FACULTEIT INGENIEURSWETENSCHAPPEN EN ARCHITECTUUR
DEPARTMENT OF INFORMATION TECHNOLOGY
PHOTONICS RESEARCH GROUP

GAAS NANO-RIDGE LASERS ON SILICON

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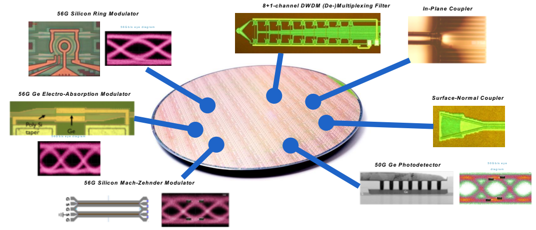
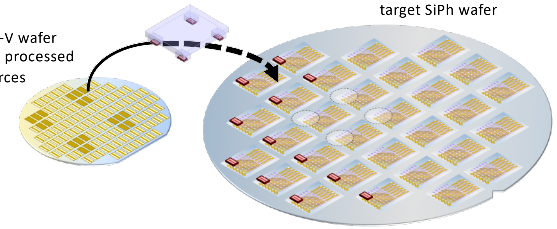
SILICON PHOTONICS MISSES A LASER…

E.g. IMEC iSIPP50G-platform



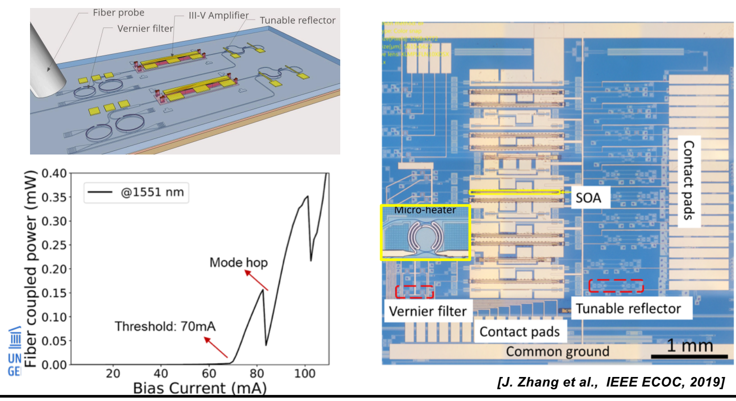
No laser source ➔ **need for a III-V/silicon photonic integration platform**

OUR OPTION #1 : TRANSFER PRINTING



µTP combines advantages of flip-chip and die-to-wafer bonding

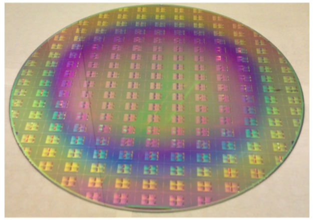
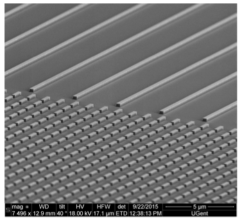
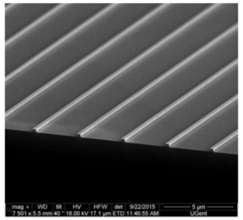
III-V-ON-SI WIDELY TUNABLE LASER WITH µTP



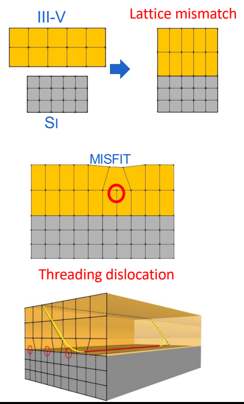
[J. Zhang et al., IEEE ECOC, 2019]

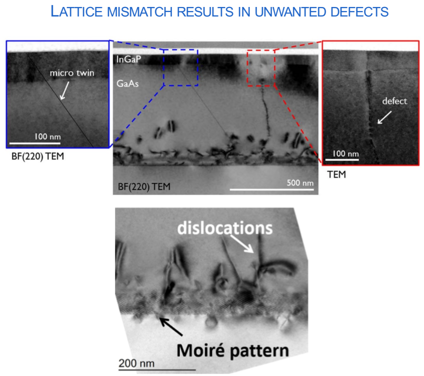
OUR OPTION #2: DIRECT EPITAXY ON SILICON

- Why ?
  - Ultimate scalability: selective growth using MOCVD on 300mm wafers
  - It's fun

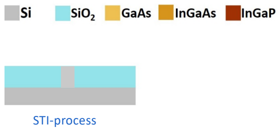




HETEROEPITAXY- CHALLENGES



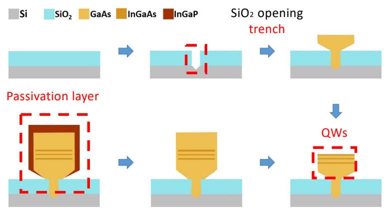


ASPECT-RATIO-TRAPPING (ART)

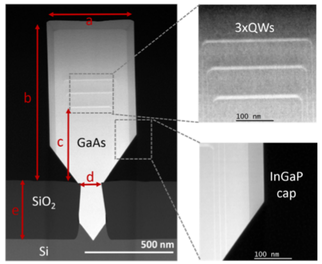


ASPECT-RATIO-TRAPPING (ART)

Basic processing scheme

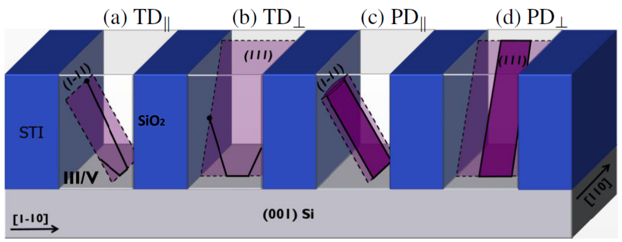


Reference sample



ASPECT RATIO TRAPPING (ART)

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



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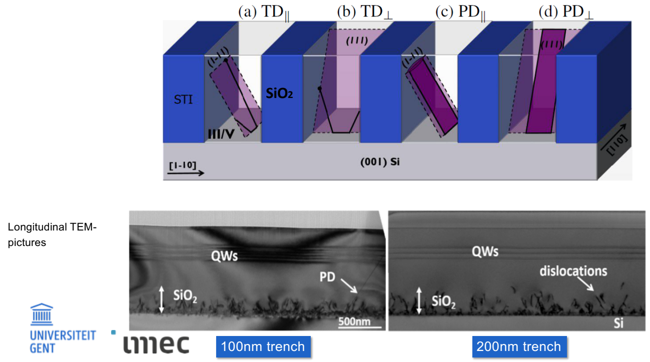

TD < $3x10^6 cm^{-2}$
(limited by measurement)
PD < 0.14–0.45µm-1

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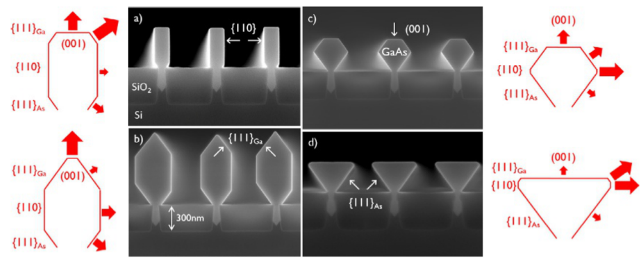
NANO-RIDGE ENGINEERING (NRE)

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**



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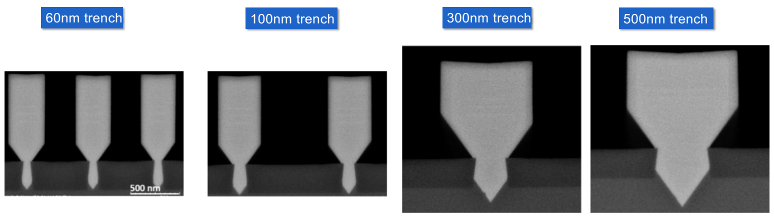
NANO-RIDGE ENGINEERING (NRE)



Increasing trench width: shape and volume of nano-ridge changes

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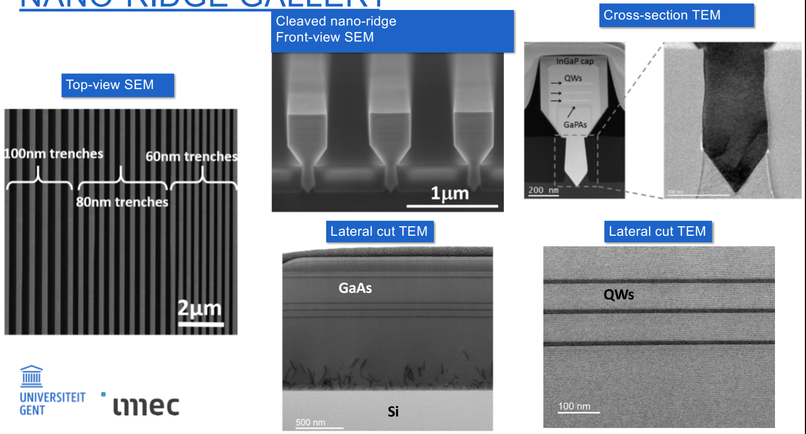
NANO-RIDGE GALLERY



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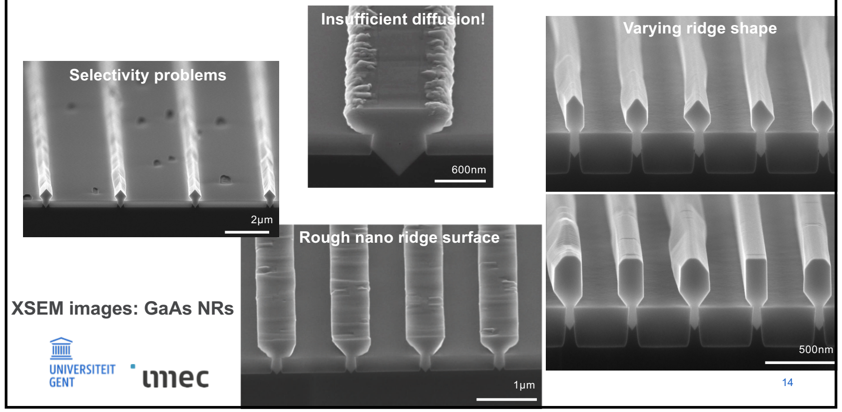
HIGH QUALITY DOES NOT COME FORE FREE !



XSEM images: GaAs NRs

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BASIC CHARACTERIZATION OPTICAL PROPERTIES

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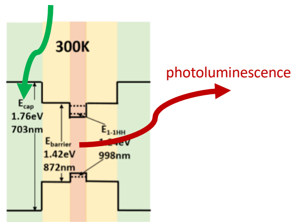
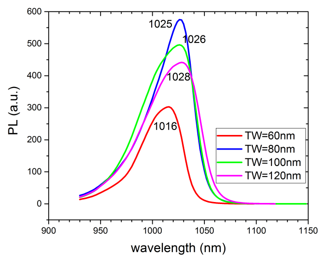
ROOM TEMPERATURE PHOTOLUMINESCENCE

532nm optical excitation



PL spectra for reference sample



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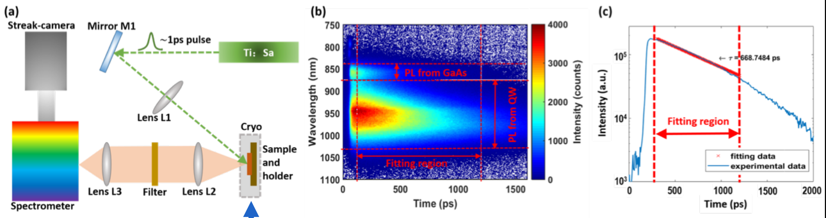
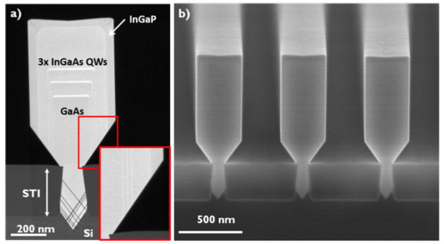
TIME RESOLVED PHOTOLUMINSCENCE (TRPL)



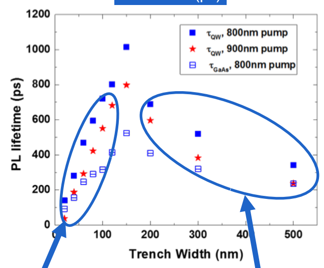
Cryo only used in LT measurements

Collaboration with Nils Gerhardt, Bochum University

TRPL FOR REFERENCE STRUCTURE



PL-lifetime (ps)



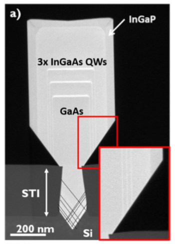
Reference structure:
- 3 x InGaAs QW
- InGaP passivation-layer

Narrow trenches = surface effects ?

Wide trenches = defects

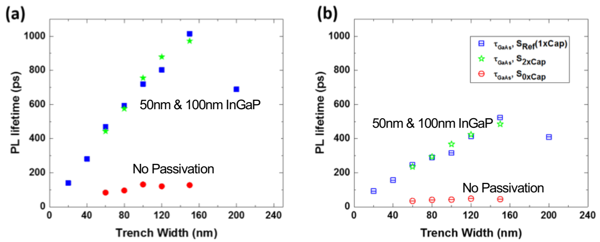
Collaboration with Nils Gerhardt, Bochum University

TRPL : EFFECT OF InGaP PASSIVATION LAYER



PL-lifetime QW emission (ps)

PL-lifetime GaAs emission (ps)

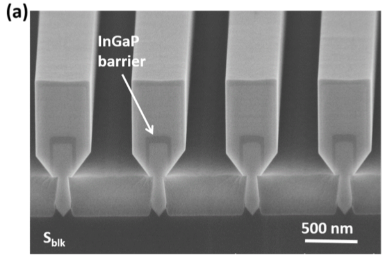


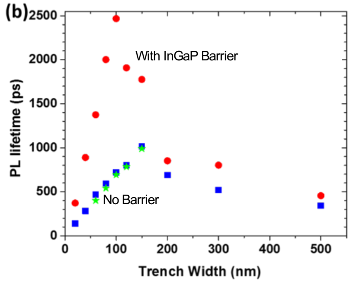
InGaP passivation layer is critical to suppress surface recombination

Collaboration with Nils Gerhardt, Bochum University

TRPL : EFFECT OF InGaP BARRIER

PL-lifetime QW emission (ps)



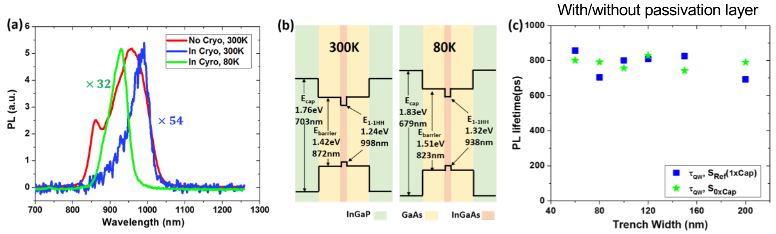


InGaP barrier suppresses leakage to defective trench

Collaboration with Nils Gerhardt, Bochum University

TRPL : LOW TEMPERATURE (80K)

With/without passivation layer



(Pump in QWs)

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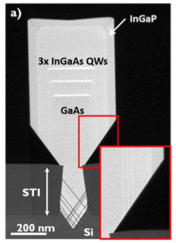
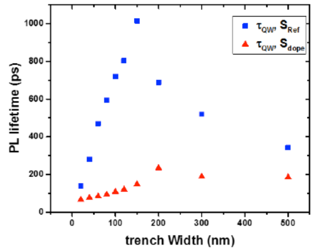
TRPL : EFFECT OF DOPING



PL-lifetime QW emission (ps)



Doping decreases lifetime: defects or more efficient recombination ?

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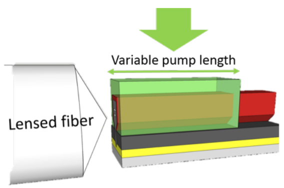
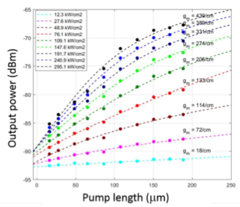
OPTICAL GAIN FROM VSL-MEASUREMENT

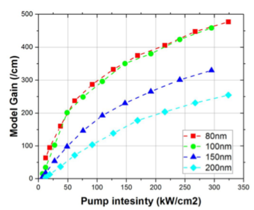
Variable strip length



PL power vs pump length



Modal gain



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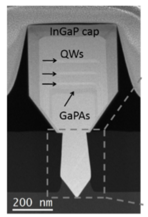
KEY MESSAGES MATERIAL QUALITY

- The GaAs nano-ridges emit at 1 μm.
- Narrow trenches (<150nm) can efficiently traps defects.
- Surface recombination is a dominant carrier loss mechanism
  - passivation of the surface with InGaP strongly supresses the loss
- Recombination in the defective trenches is another carrier loss mechanism: inserting InGaP carrier-blocking layer suppresses the loss and improves the lifetime up to 2.5ns
- The material gain was estimated to be above 5000cm^{-1}.
- **High-quality GaAs nano-ridge on Si can be obtained.**



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1μM-WAVELENGTH NANO-RIDGE LASER

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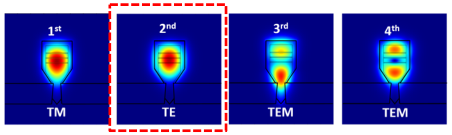
1μM-WAVELENGTH NANO-RIDGE LASER

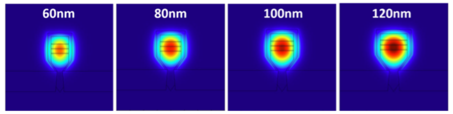
TRANSVERSAL OPTICAL MODES IN NANO-RIDGE WITH 100NM-TRENCH WIDTH



TE-LIKE GROUND MODE
- highest confinement in QWs
- lowest leakage loss towards Si substrate

is believed to be the dominant waveguide mode.
Higher optical gain due to the strain effect

TE-LIKE GROUND MODES IN NANO-RIDGES



n_{eff} is increasing for nano-ridges with wider trench

d(nm)	n_{eff}
60	3.022
80	3.122
100	3.167
120	3.210

Y. Shi, OPTICA, 4(12), p.1468-1473 (2017)

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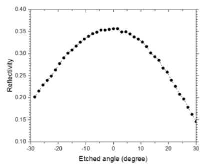
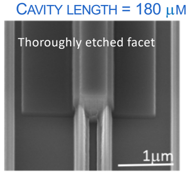
FABRY PEROT (FP) LASER

Optical excitation
5ns pulses at 532nm

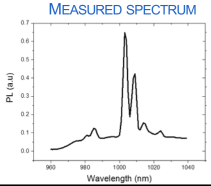
FACET REFLECTIVITY SIMULATION



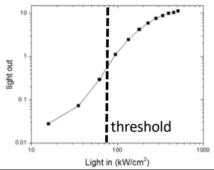
CAVITY LENGTH = 180 μM



MEASURED SPECTRUM



LIGHT-IN LIGHT OUT



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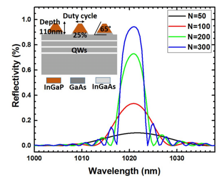
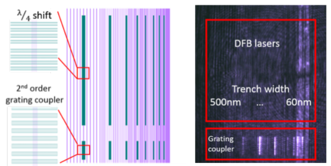
λ/4-SHIFT INDEX COUPLED DFB LASER

Optical excitation
5ns pulses at 532nm

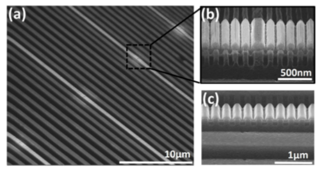
GRATING REFLECTIVITY SIMULATION



DFB CAVITY ON DIFFERENT NANO-RIDGE



SAMPLE FABRICATED BY EBEAM-LITHO AND ICP



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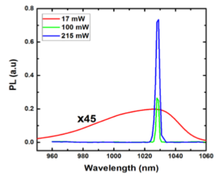
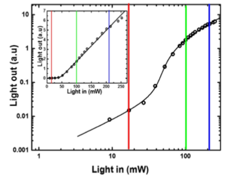
λ/4-SHIFT INDEX COUPLED DFB LASER

Y. Shi, Optica, 4(12), p.1468-1473 (2017)

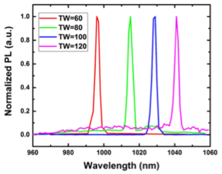
MEASURED SPECTRUM



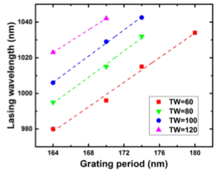
LIGHT-IN LIGHT OUT



SPECTRA FOR NANO-RIDGES WITH DIFFERENT TRENCH



WAVELENGTH TUNING



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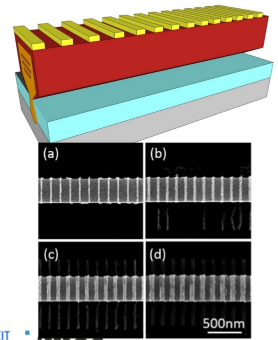
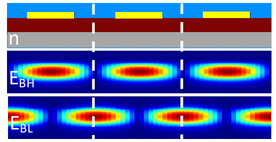
DFB-LASER WITH METAL GRATING

METAL GRATING ON NANO-RIDGE



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

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



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

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

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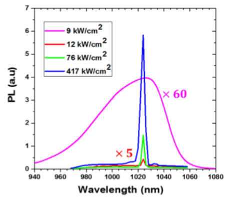
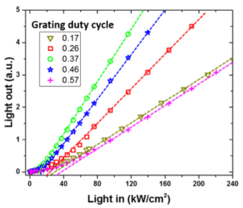
DFB-LASER WITH METAL GRATING

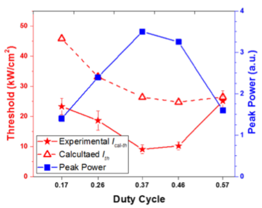
MEASURED SPECTRUM



LIGHT-IN LIGHT OUT



THRESHOLD/POWER VS DUTY CYCLE



Trade-off between coupling factor and loss results in optimal duty cycle of 40%

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O-BAND EMISSION

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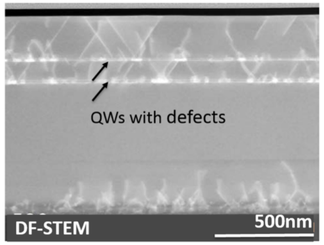
APPROACH 1

– Increase Indium content in QW's to 45%



Huge strain leads to new threading dislocations appearing at QW-layers

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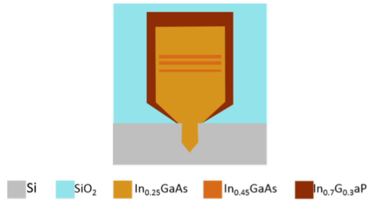
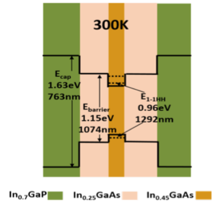
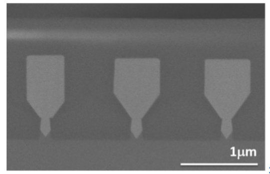
APPROACH 2

– Replace GaAs buffer by InGaAs Buffer







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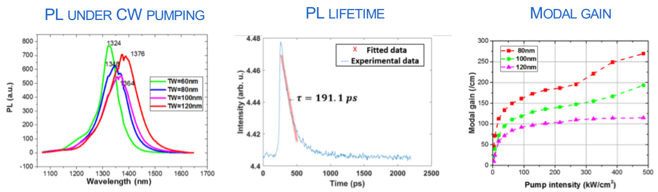
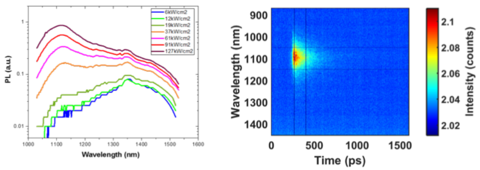
CHARACTERIZATION OPTICAL PROPERTIES



NANO-RIDGE BARRIER EMISSION UNDER PULSED EXCITATION



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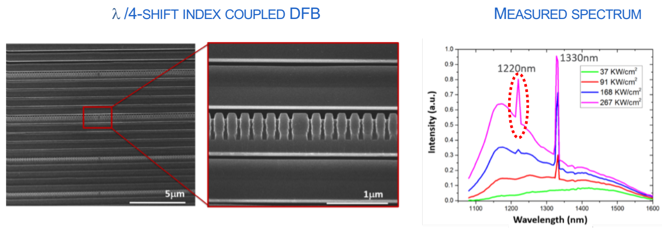
OPTICAL PUMPING λ/4-SHIFTED CAVITY



Lasing ?

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FUTURE: COUPLING WITH SILICON WAVEGUIDES?

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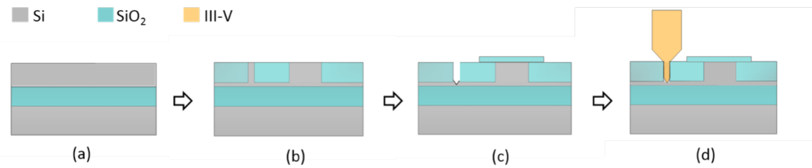
PROPOSED INTEGRATION FLOW



(a) SOI wafer with 300nm silicon layer
(b) STI-process defines trench and waveguide
(c) KOH etch to open trench. Waveguide is protected
(d) III-V epitaxy

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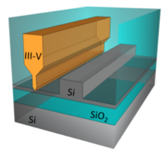
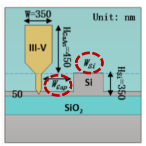
Y. Shi, Optics Express 27(26), p.37781-37794 (2019)

1ST GENERATION: DIRECTIONAL COUPLER

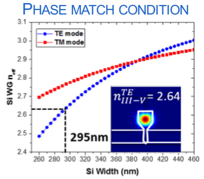
PROPOSED CONFIGURATION



CROSS SECTION

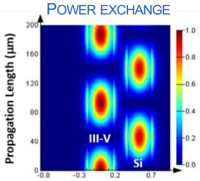


PHASE MATCH CONDITION

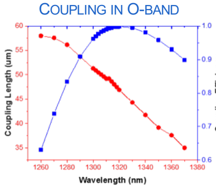


100% coupling
Sensitive to variation

POWER EXCHANGE



COUPLING IN O-BAND



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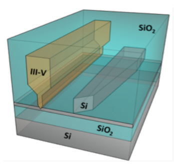
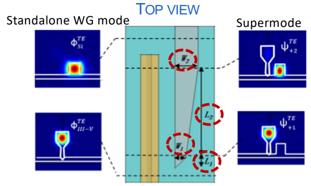
2ND GENERATION: LINEARLY TAPERED COUPLER

PROPOSED CONFIGURATION

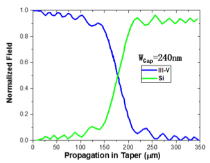


TOP VIEW

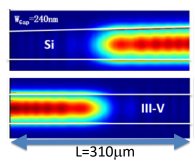


98% coupling
Long footprint

POWER EXCHANGE



POWER EXCHANGE



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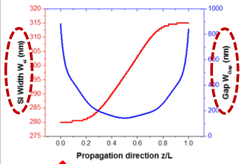
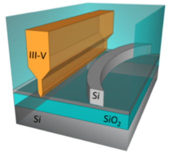
3RD GENERATION: OPTIMIZED ADIABATIC COUPLER

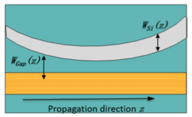


99% coupling
Compact size
High tolerance

PROPOSED CONFIGURATION



TOP VIEW



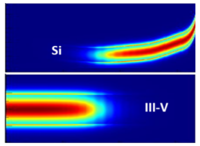
BLACKMAN FUNCTION

$$\kappa(z) = \kappa_{max} \cdot sin\theta(z)$$

$$\Delta\beta(z) = -\Delta\beta_{max} \cdot cos\theta(z)$$

$$\theta(z) = \frac{\pi z}{L} - 0.25 sin\frac{2\pi z}{L} - 0.07 sin\frac{4\pi z}{L}$$

POWER EXCHANGE



Hsien-kai Hsiao, et al. Midinfrared broadband achromatic astronomical beam combiner for nulling interferometry. Applied optics, 49(35):6675–6688, 2010.

Y. Shi, Optics Express 27(26), p.37781-37794 (2019)

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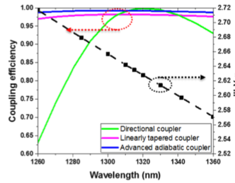
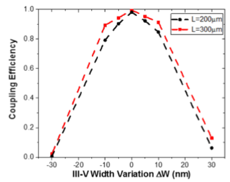
TOLERANCE TO VARIATIONS

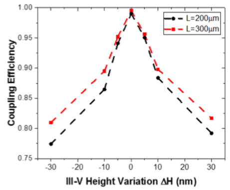
OVER O-BAND



VARIATION IN III-V WIDTH



VARIATION IN III-V HEIGHT



POSSIBLE TO COUPLE WITH SI DEVICES
GOOD CONTROL ON THE SIZE OF NANO-RIDGE DURING GROWTH

Y. Shi, Optics Express 27(26), p.37781-37794 (2019)

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CONCLUSION AND PERSPECTIVES

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CONCLUSION

- Aspect Ratio Trapping combined with nanoridge engineering allows to grow excellent material on 300 mm wafers
- We demonstrated:
  - PL-lifetime > 1 ns
  - Material gain > 4000 cm^{-1}
  - Optically pumped lasing with high SMSR at 1.05 µm
    - With both index and loss coupled gratings
  - Emission at 1.3 µm
  - Efficient coupling scheme to silicon waveguides

PhD-thesis Yuting Shi, available from http://photonics.intec.ugent.be/contact/people.asp?ID=425

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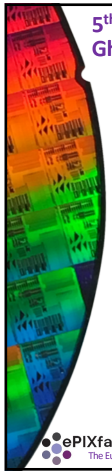
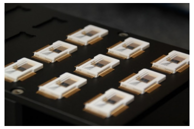


5th ePIXfab Silicon Photonic Summer School
Ghent University (Belgium)

DATE :15 – 19 June 2020

KEY FEATURES
- Learn all about silicon photonics: from technology to applications
- Geared towards industrial and academic participants
- A perfect blend of learning and networking

MORE INFO:
e-mail: info@ePIXfab.eu
web: https://epixfab.eu/epixfab-silicon-photonics-summer-school-5th-edition/



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The European Silicon Photonics Alliance

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ePIXfab
Summer Schools
Design Courses
(On site) Trainings

Upcoming Activities

2020

Training Program

ePIXfab trainings are design to address needs of both industrial and academic workforce with the mindset to enable seamless entry into the field of silicon photonics

- **China-Europe Silicon Photonics Symposium**
  28-30 May 2020, Chongqing, China
- **Silicon Photonics School, 5th edition**
  15-19 June 2020, Ghent University, Belgium
- **Design Course, 3rd edition**
  8 - 12 June 2020, Ghent University, Belgium
- **Hands-on design software training**
  22 June 2020, ECIO Conference, Paris, France
- **European Photonic Integration Forum**
  September 2020, Brussels, Belgium

...lliance http://epixfab.eu 47

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Presentation Only

9 March 2020

GaAs nano-ridge lasers on silicon (Conference Presentation)

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Author Affiliations +

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https://doi.org/10.1117/12.2548320
Event: SPIE OPTO, 2020, San Francisco, California, United States

Abstract

The silicon photonics platform is still missing a native source. Therefore, using a novel epitaxial process based on aspect ratio trapping and nano-ridge engineering we demonstrated an powerfull approach to fabricate GaAs-InGaAs lasers directly on a standard silicon substrate. In depth morphological and optical characterisation confirms the high quality of the material. We demonstrated lasing from DFB-type devices with etched gratings and with metal gratings. In the presentation we will also discuss the possibility for coupling to standard silicon waveguides and for extending the emission to longer wavelengths.

Conference Presentation