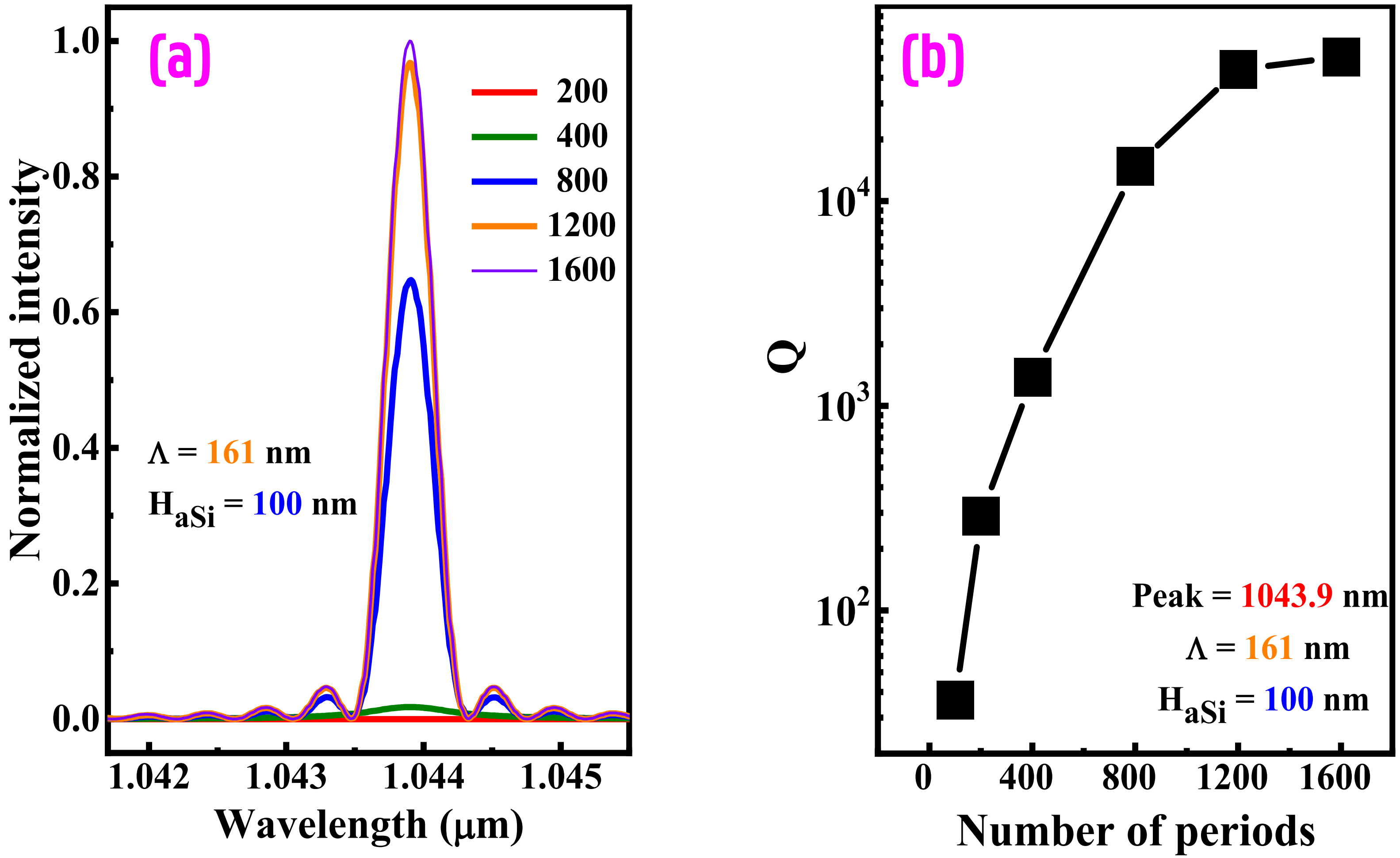




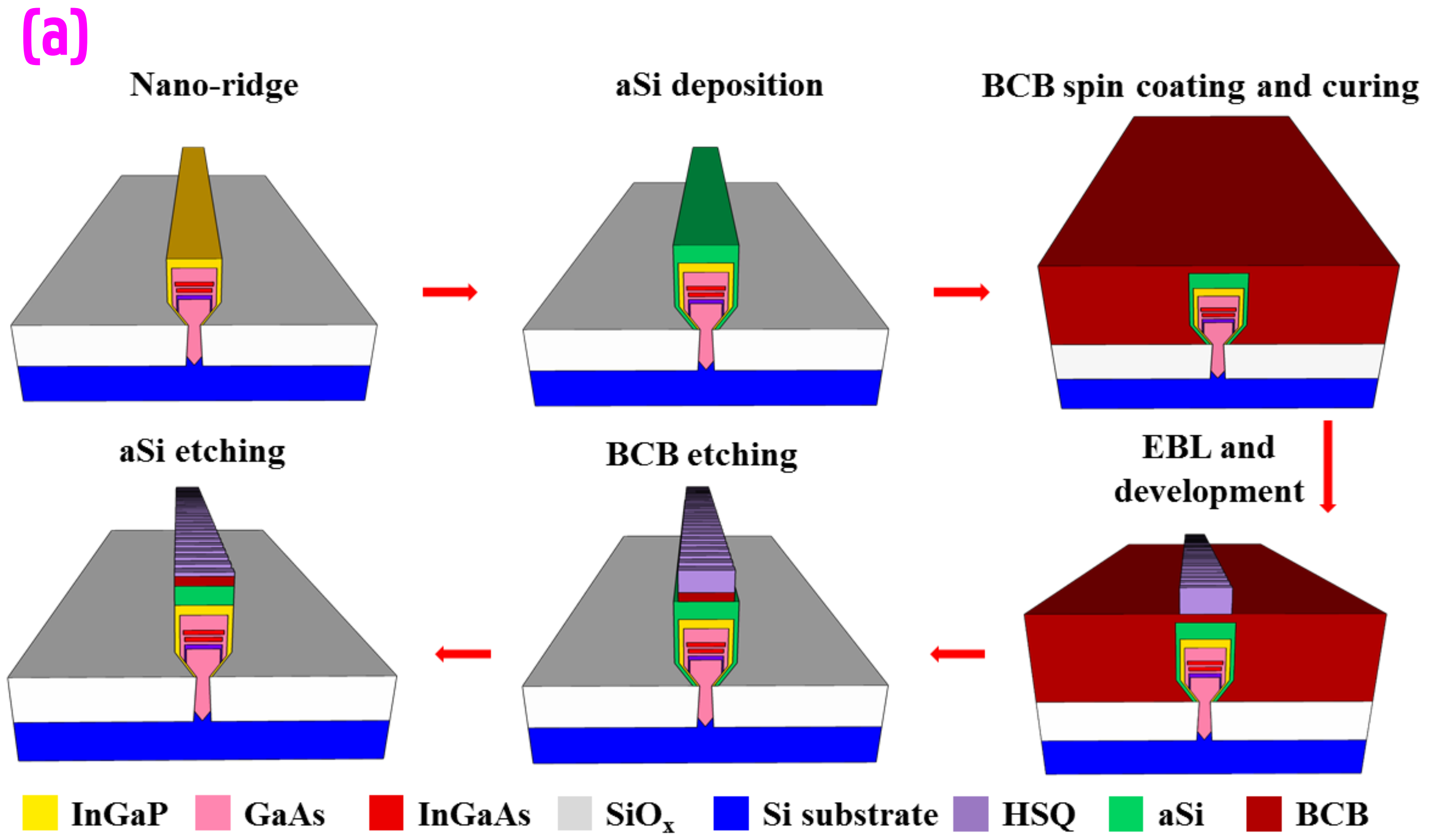


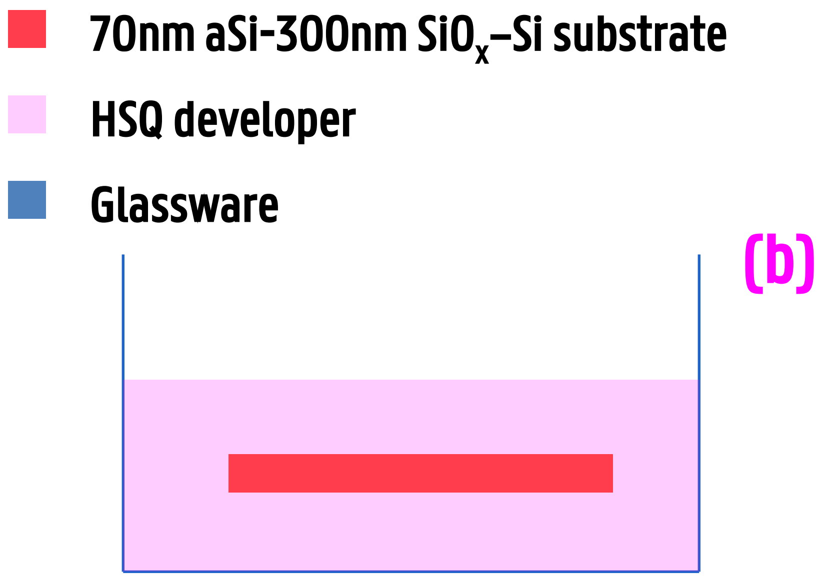
The height of aSi grating was chosen as 100 nm.

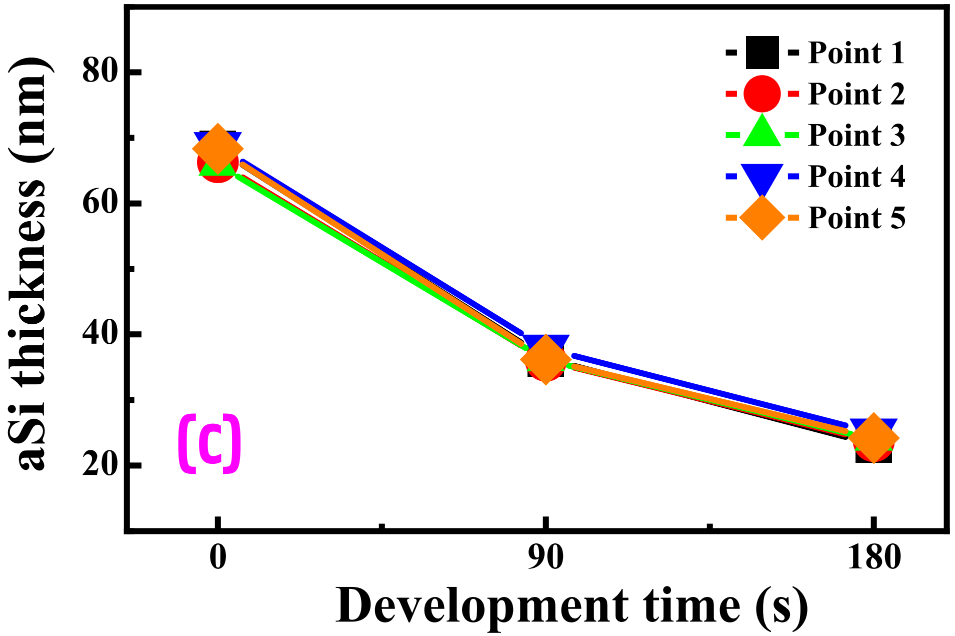
Simulated spectrum and Q-factor



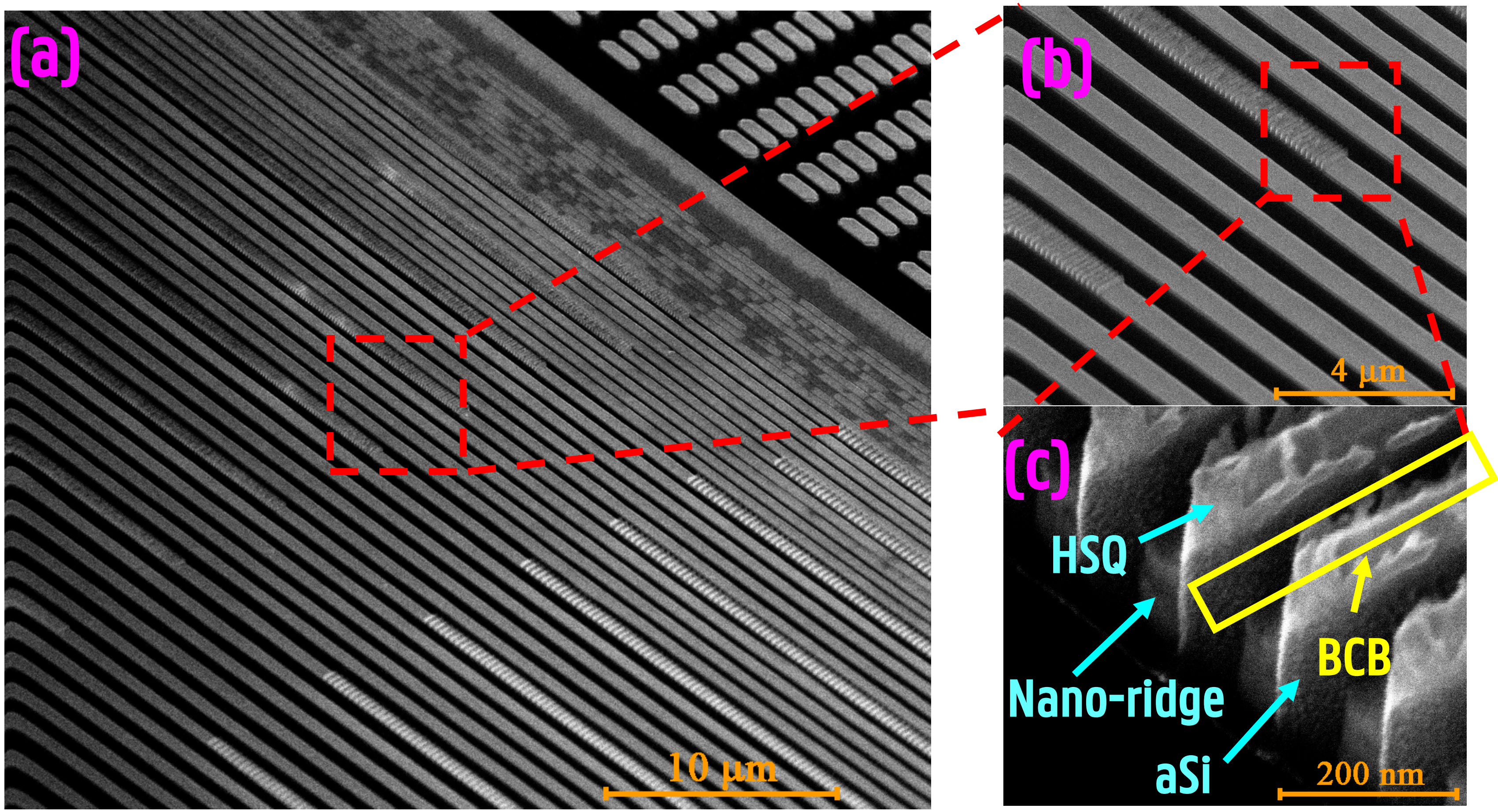
Process flow-BCB protection layer



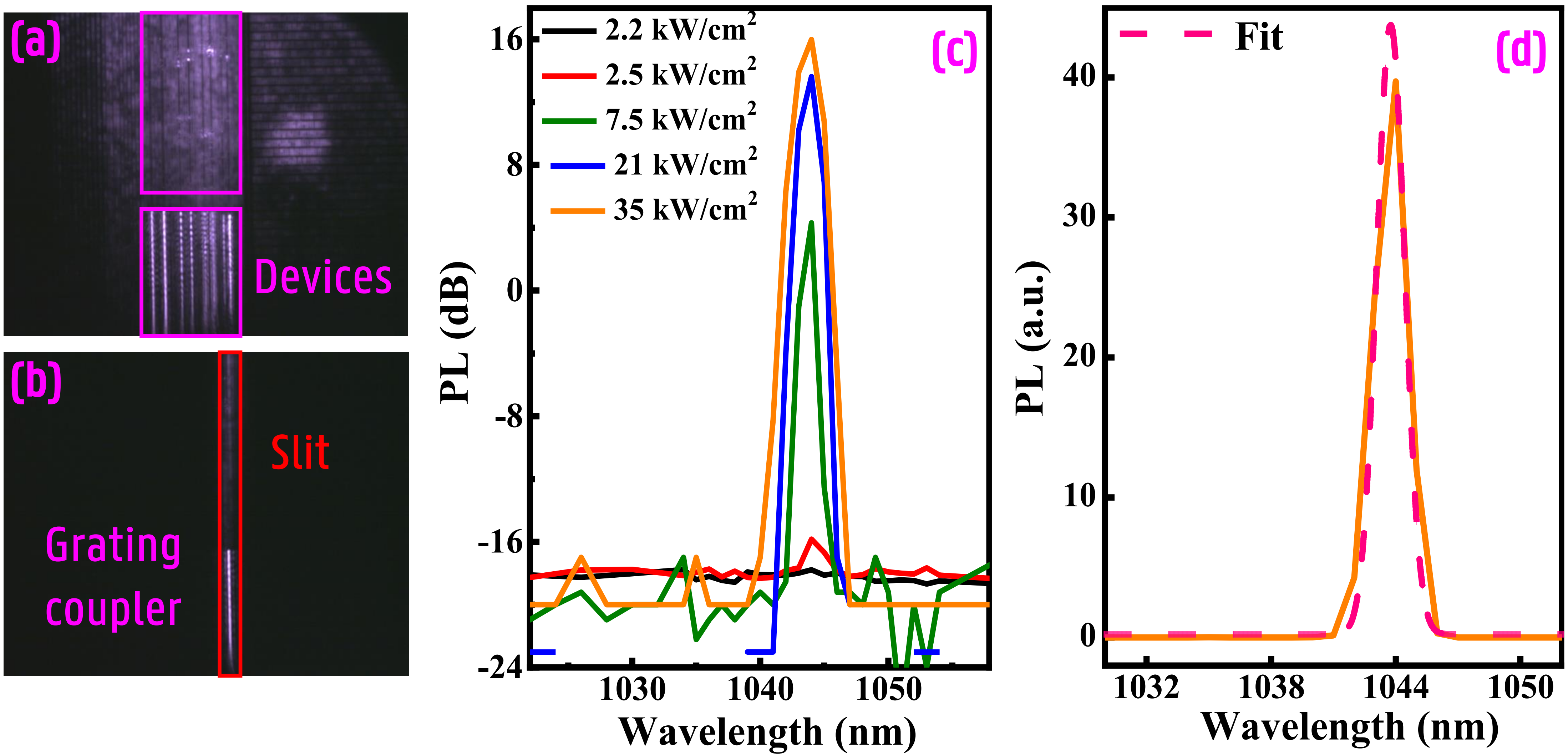




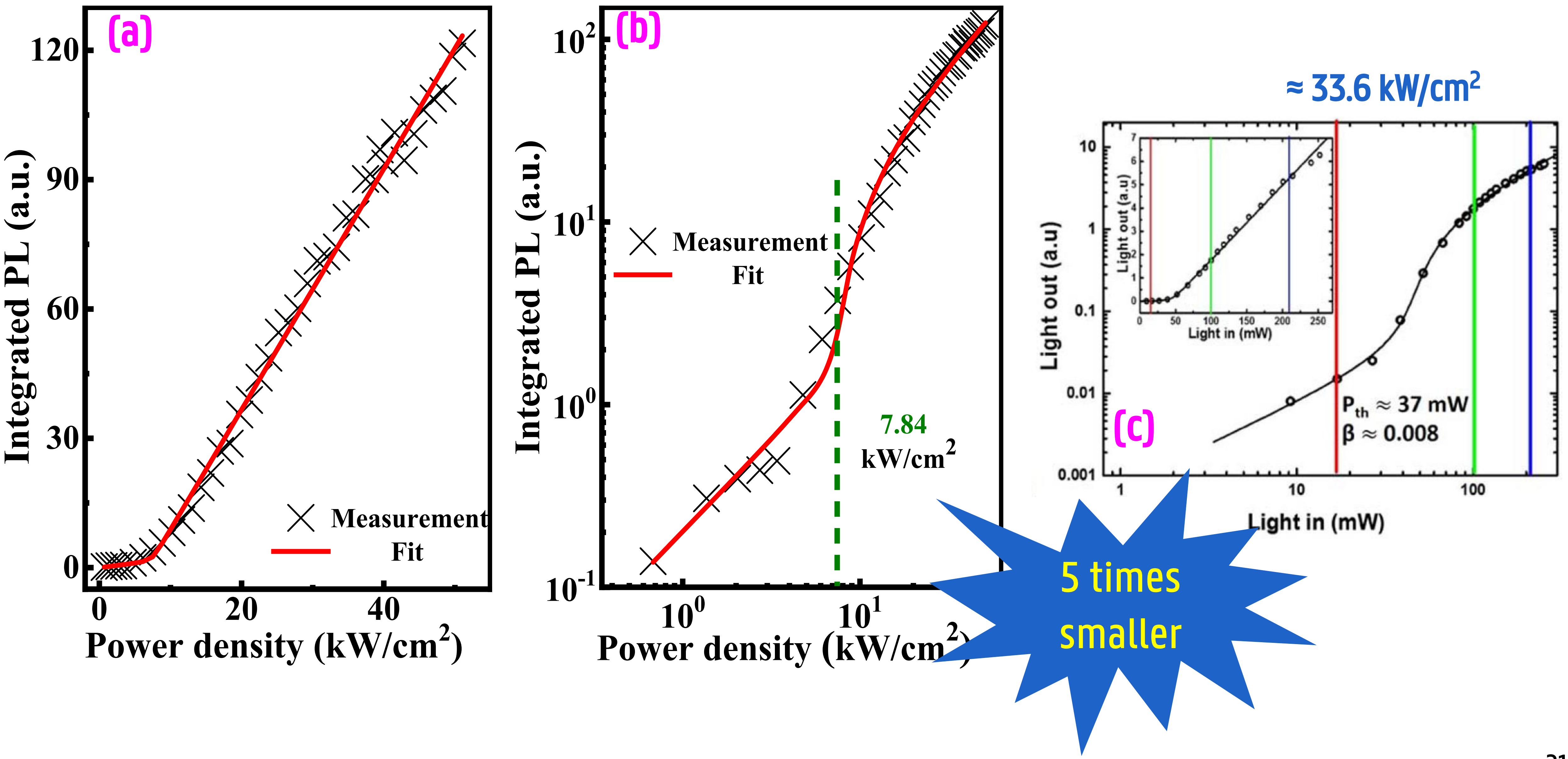
Process flow- devices overview



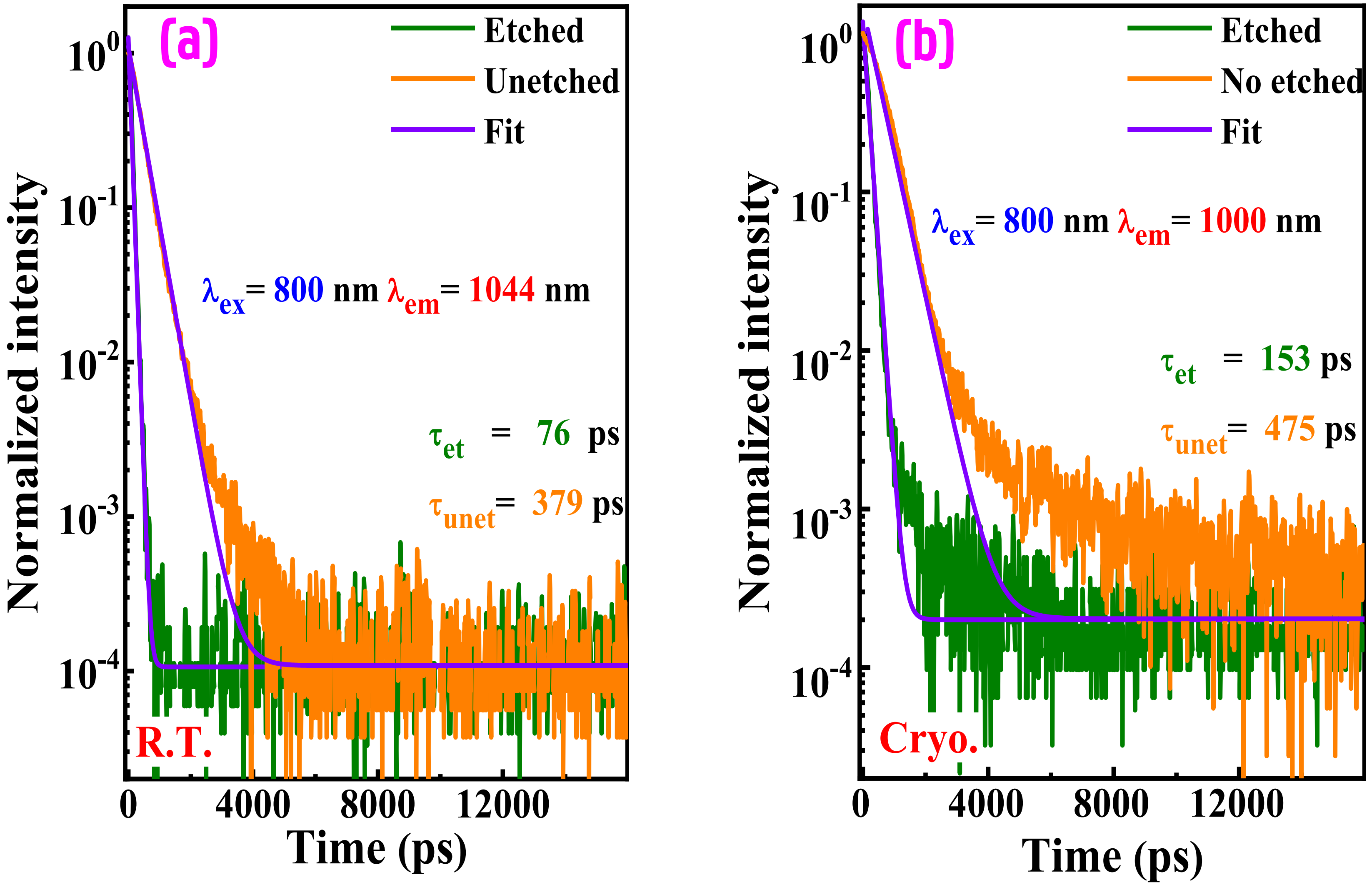
Measurement-PL spectrum



Measurement-light in – light out curve



Measurement-TRPL



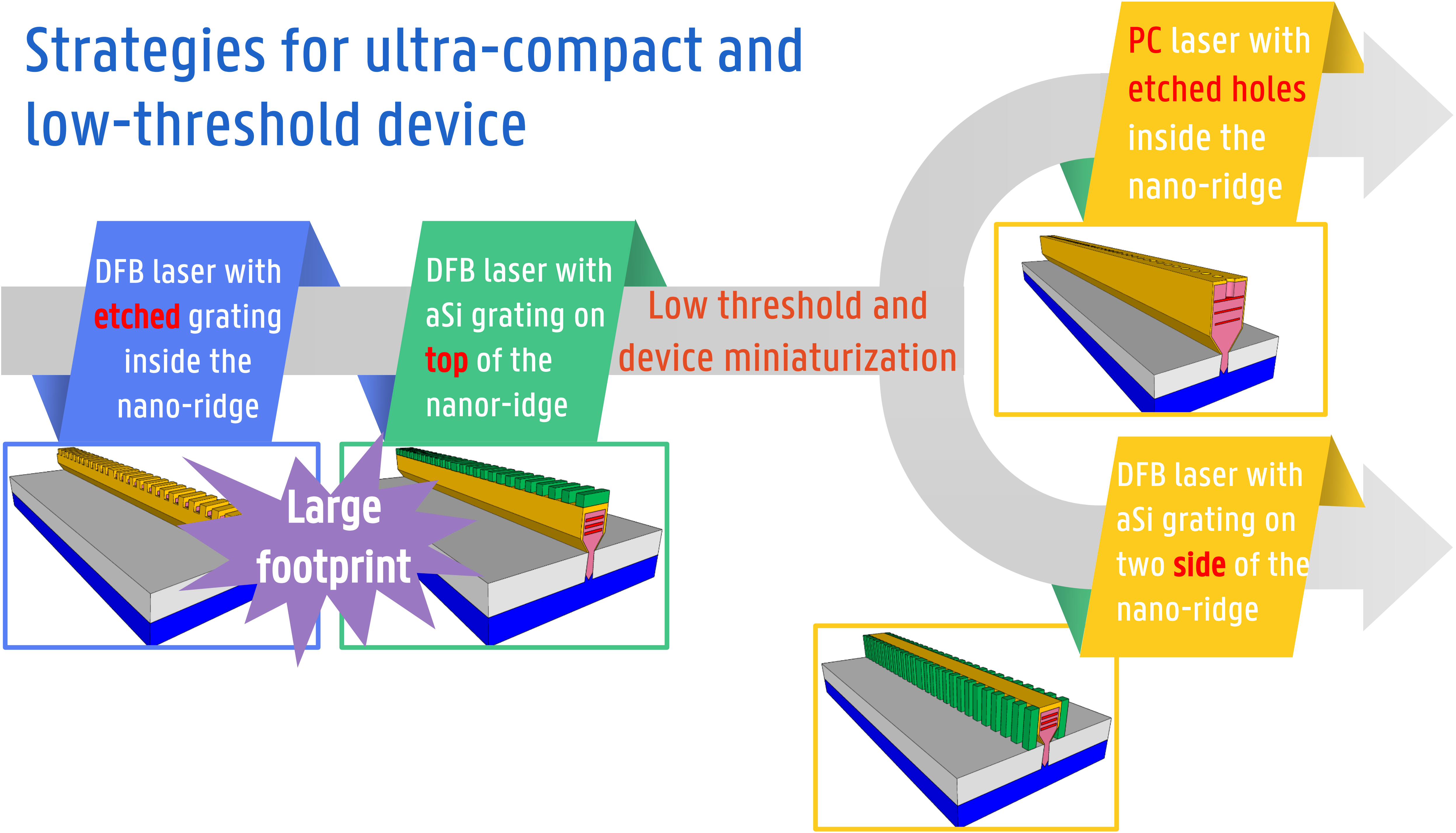
- The aSi grating minimizes carrier loss at the GaAs-air interface and prevents damage to QWs.

Take-home message – lasers with aSi grating on top

- With the aSi grating on the top of nano-ridge, lasing is achieved.

- The minimum threshold of 7.84 kW/cm^2 is 5 times lower than that of the nano-ridge laser with an etched grating.

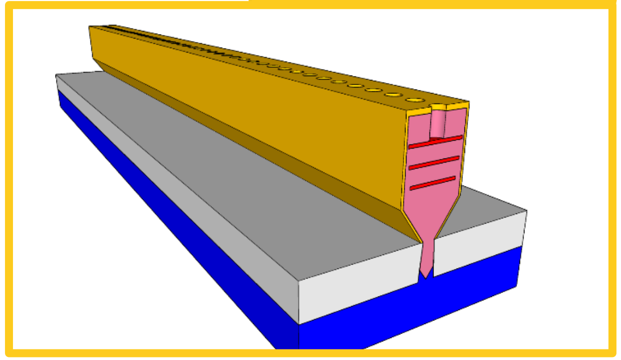
Strategies for ultra-compact and low-threshold device



Motivation-Why photonic crystal(PC) inside nano-ridge?

PC laser with etched holes inside the nano-ridge

Low threshold and device miniaturization



- InGaP
- SiO_x
- $In_{0.25}Ga_{0.75}As$
- $In_{0.45}Ga_{0.55}As$
- Si substrate

Photonic crystal

01 Enhanced light confinement

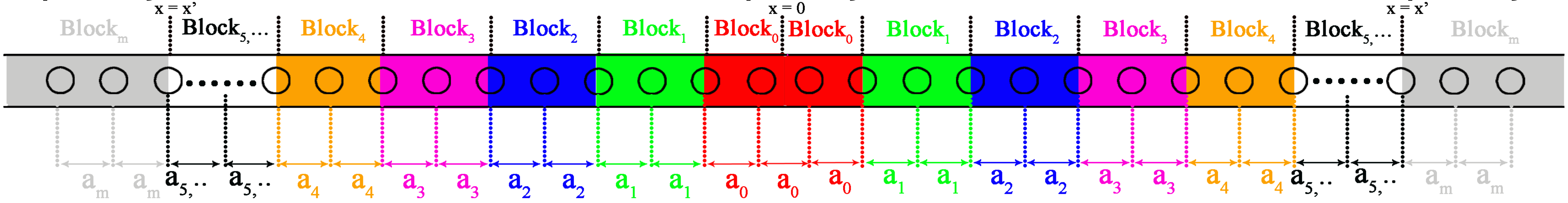
Ultra-compact device

02 Apodization design

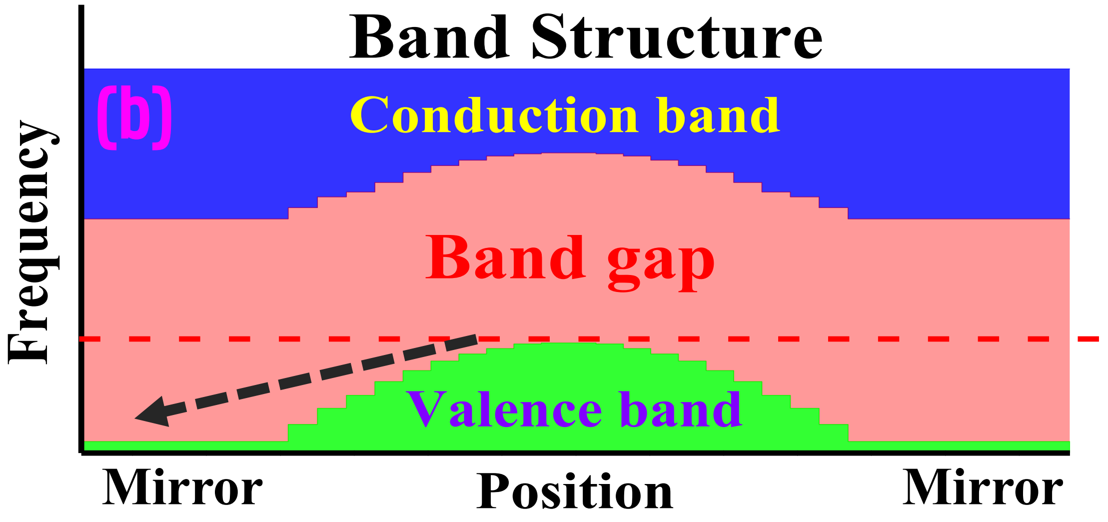
Light loss manipulation and low-threshold device

Design principle

Mirror (fixed period) center (fixed period) Mirror (fixed period)



(a) a_0(fixed) < a_1 < a_2 < …… < a_m(fixed)



Approach:

- Keep hole radius constant ~65 nm.
- Fix central period and mirror period.
- Periods of intermediate blocks are optimized to obtain Gaussian electric field envelope along the light propagation direction.

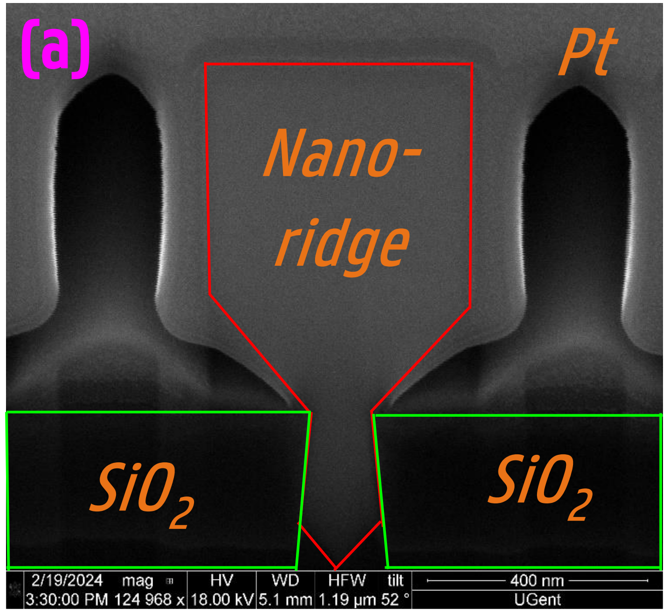
✓ Increasing period shifts bandgap downwards.

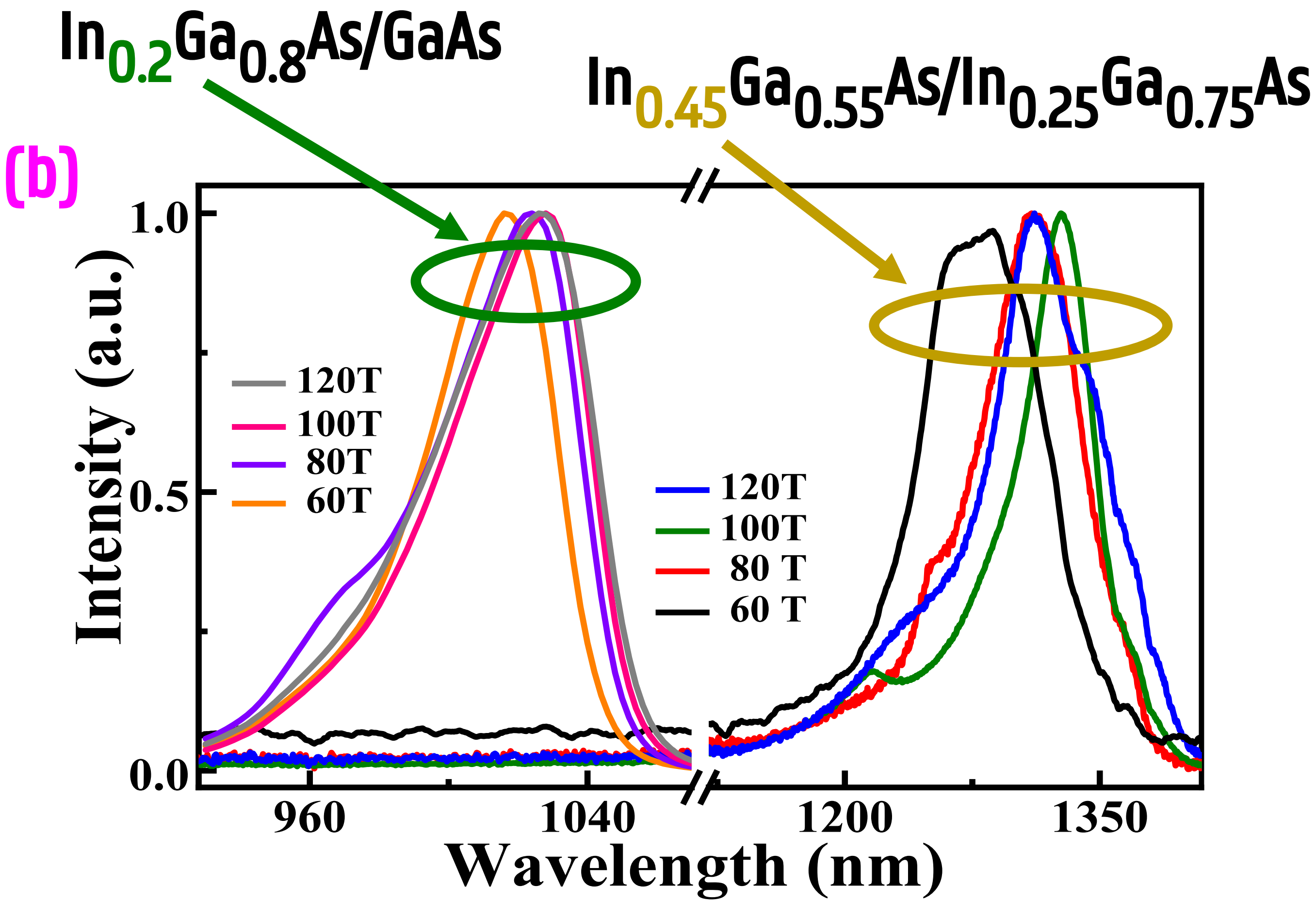
✓ Light emitted at center falls in the mid-bandgap of left and right mirror block.

Nano-ridge dimension and emission wavelength

- Which structure and wavelength range?

➢ Dimensions in design are taken from real size of nano-ridge in tilted-SEM image





➢ With increasing Indium ratio in quantum well layers, nano-ridge enables 1300 nm emission.

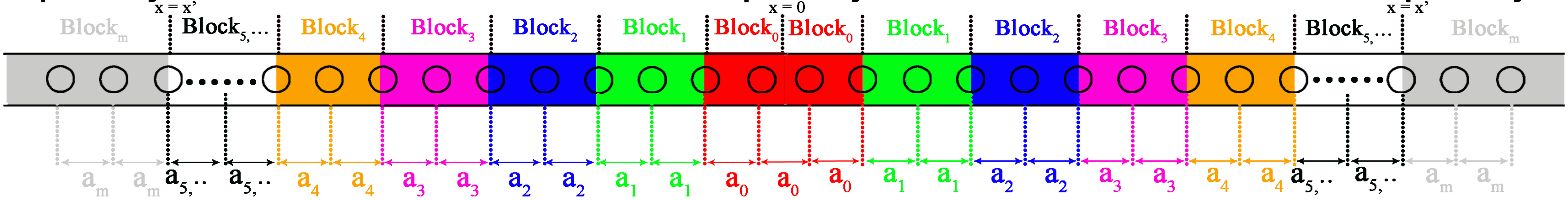
➢ Target design wavelength: 1260-1340 nm.

Simulation model

(b)

Top-view of the device model

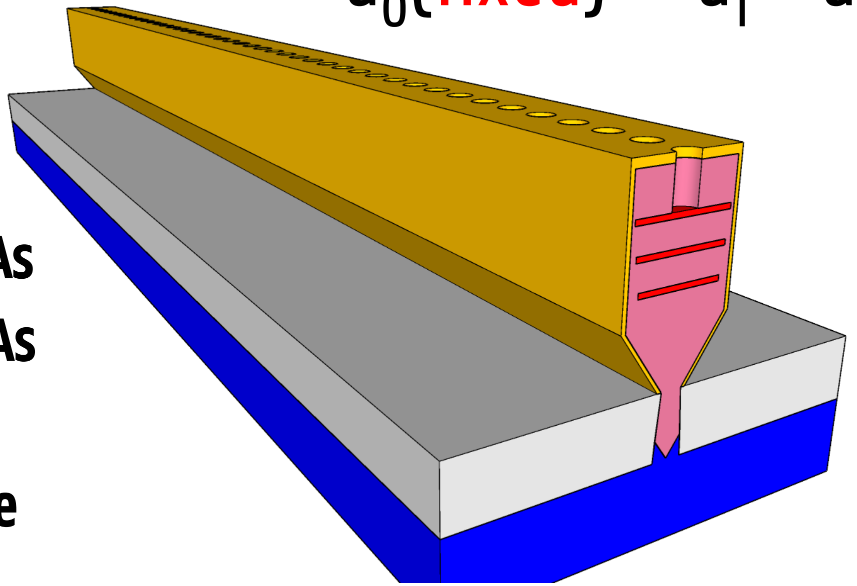
Mirror (fixed period) center (fixed period) Mirror (fixed period)



$$a_0(\text{fixed}) < a_1 < a_2 < \ldots\ldots < a_m(\text{fixed})$$

(a)

- InGaP
- $In_{0.25}Ga_{0.75}As$
- $In_{0.45}Ga_{0.55}As$
- SiO_x
- Si substrate

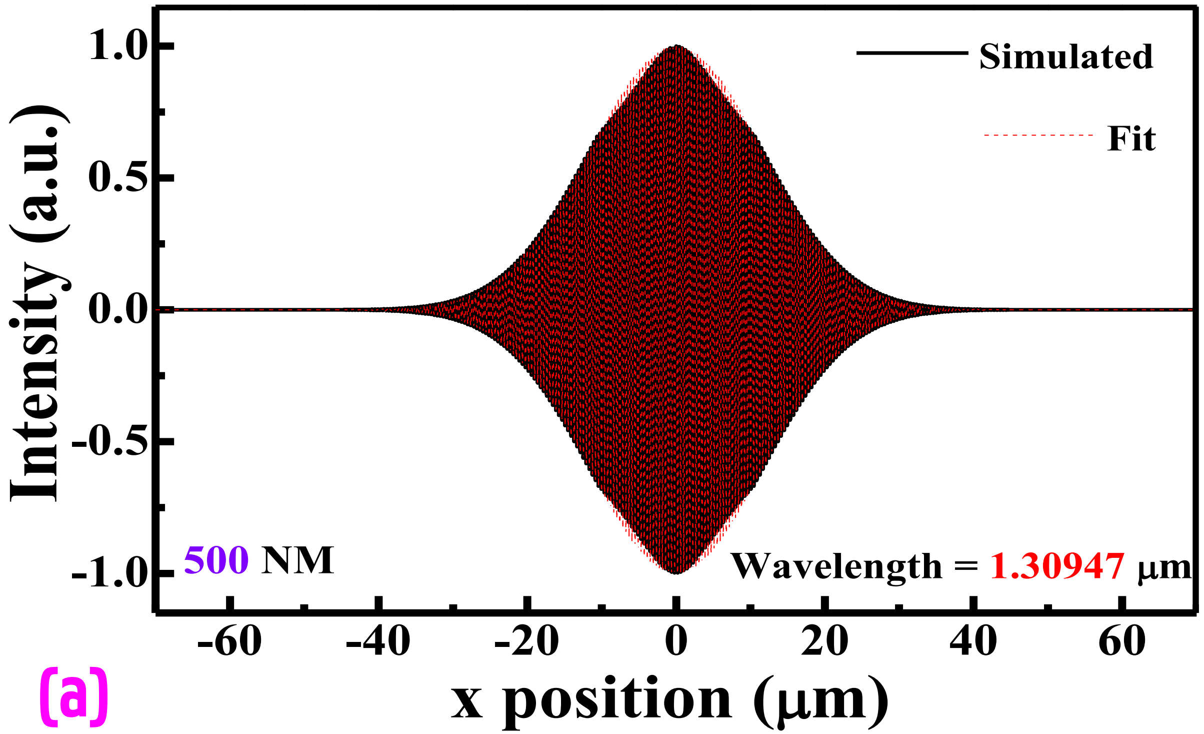


Simulation:

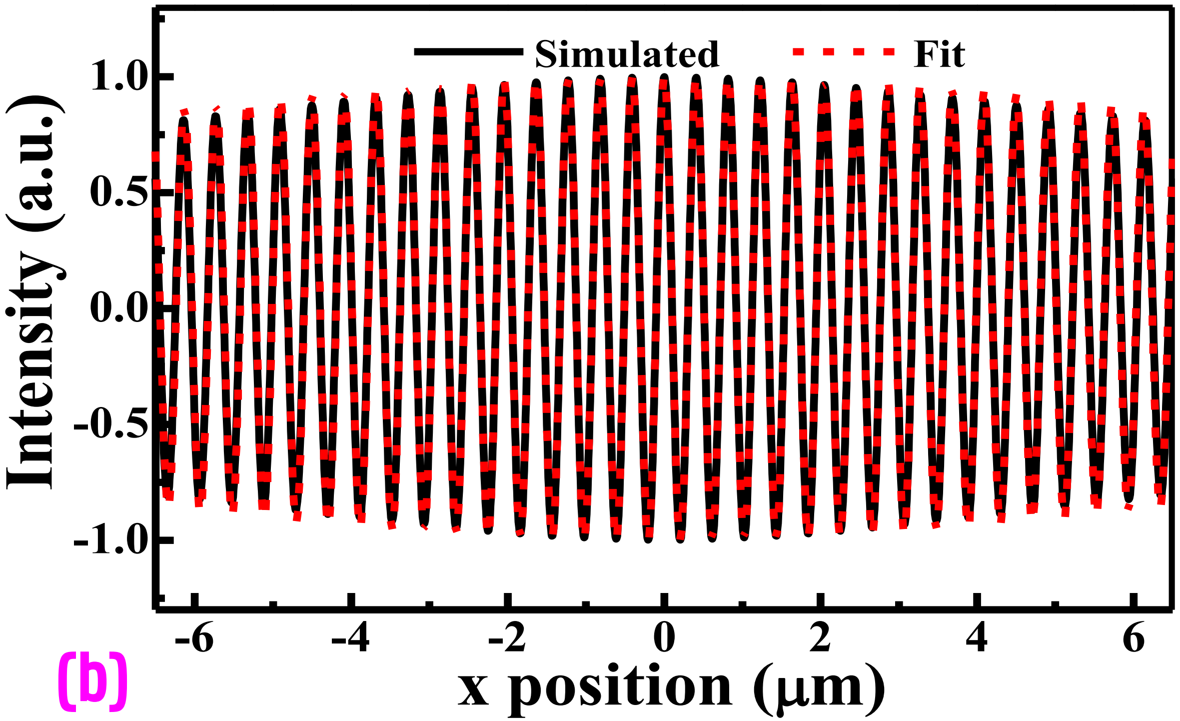
- Design period: 201 - 217 nm.
- The etching depth: 180 nm.
- The total number of periods in mirror block (NM) at each side: 55 - 400 .
- The grating couplers with 200 periods at front and back sides.

Simulated mode profiles alone light propagation and Gaussian fit

Fitting function: A*cos(π*x/ω)*exp(-q*x^2)



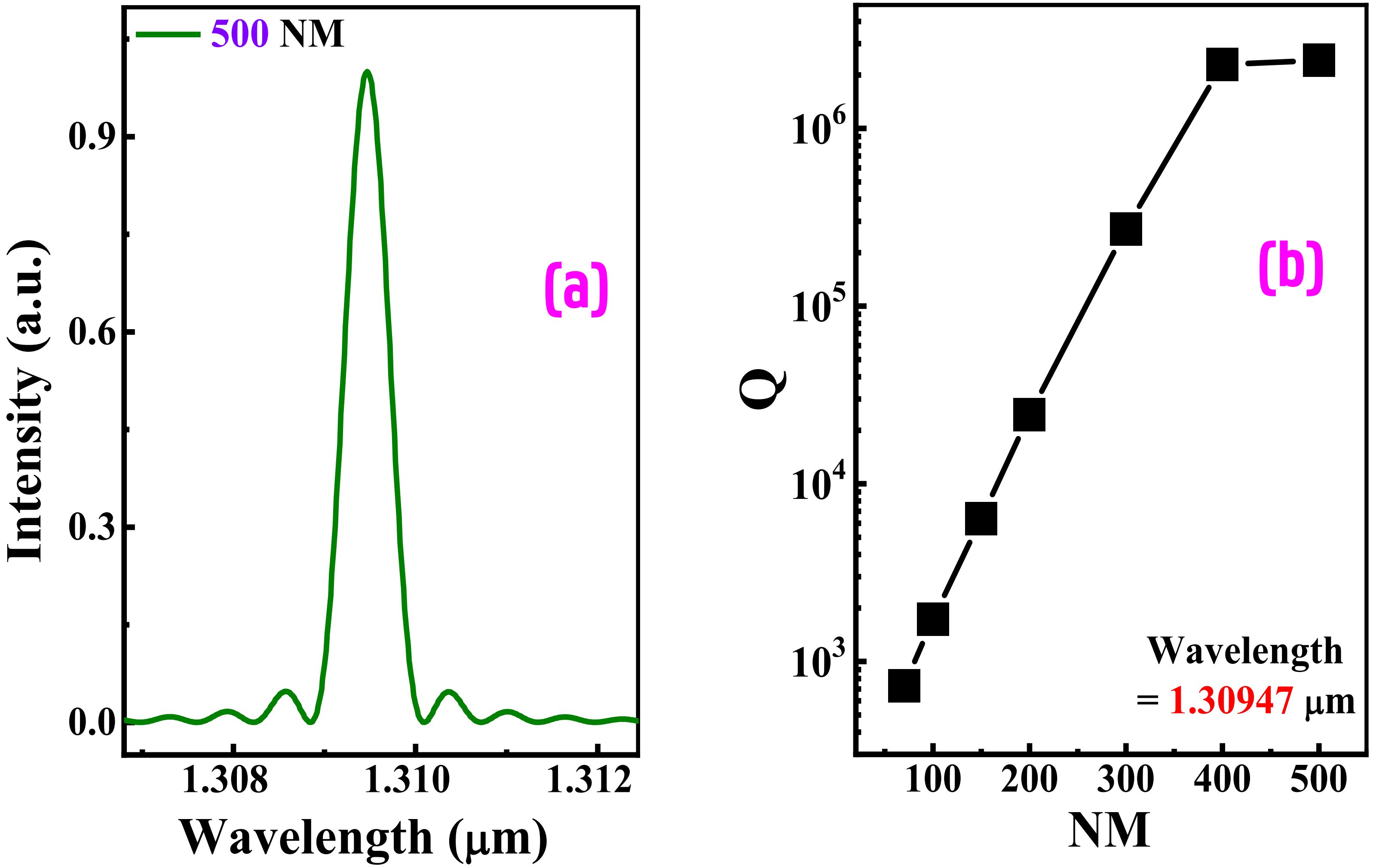
(a)



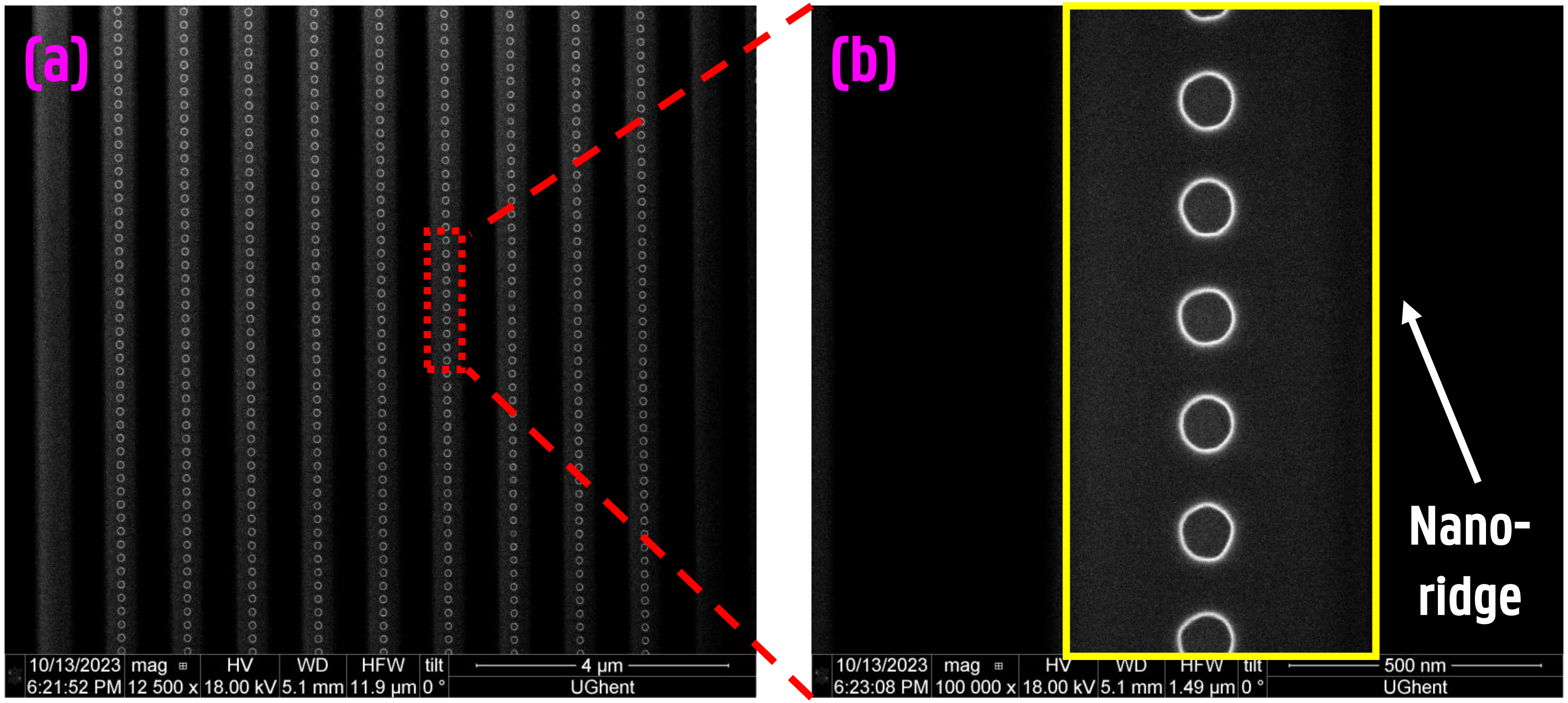
(b)

Simulated Spectrum and Q-factor

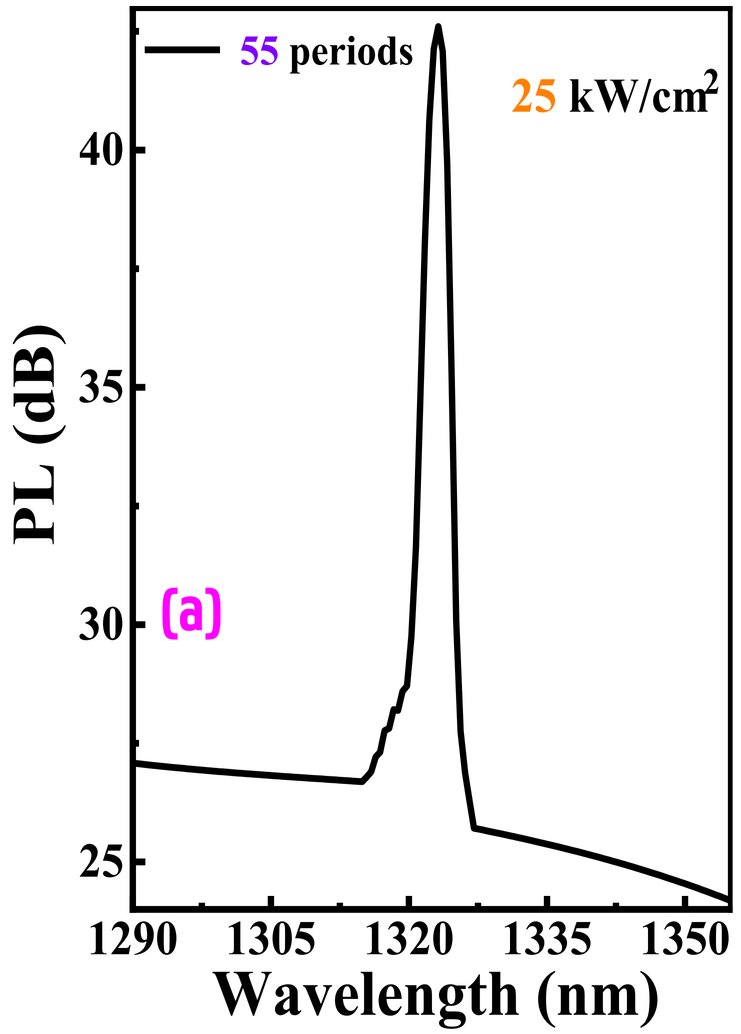
NM: number of periods in mirror block

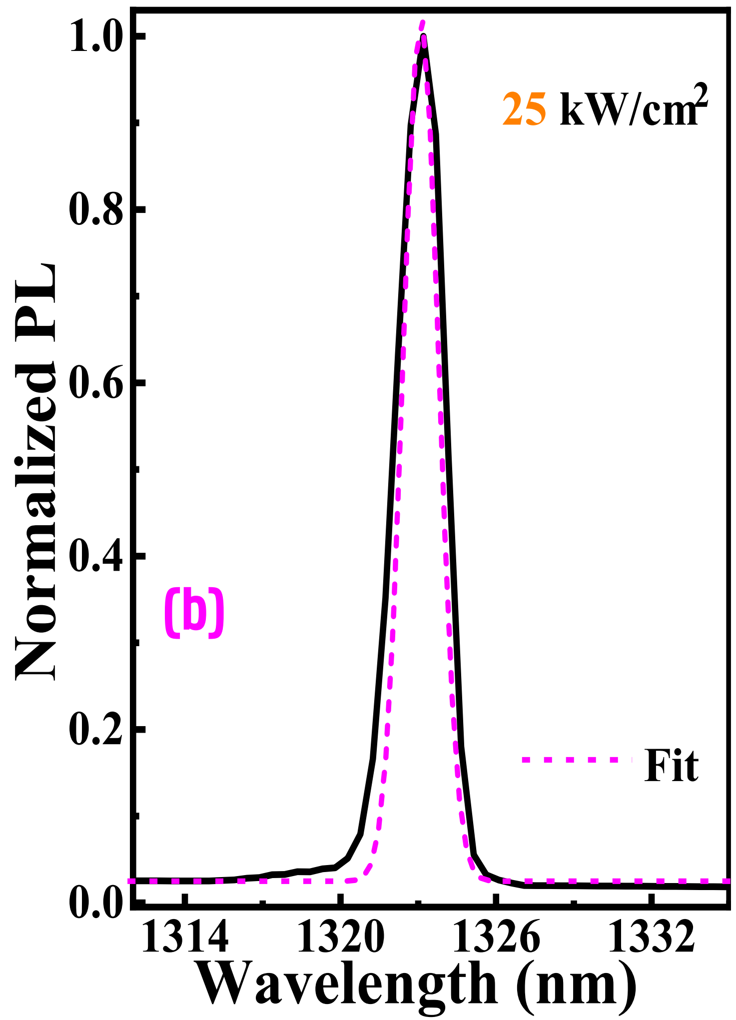


Fabricated devices overview

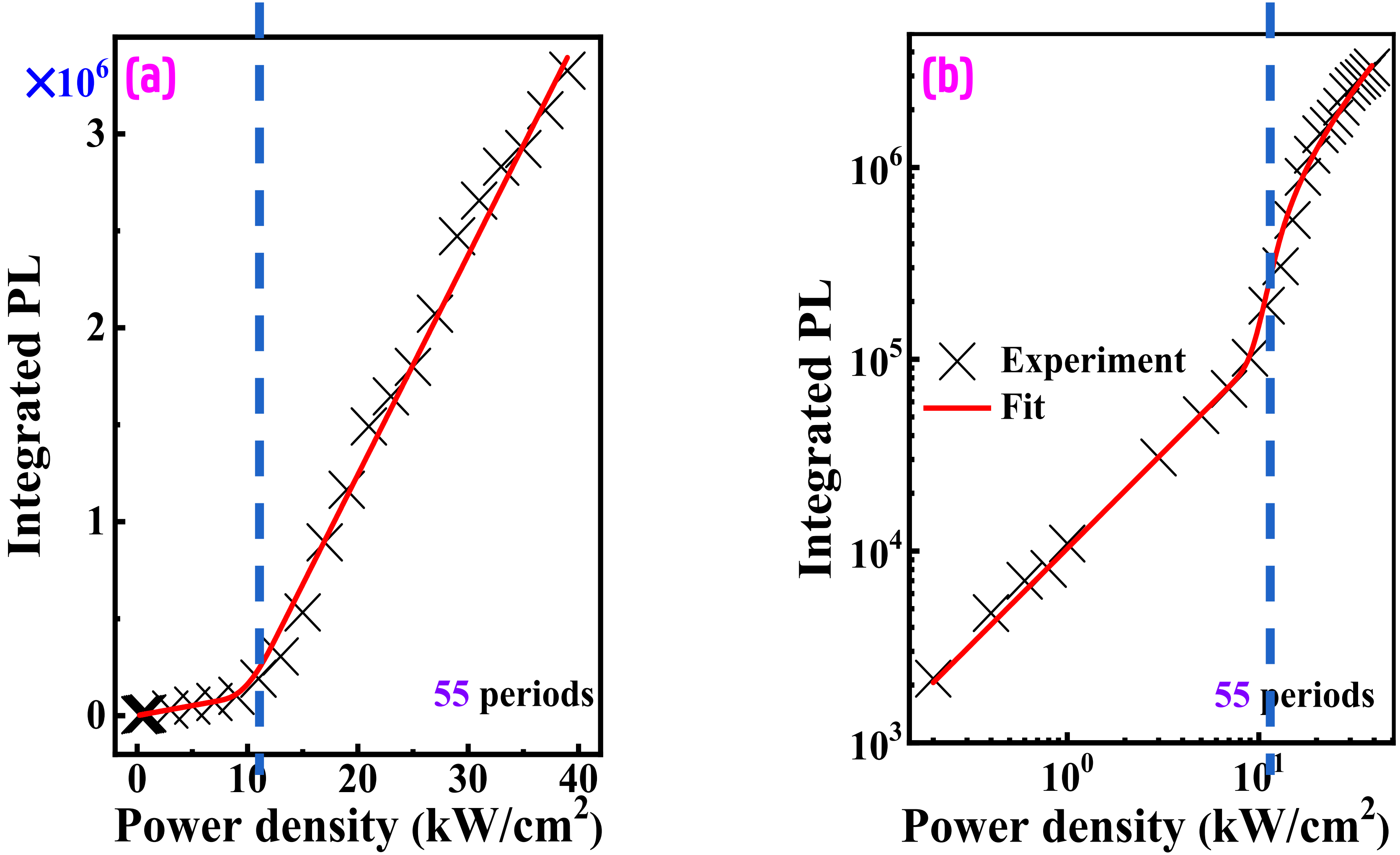


Measurement-PL spectrum





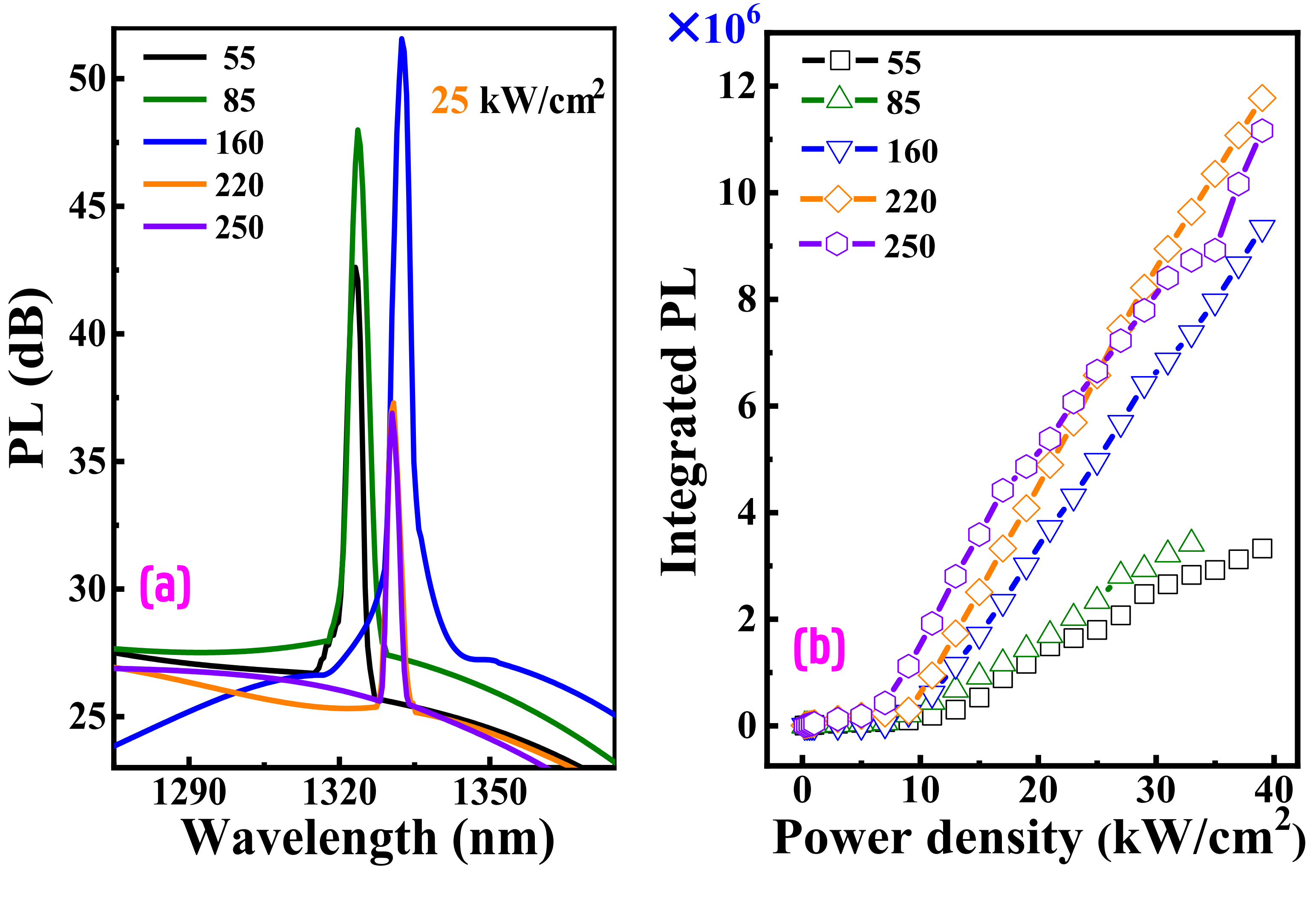
Measurement-light in – light out curve



≈ 11.8 kW/cm²

The lasing was achieved with only 55 periods in the mirror block, as smallest as 25 um length.

PL, light in – light out curve and thresholds from all devices



Take-home message – lasers with PC inside

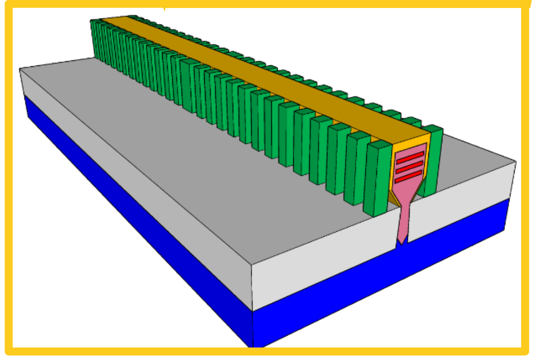
- With the electric field distribution following a Gaussian function, the high Q-factor cavity was designed.

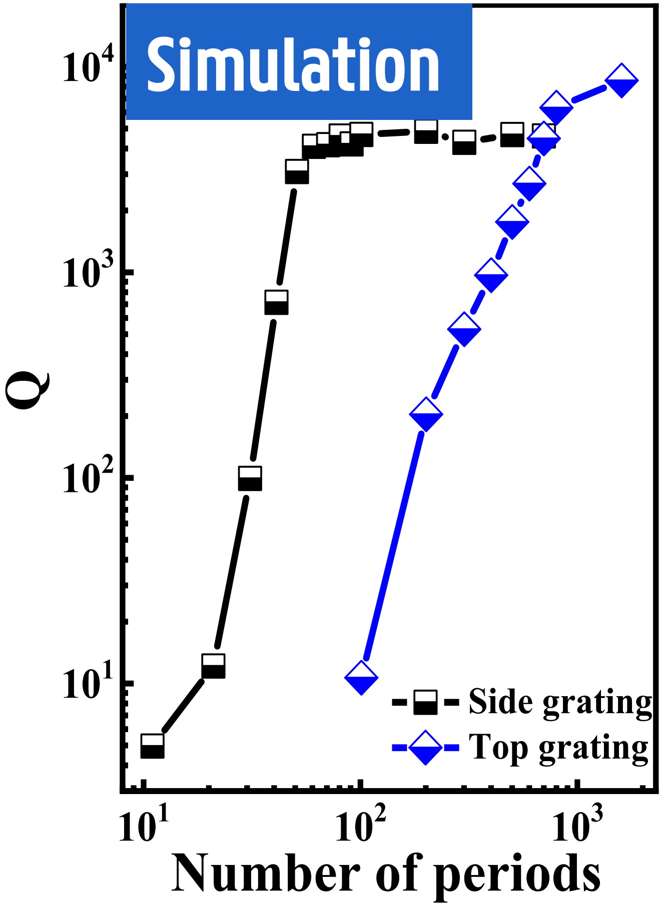
- Using a photonic crystal within the nano-ridge, lasing was achieved with a cavity length as small as 25 μm and with a threshold of 11.8 kW/cm^2.

Motivation-Why amorphous Si grating on two sides of nano-ridge?

DFB laser with aSi grating on two **side** of the nanor-idge

Device miniaturization and scalability

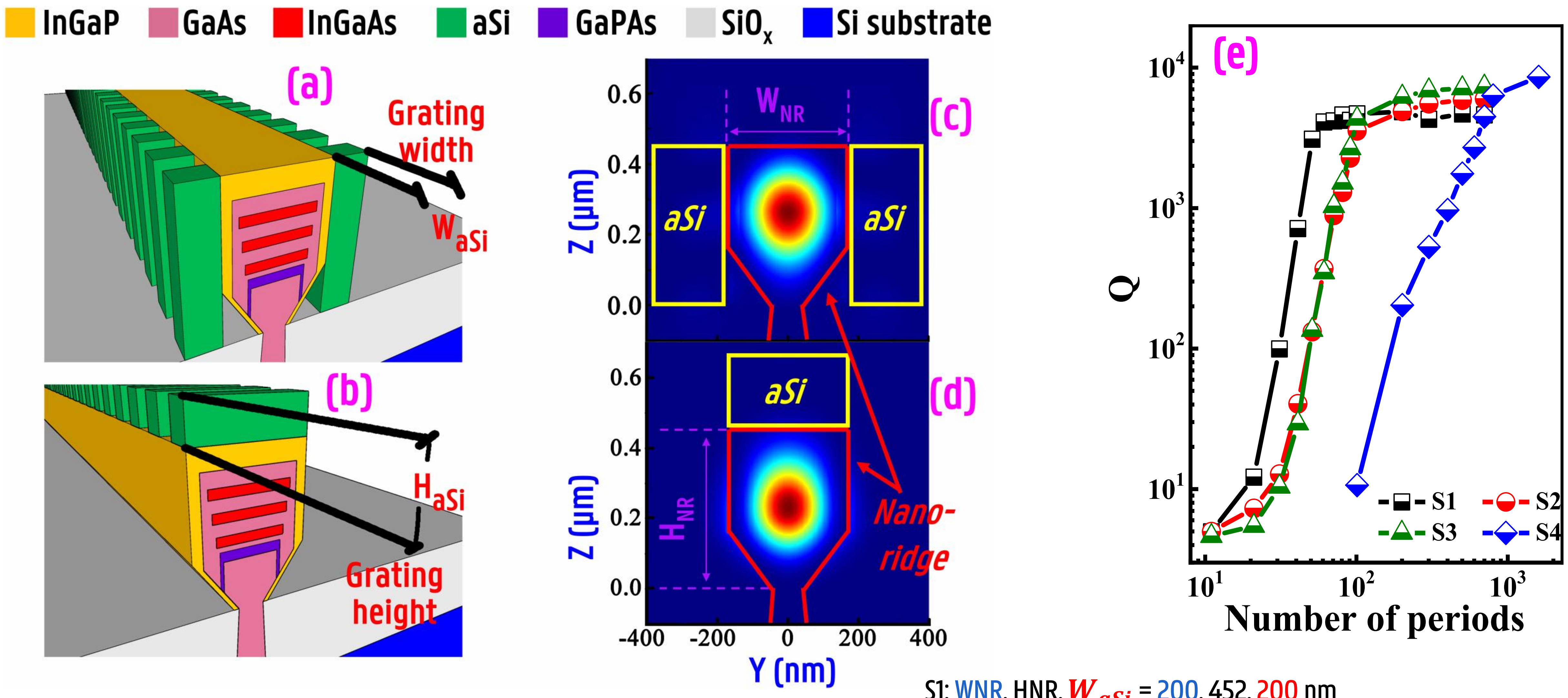




- Enhance **light confinement**
- Minimize **cavity dimension**

InGaP | aSi
GaAs | SiO_x
$In_{0.2}Ga_{0.8}As$ | Si substrate

Dimension definition and simulated modes, Q-factor



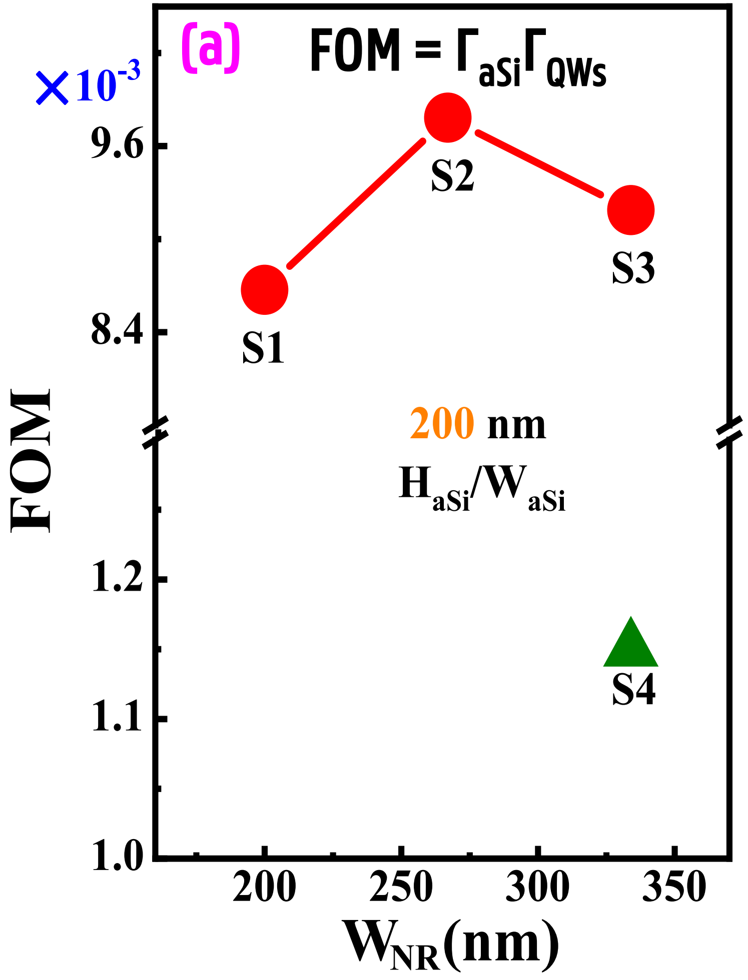
S1: WNR, HNR, W_{aSi} = 200, 452, 200 nm

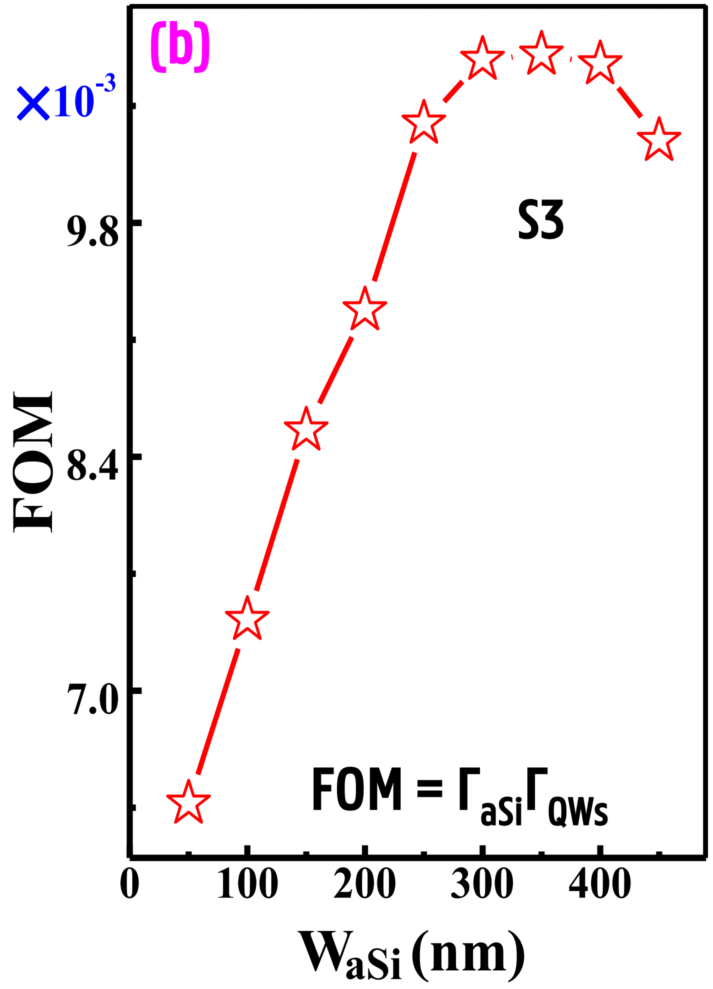
S2: WNR, HNR, W_{aSi} = 267, 452, 200 nm

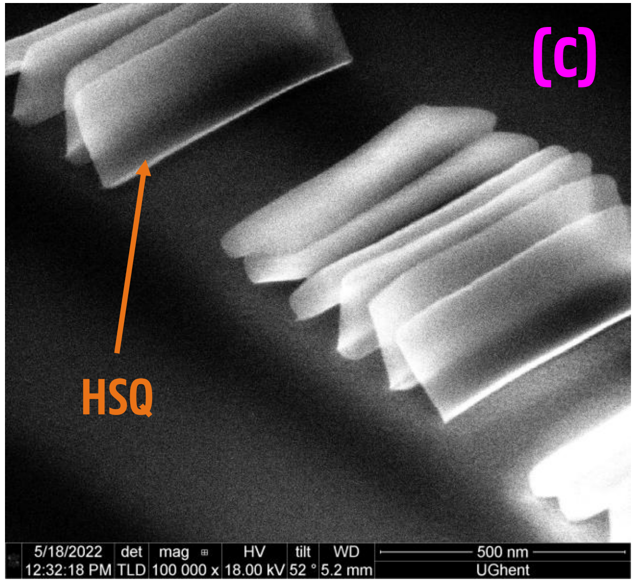
S3: WNR, HNR, W_{aSi} = 334, 452, 200 nm

S4: WNR, HNR, H_{aSi} = 334, 452, 200 nm

FOM and simulated spectrum







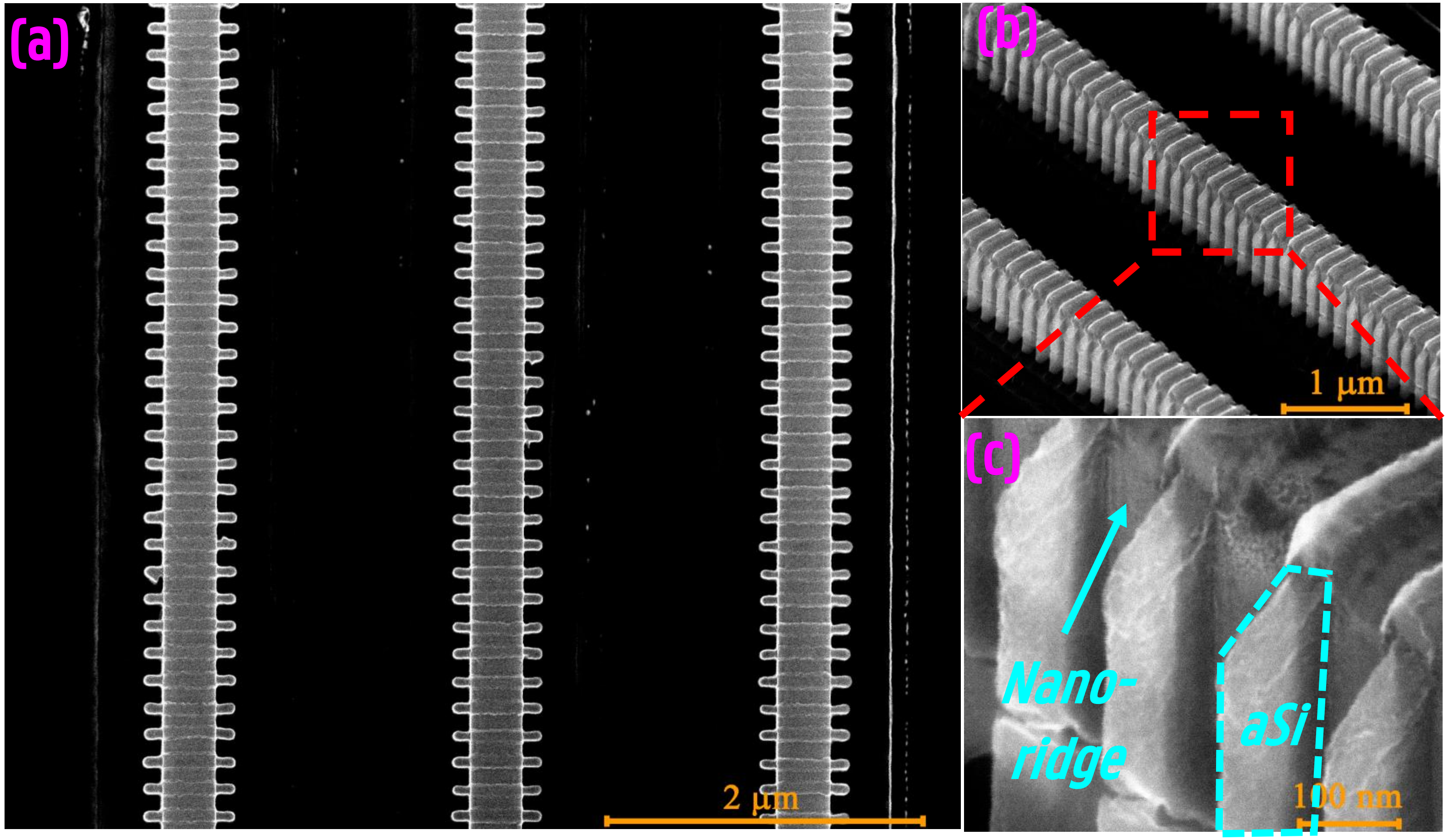
S1: WNR, HNR, W_{aSi} = 200, 452, 200 nm

S2: WNR, HNR, W_{aSi} = 267, 452, 200 nm

✓ S3: WNR, HNR, W_{aSi} = 334, 452, 200 nm

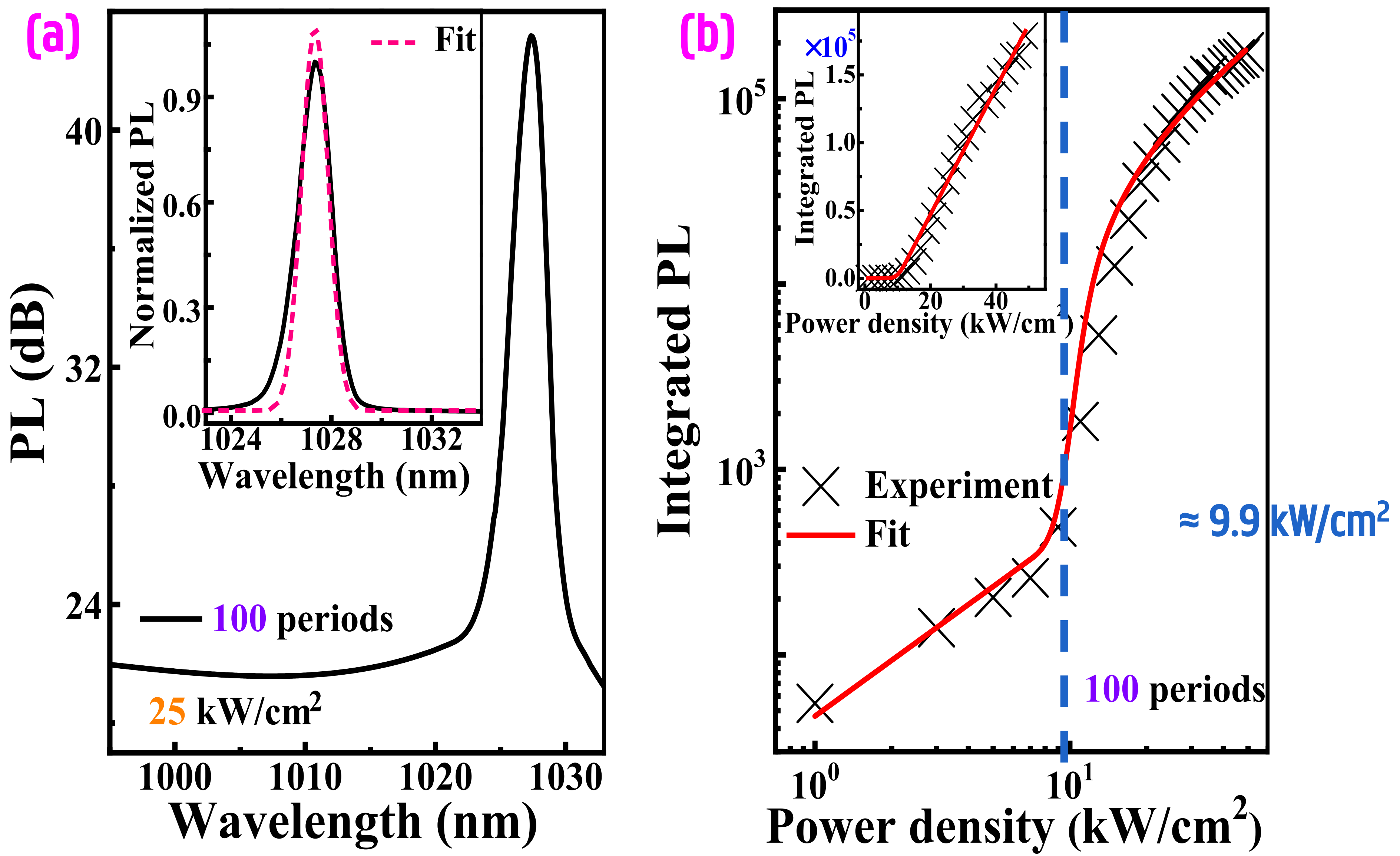
S4: WNR, HNR, H_{aSi} = 334, 452, 200 nm

Fabricated devices overview

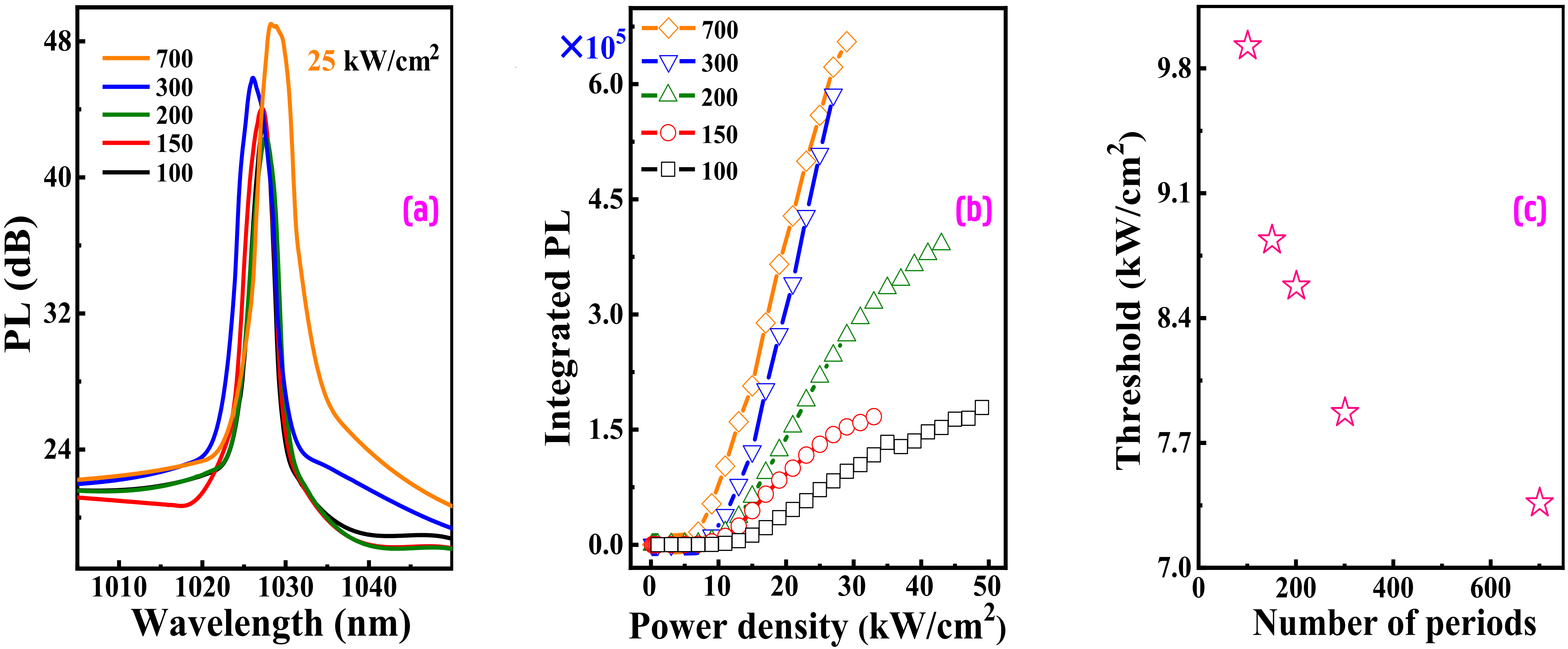


Measurement-PL spectrum, light in – light out curve

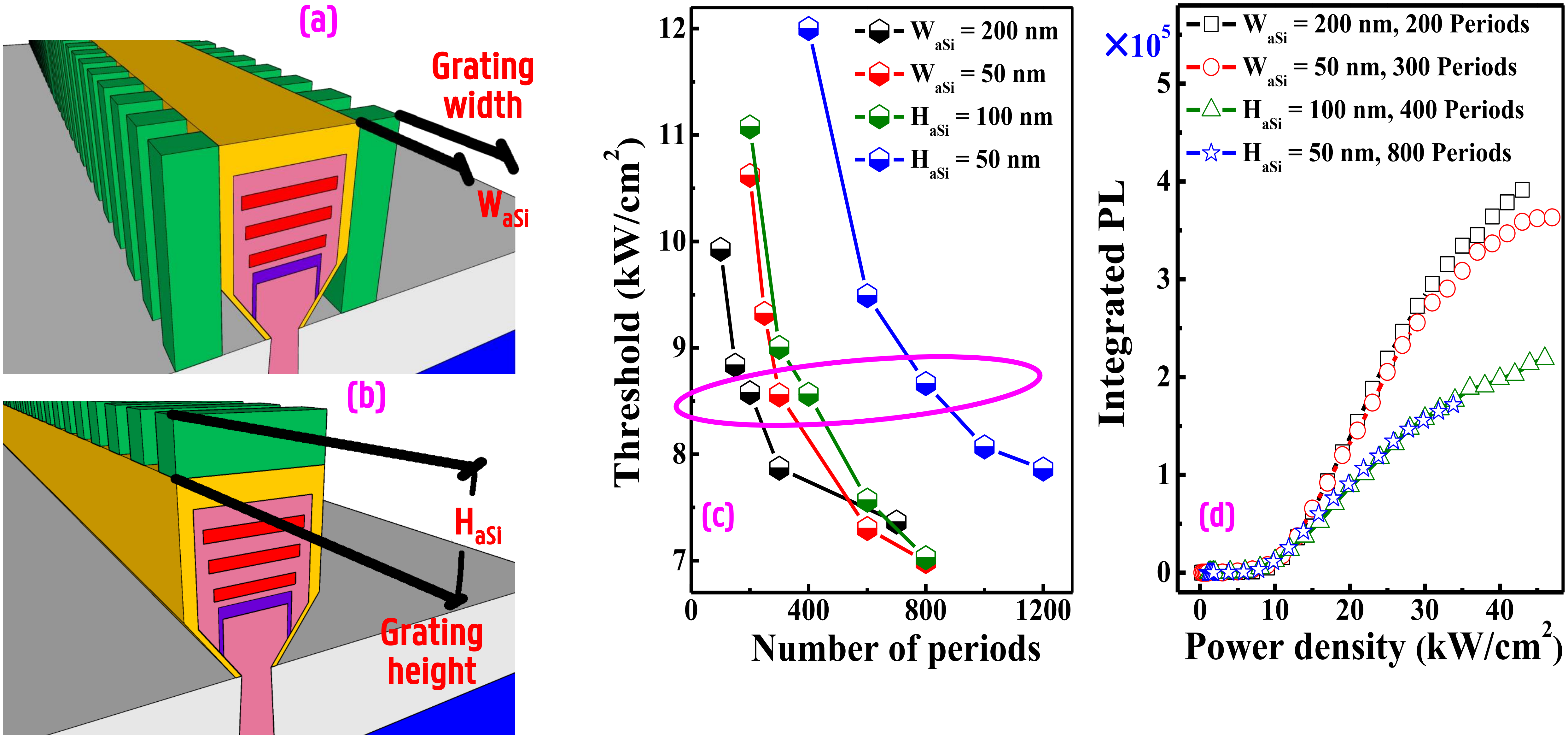
➢ Lasing was achieved with only 100 periods and with the cavity length as small as 16 μm.



PL, light in – light out curve and thresholds from all devices



Comparison between devices with aSi grating on top and two sides



Take-home message – lasers with aSi grating on two sides

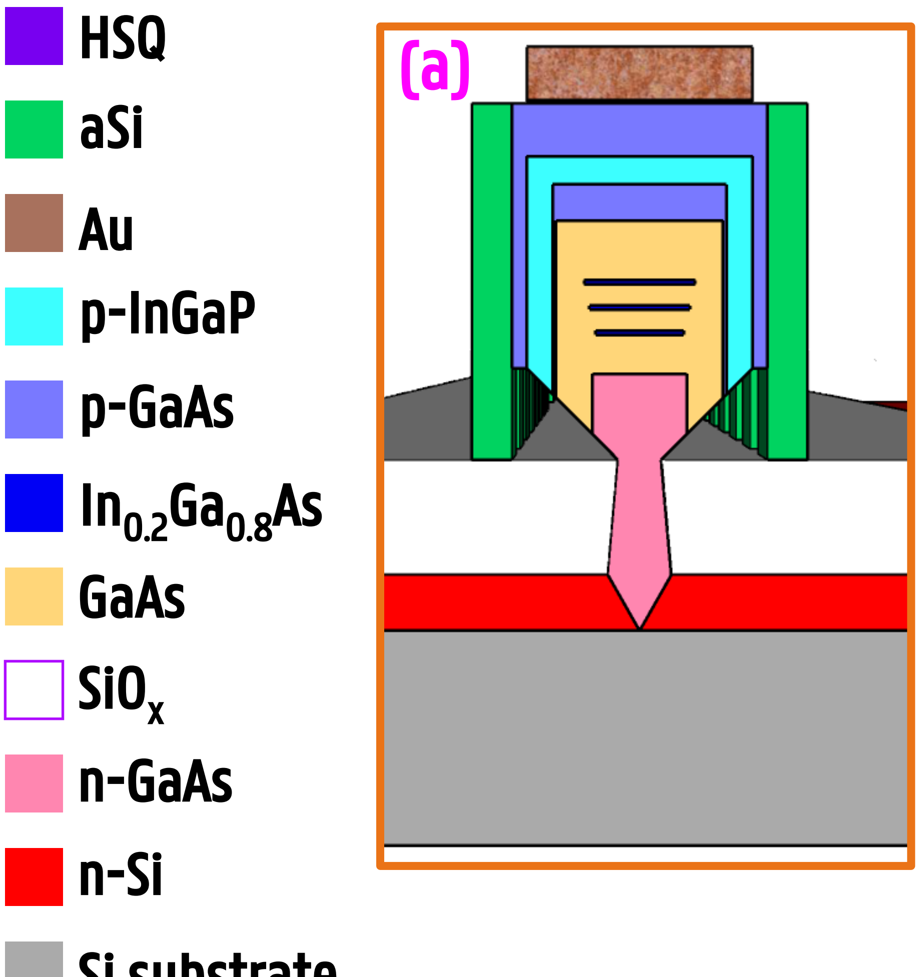
- The stronger light interaction is achieved with aSi on both sides compared to on top.

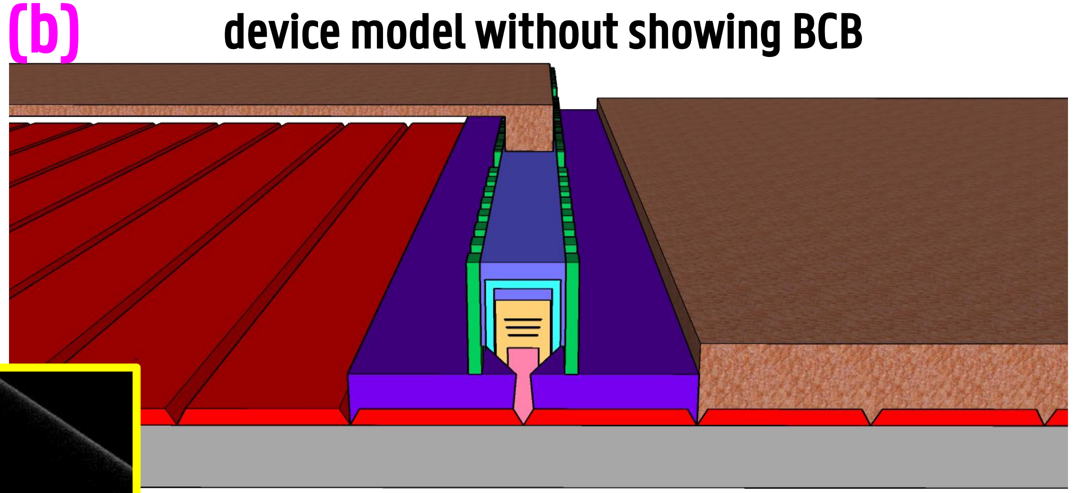
- With the aSi grating on the two sides of nano-ridge, lasing was achieved with a cavity length as small as 16 μm, with a threshold of 9.9 kW/cm^2.

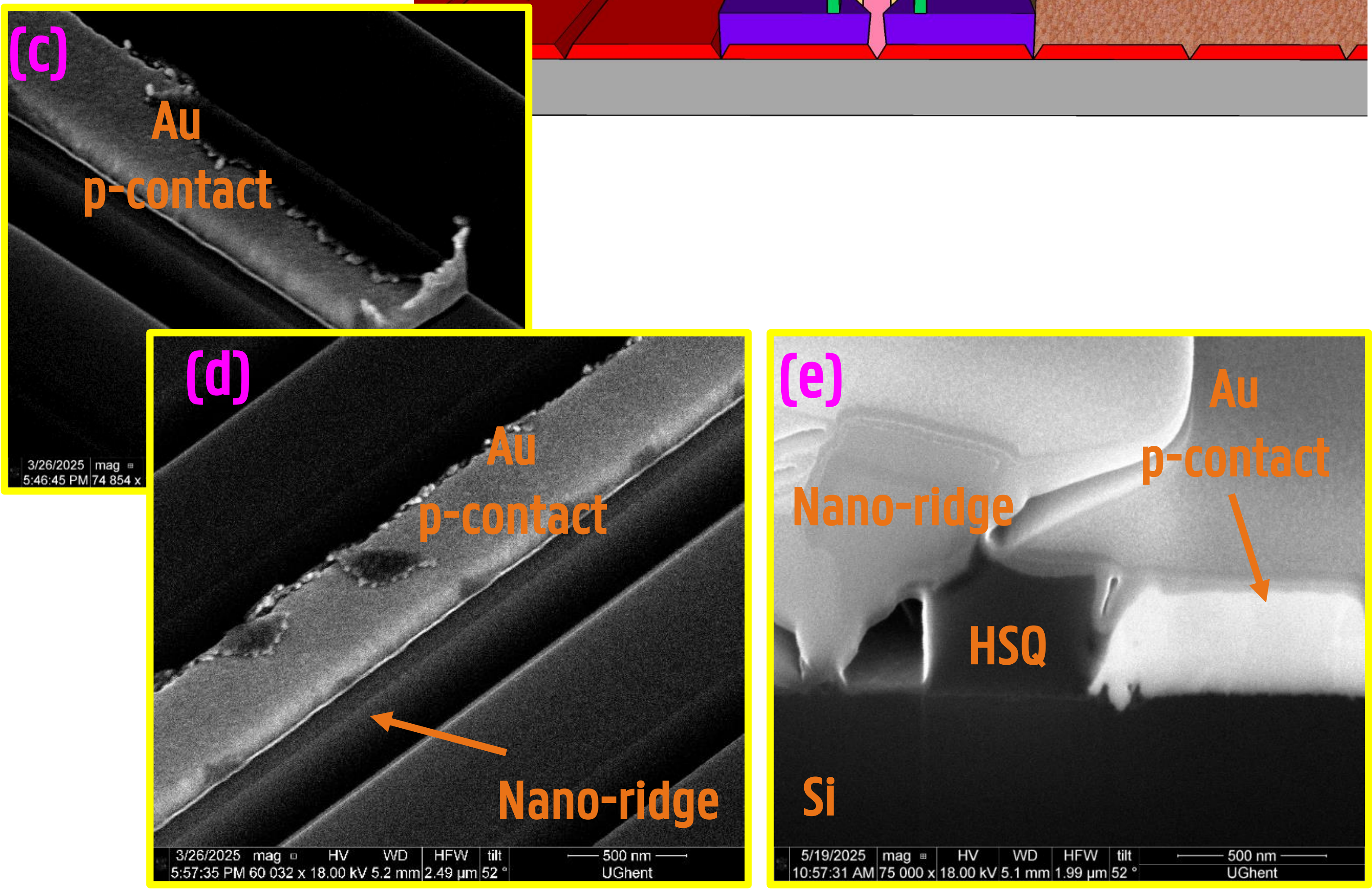
Conclusion

- We demonstrated reduced-threshold DFB nano-ridge lasers with the amorphous silicon grating on the top.
- We demonstrated PC nano-ridge laser and DFB nano-ridge laser with amorphous silicon grating on side, achieving both reduced threshold and device miniaturization.

Outlook – electrically-driven laser with aSi grating on sides







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Thanks for your attention!

PHOTONICS RESEARCH GROUP


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