Heterogeneous Integration Overview, Iincluding Upcoming Tech

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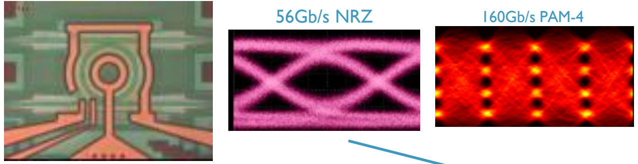
imec Silicon Photonics Platform (iSiPP)

Versatile 56Gb/s+ Silicon Photonics Technology

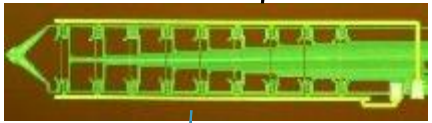
56+Gb/s Silicon Ring Modulator



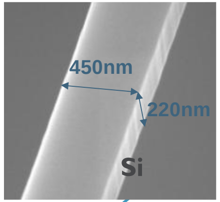
56Gb/s NRZ

160Gb/s PAM-4

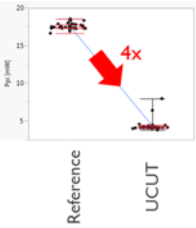
Silicon WDM filters



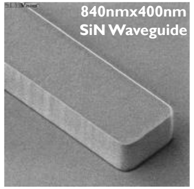
Low-loss high-density passive waveguide circuits

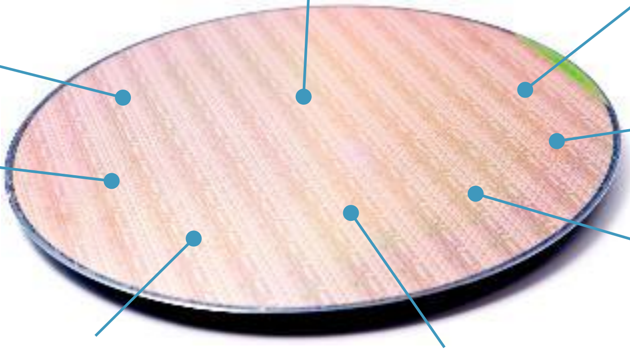


Low Thermo-Optic Power Consumption



Integrated SiN waveguides (0.2-2.5dB/cm)

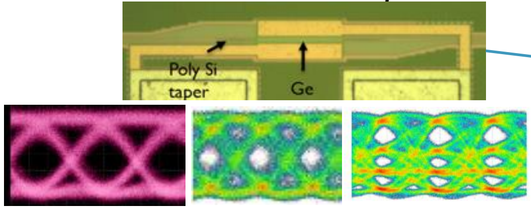




Edge Coupler 3um MFD (<2dB)

SiN Edge Coupler 9um MFD (<3dB)

56-128Gb/s GeSi Electro-Absorption Modulator

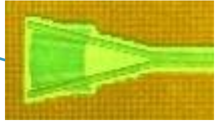


56Gb/s NRZ

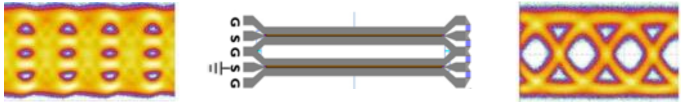
100Gb/s NRZ

128Gb/s PAM-4

SMF Grating Coupler (2dB/5dB)



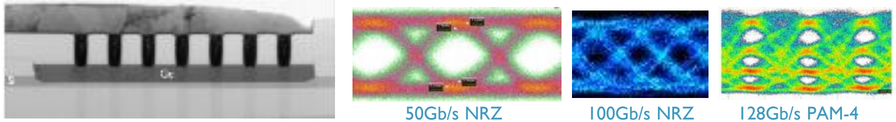
56Gb/s Silicon Mach-Zehnder Modulator



106Gb/s PAM-4

56Gb/s NRZ

56-128Gb/s Ge Photodetector



50Gb/s NRZ

100Gb/s NRZ

128Gb/s PAM-4

Fully Integrated Silicon Photonics Platform for 1310nm/1550nm Wavelengths

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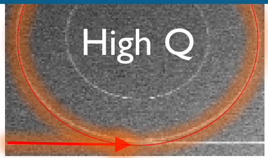
imec PECVD / LPCVD SiN platform

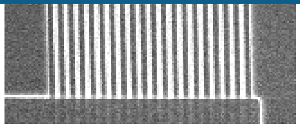
A large library of experimentally verified components is available

Waveguides

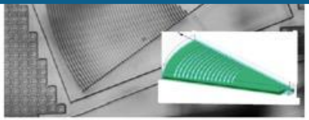
Ring Resonators



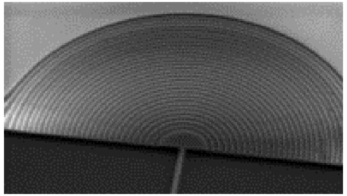
Fiber-to-WG



Low reflection

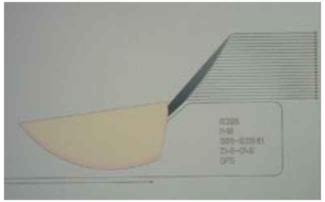


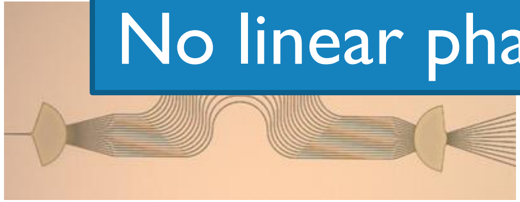
Focusing



What about the light source ? amplifiers ?

Basic spectrometers

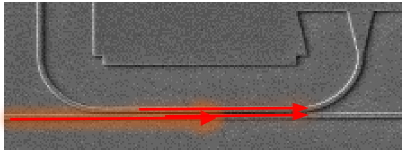




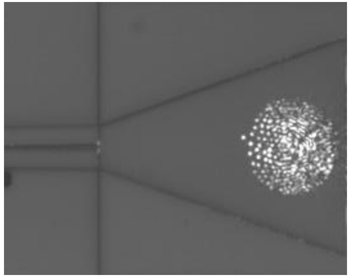
Multi-mode interferometer

No linear phase modulators ?

Evanescent coupler



Pseudo-random



Passive SiN platform

- No active devices => need for a III-V/silicon photonic integration platform (VIS-SWIR)

Options for III-V integration: from hybrid to monolithic

III-V/Si integration

pick-and-place of packaged lasers

cisco

flip-chip bare dies

Rockley PHOTONICS

imec

die-to-wafer bonding

intel

Tower Semiconductor

micro-transfer printing

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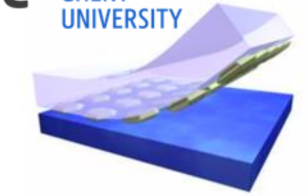
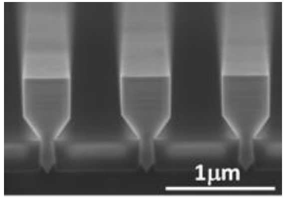


hetero-epitaxial growth



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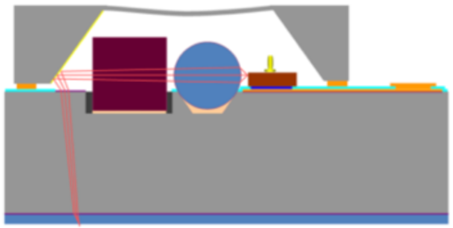
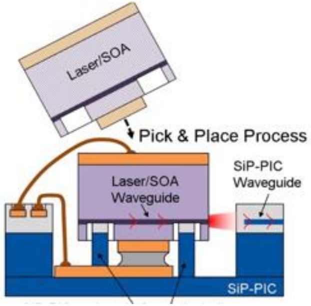
Established III-V-on-silicon technologies

LaMP



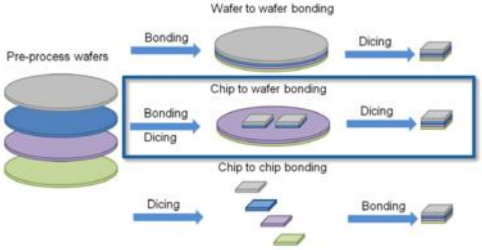
Use mature III-V technology
Fairly efficient optical coupling
No waveguide-in / waveguide-out devices
Known good die
Sequential population of SiPh wafer
Can be integrated on back-end stack

Flip-chip integration



Use mature III-V technology
Fairly efficient optical coupling
Waveguide in-out devices difficult
Known good die
Sequential population of SiPh wafer
Requires local back-end removal

Die-to-wafer bonding

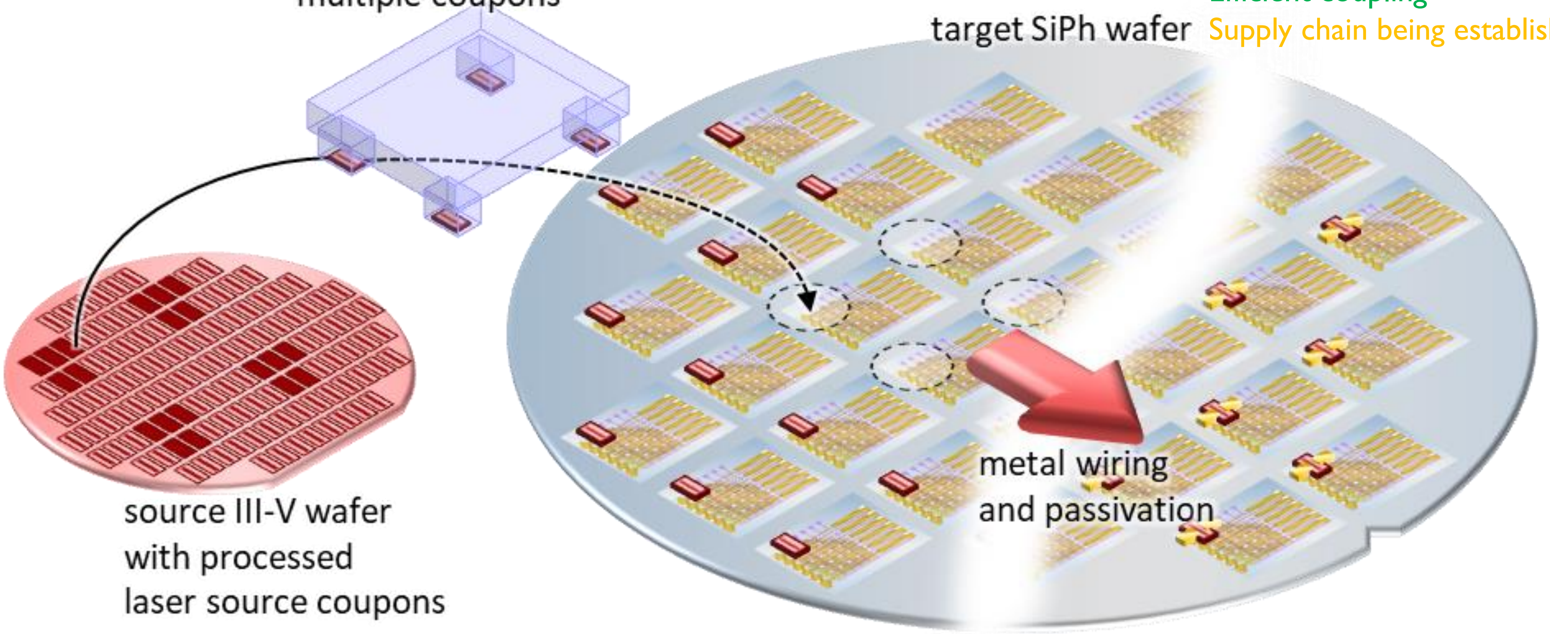


III-V processing on target wafer
Efficient optical coupling
Waveguide in-out devices
No known good III-V components
Parallel processing of devices
Front-end / back-end NRE

Micro-transfer printing

III-V integration on SiPhotonics through micro-transfer printing

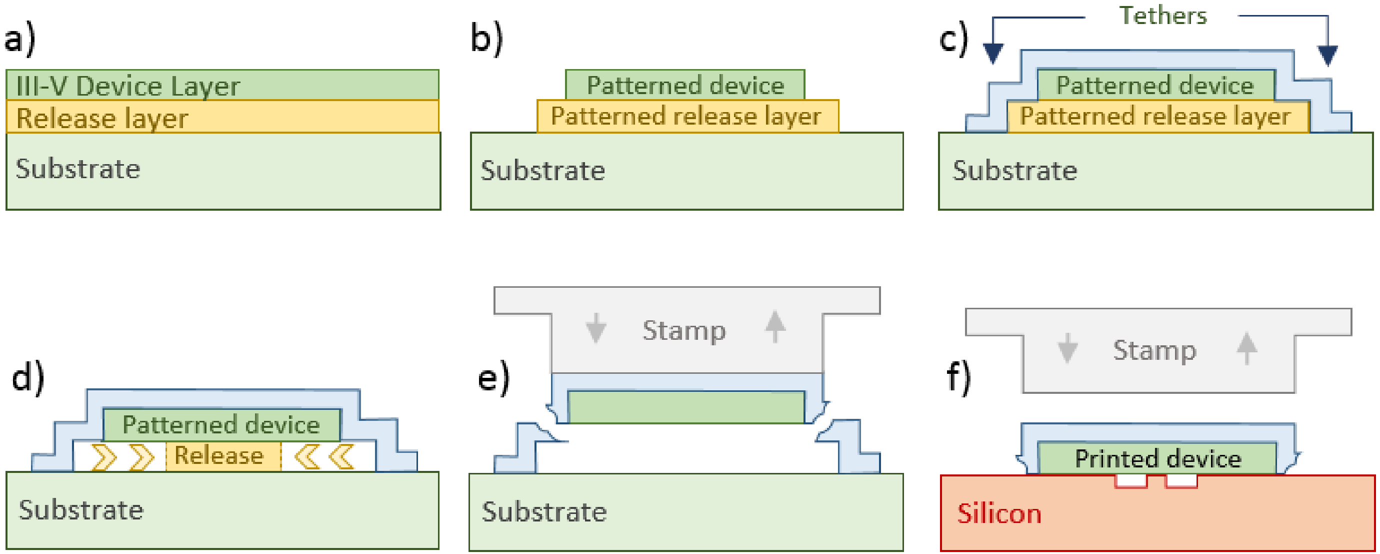
- III-V process & test prior to integration
- Back-end integration
- High throughput integration
- Efficient coupling
- Supply chain being established



Combines advantages of flip-chip & die-to-wafer bonding

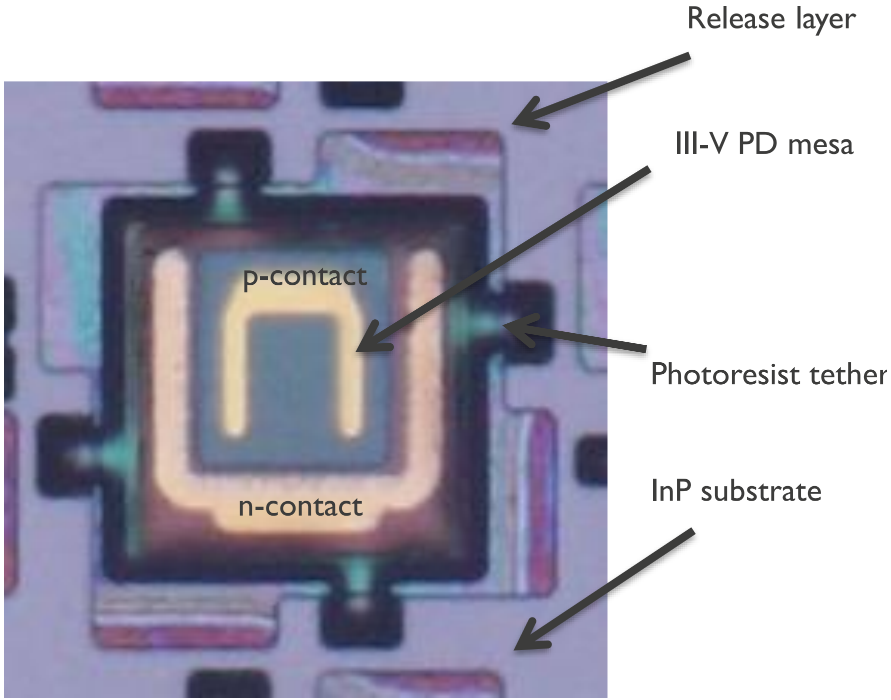
Micro-transfer printing basics

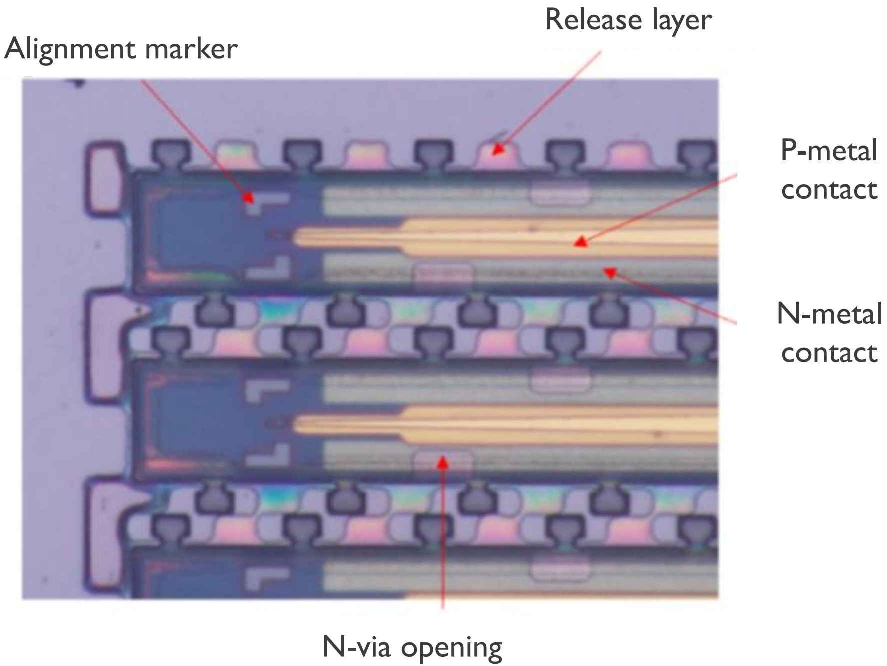
Device processing, release, pick-up & print



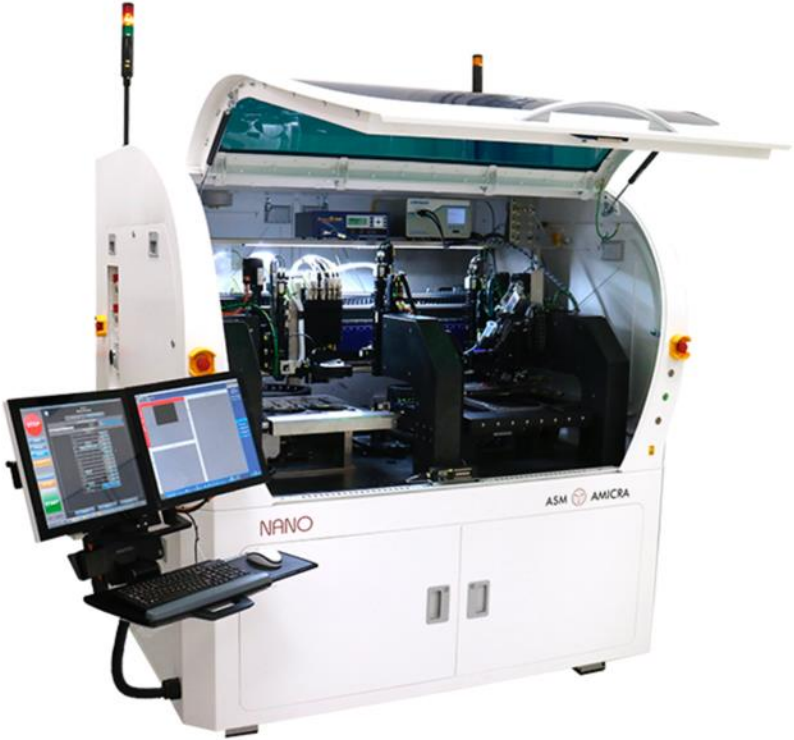
Transfer of released, micro-scale III-V devices to a Si target wafer

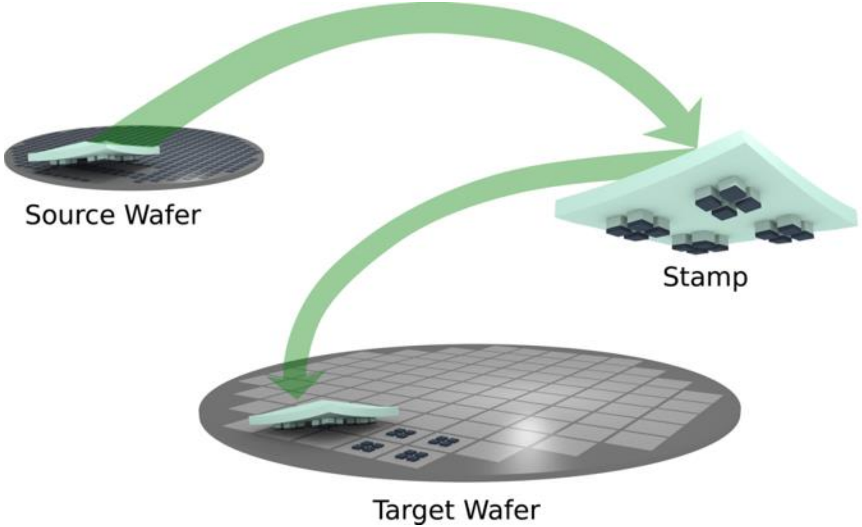
Example of transfer-print ready III-V devices





Micro-transfer printing

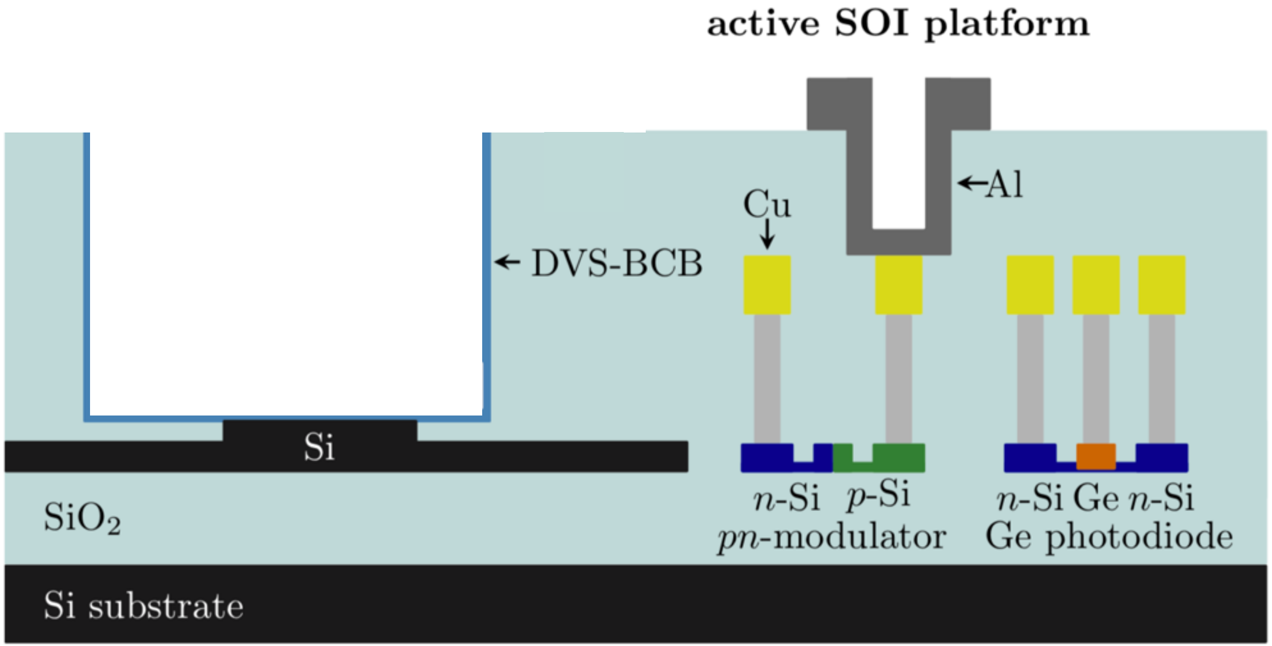




New tools: position tolerance of +/- 0.5 μm at 3σ in medium arrays (about 1”x 1”) – 1 print cyle <60 sec

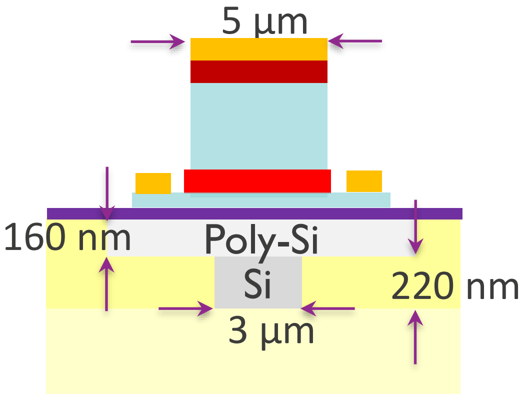
Micro-transfer printed III-V amplifiers / lasers on silicon photonics

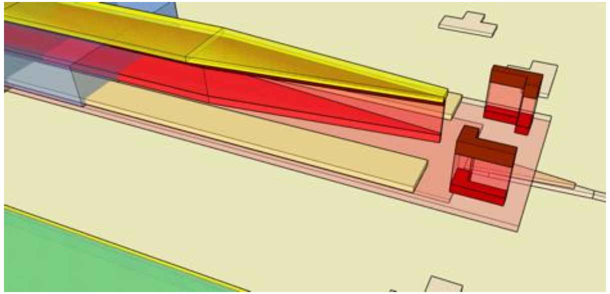
Combining the assets of flip-chip integration and wafer bonding



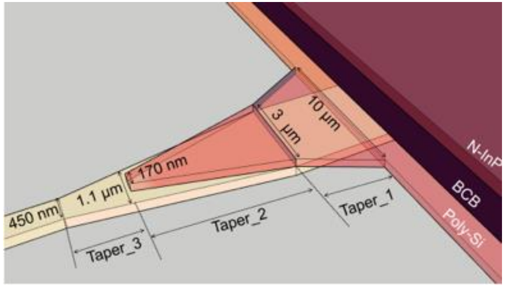
Local opening of back-end + integrate pre-fabricated thin-film optical amplifiers using an adhesive bonding agent + RDL

Alignment-tolerant III-V-Si evanescent coupling interface

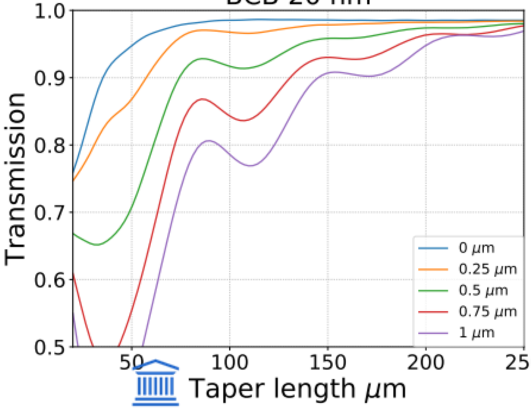




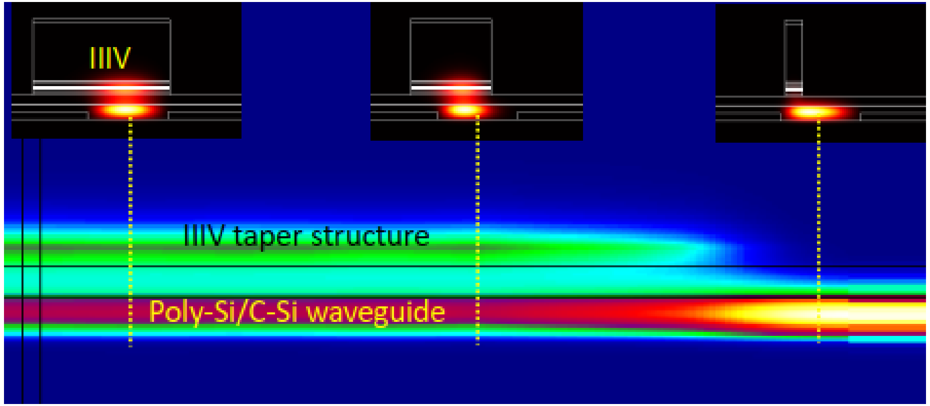
Si/poly-Si/n-InP to Si



BCB 20 nm



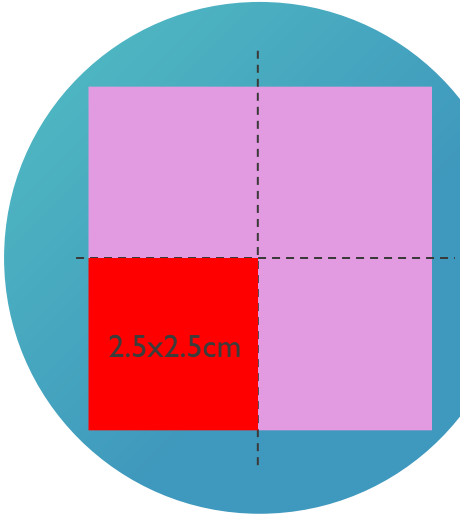
Si/poly-Si/n-InP to SOA waveguide



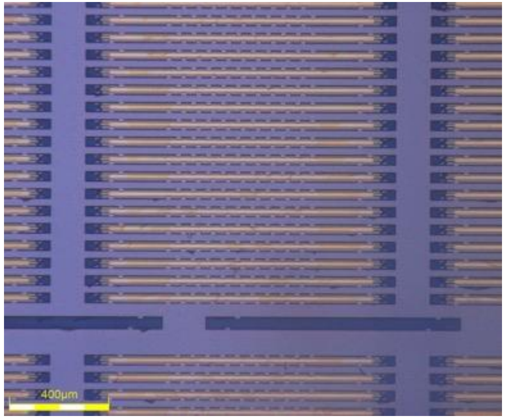
Processed opto-electronic devices on the III-V source wafer

Material systems: InP, GaAs, GaSb

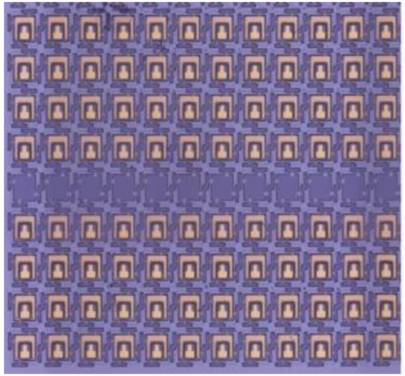
3 inch III-V wafer



55% wafer usage, but 3-10 times higher packing density of devices compared to discrete devices



Coupon pitch: 70 µm



Coupon pitch: 70 µm

Supply chain

Establishing supply chain through European projects

INSPIRE

Transfer printing of inP 1550nm laser diodes, modulators and high-speed PDs on 200mm Si/SiN Photonics wafers

Smart Photonics as III-V Foundry
X-Celeprint as TP provider

MedPhab
Photonic Medical Devices

Transfer printing of 1400-1700nm InP tunable laser diodes on 200mm SOI Photonics wafers

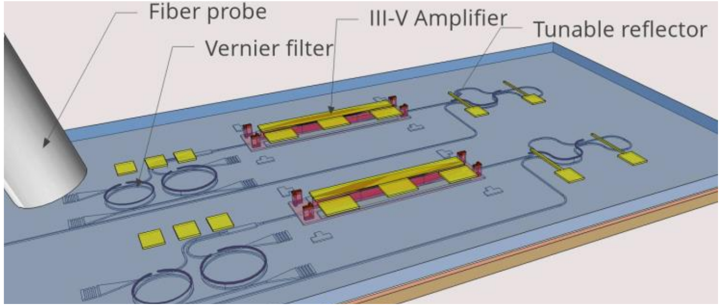
III-V Lab as III-V Foundry
X-Celeprint as TP provider (sub)

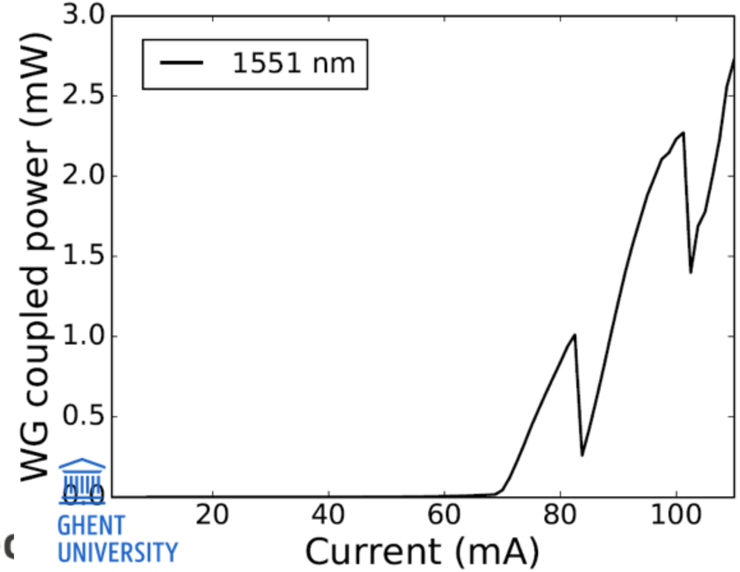
caladan

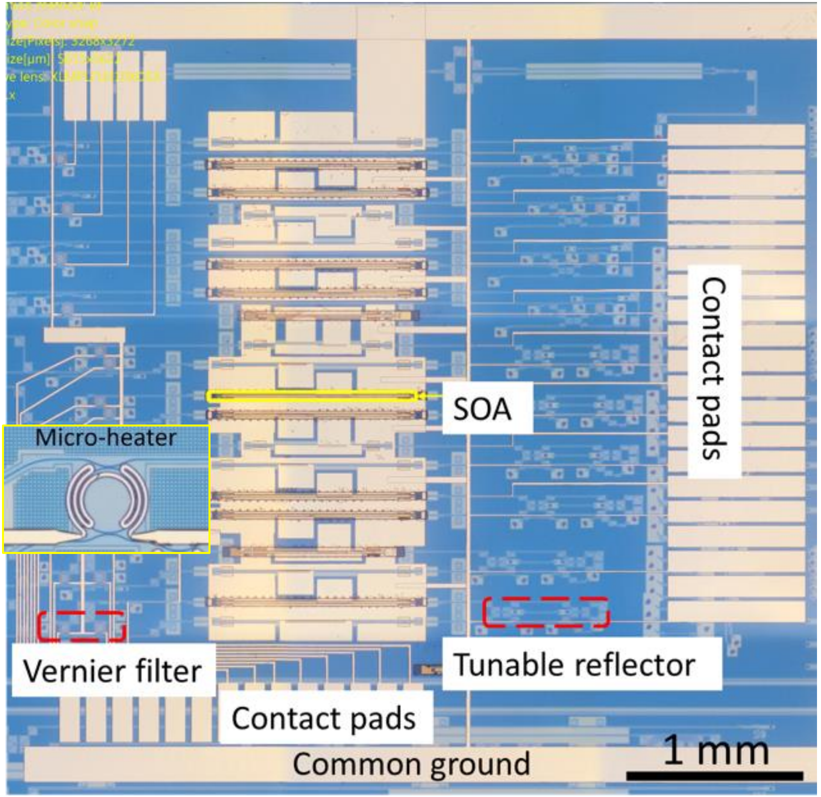
Transfer printing of 1300nm GaAs QD laser diodes on 300mm SOI Photonics wafers

Innolume as III-V Foundry
X-Celeprint as TP provider

Transfer-printed III-V-on-Si widely tunable lasers



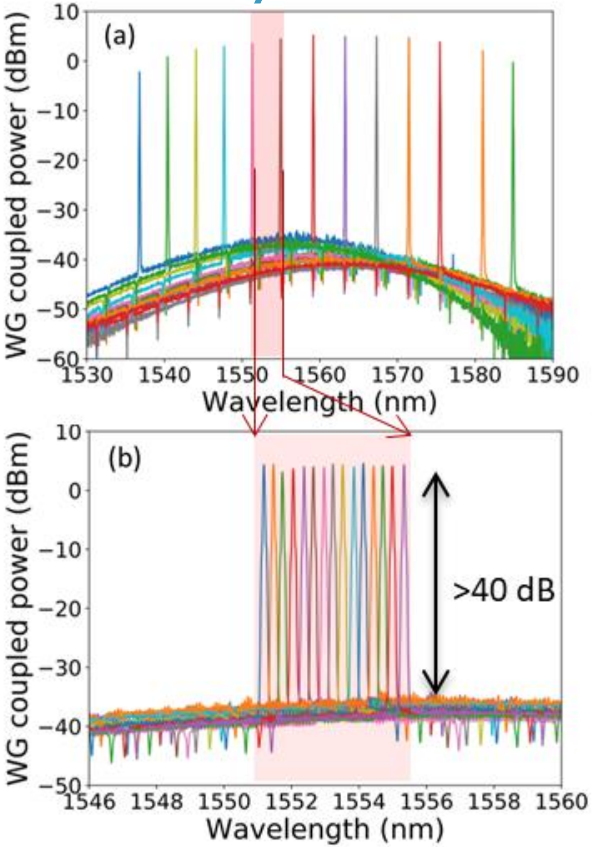


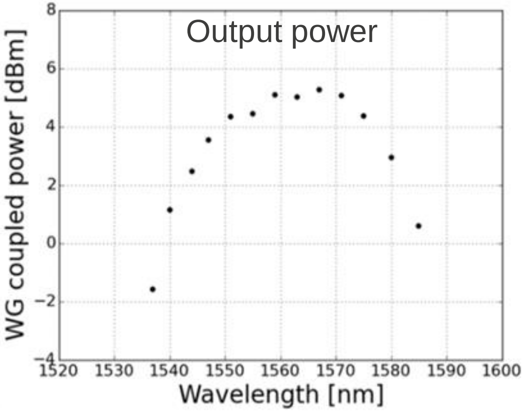


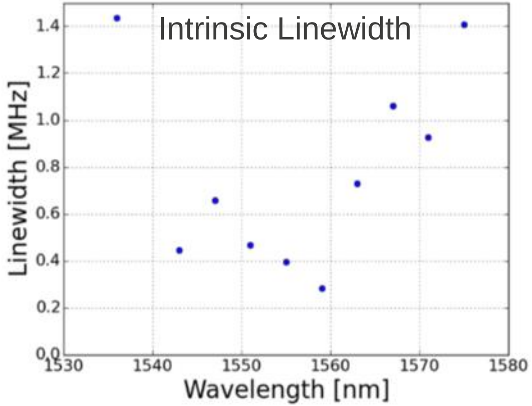
J. Zhang et al., ECOC 2019

Transfer-printed III-V-on-Si widely tunable lasers

Tuning range: 50 nm
SMSR: >40 dB
Peak output power: >5 dBm
Minimum Linewidth: 300 KHz



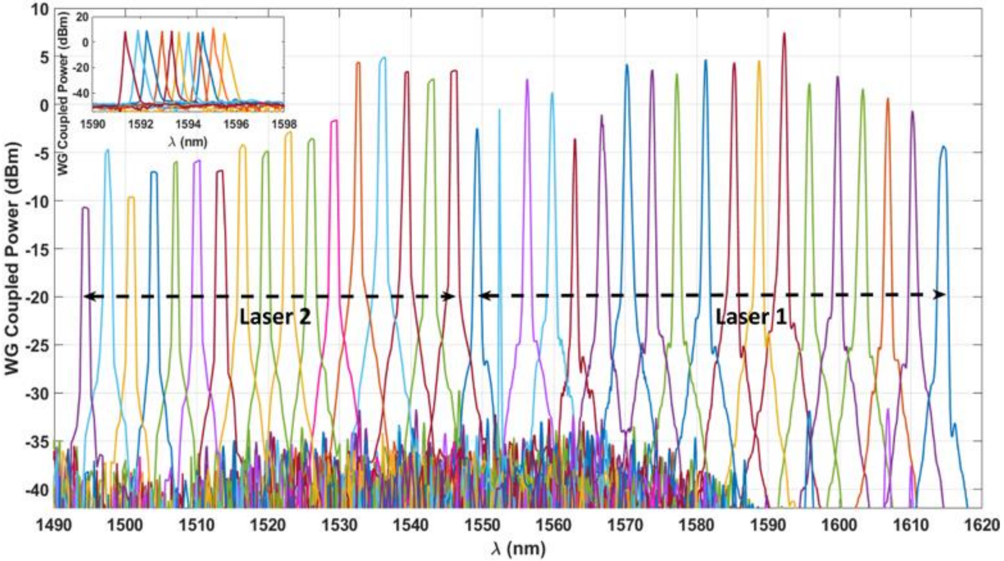




C-band SOA integration – passive Si + back-end

MedPhab
Photonic Medical Devices

- Integration of two different III-V epi-stacks (gain peak at 1525nm and 1575nm) for extended wavelength coverage



E. Soltanian et al., ECIO 2022

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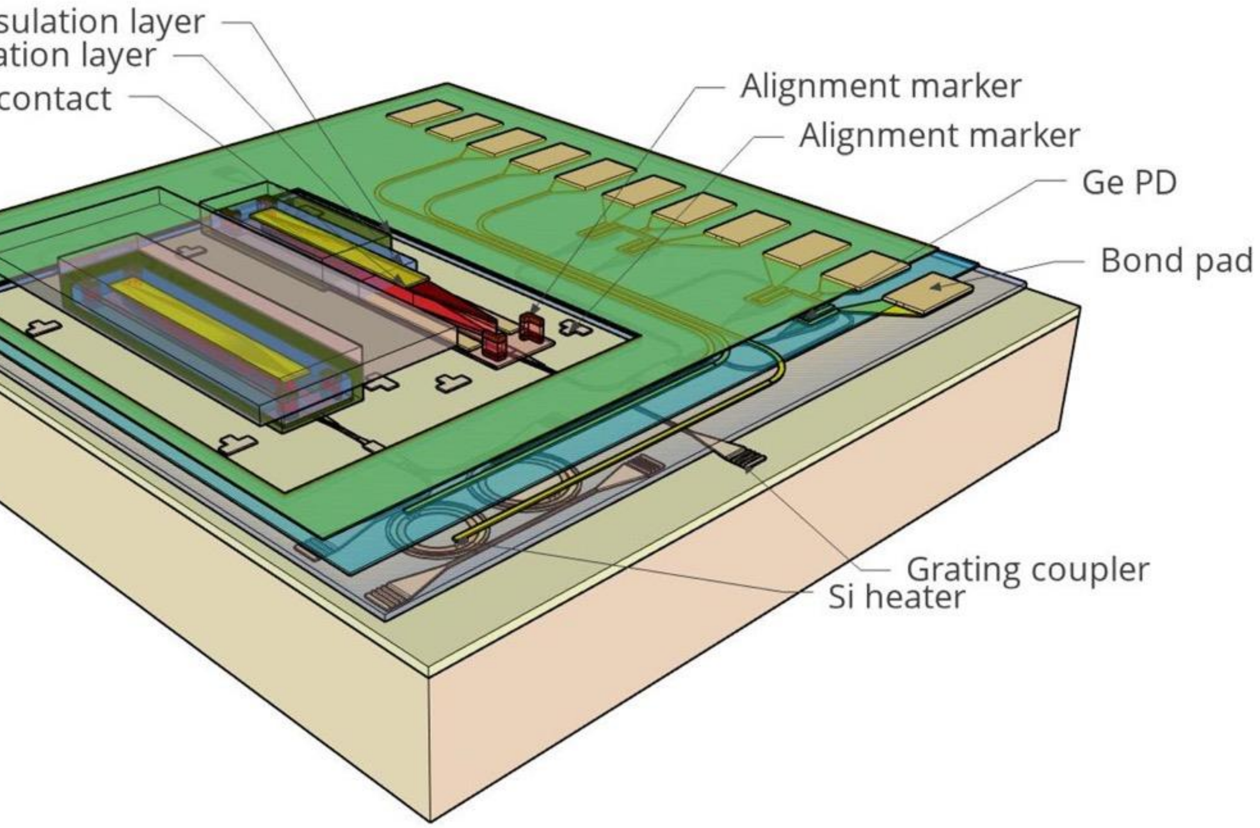
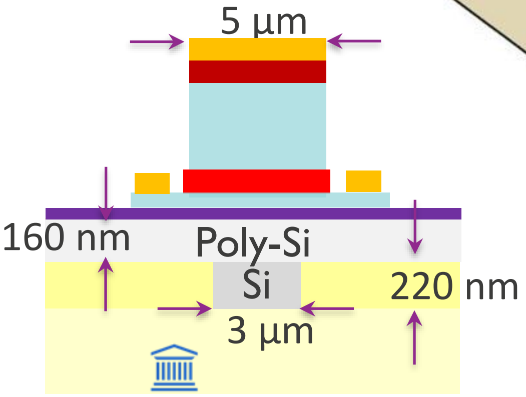
Integration on imec's iSIPP50G platform

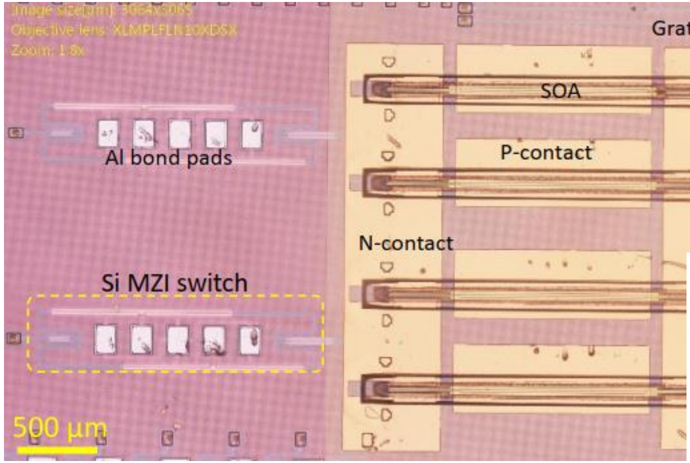


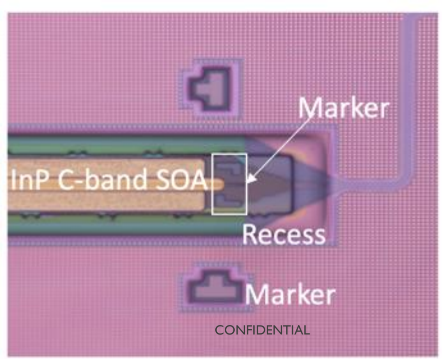


Transfer printed C-band SOAs

SOA integration on iSIPP50G (imec SOI full platform)

Small signal gain: 10dB @ 100mA
3dB gain bandwidth: 35 nm @100 mA





J. Zhang et al., ECTC 2022

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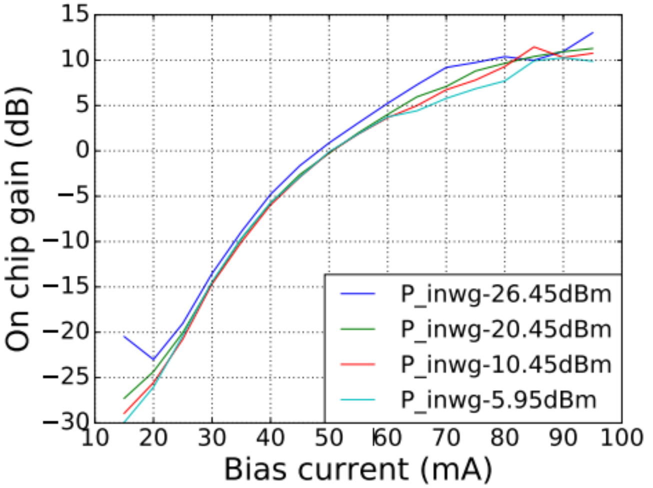
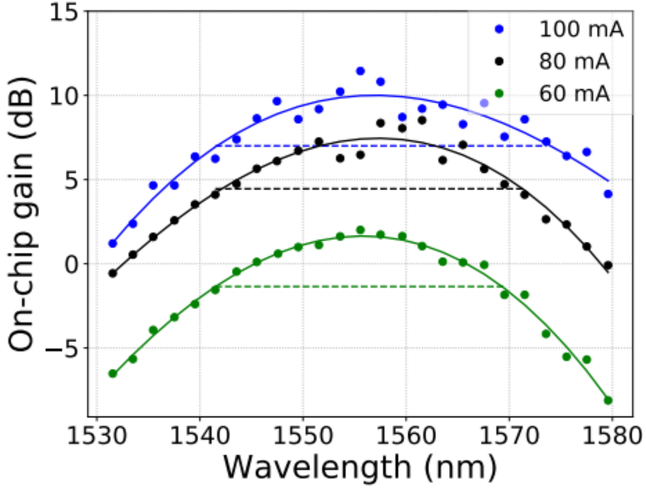
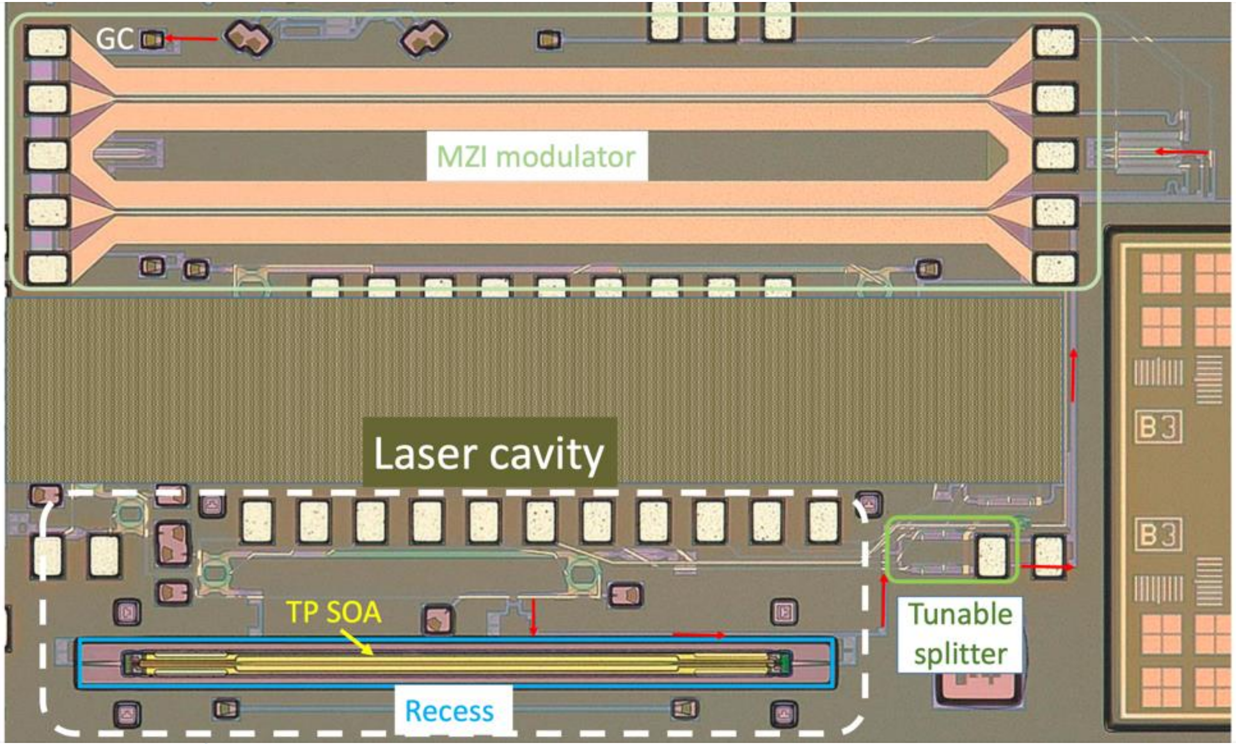
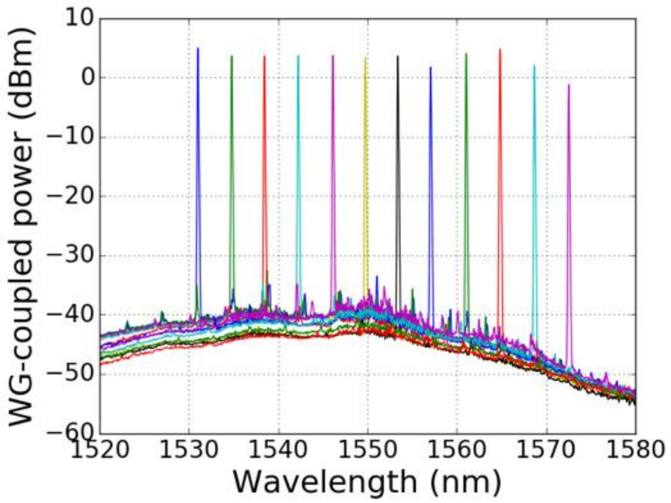


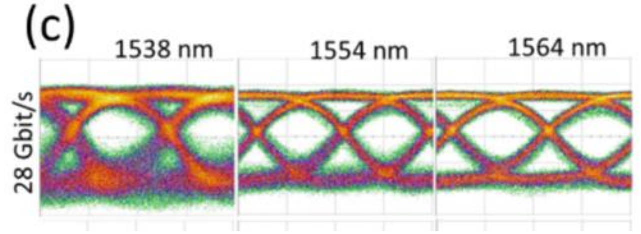


III-V-on-silicon tunable lasers

InP/Si extended cavity lasers on full SiPh platform

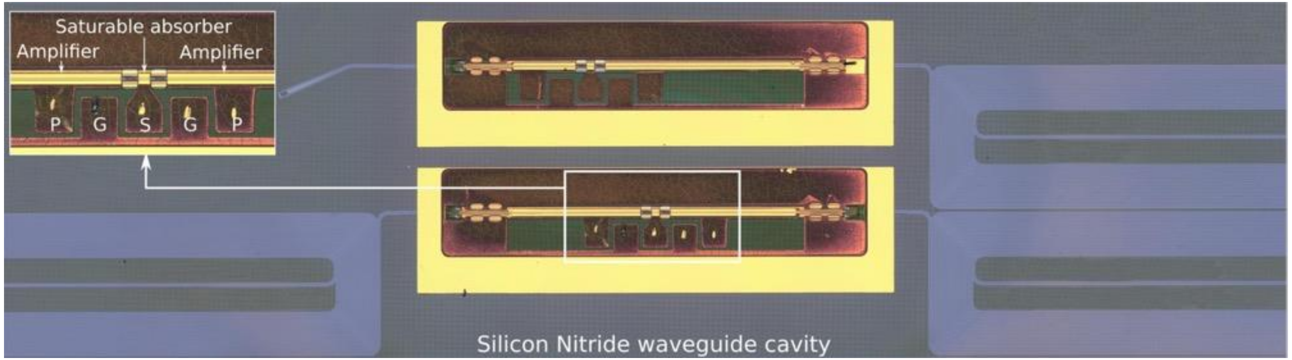


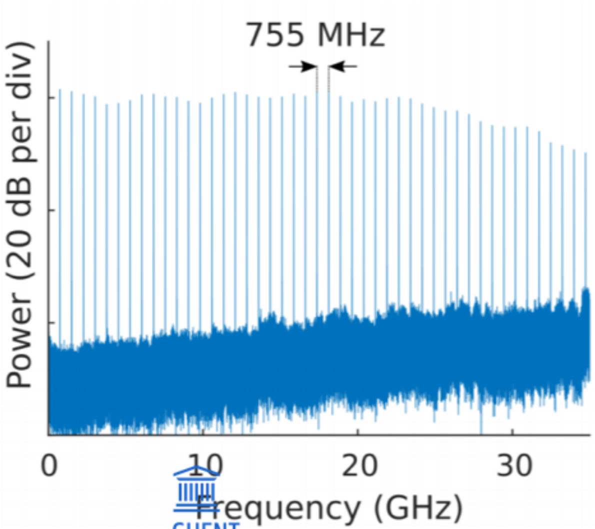


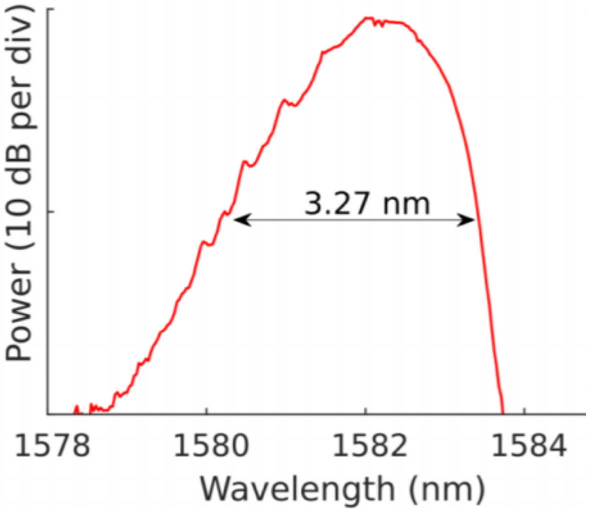


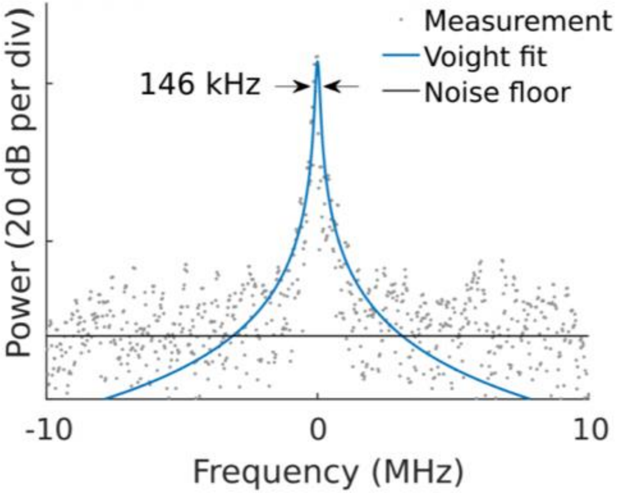
J. Zhang et al., OFC 2022

Transfer printed III-V-on-SiN modelocked laser









S. Cuyvers et al., ECOC 2020

III-V integration on LPCVD SiN PICs

C. Op de Beeck et al., Optica 2020

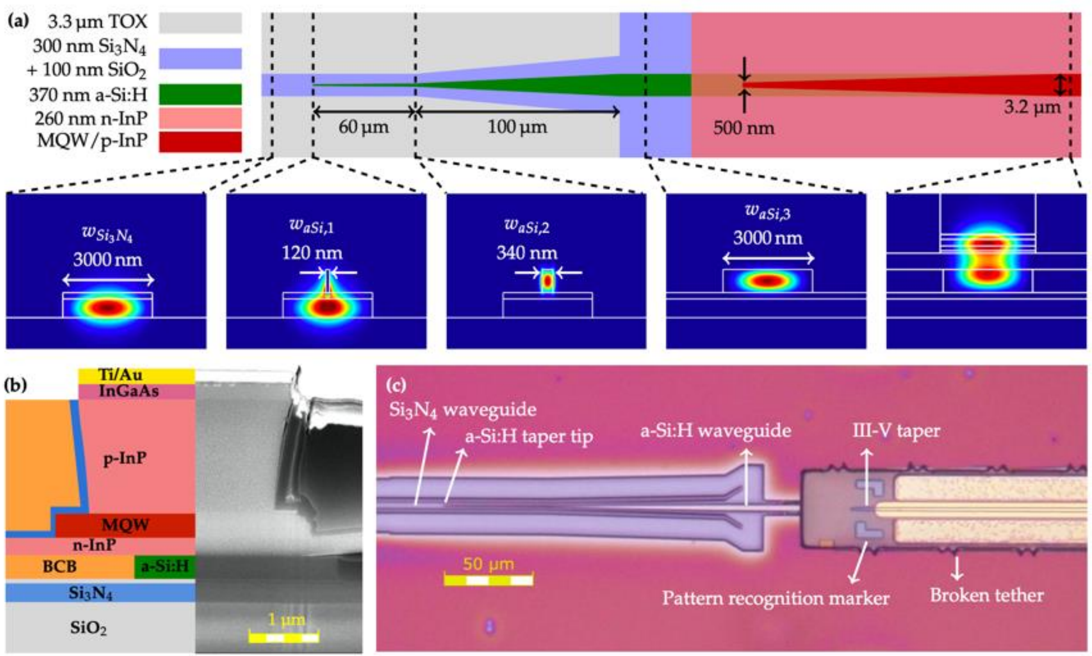
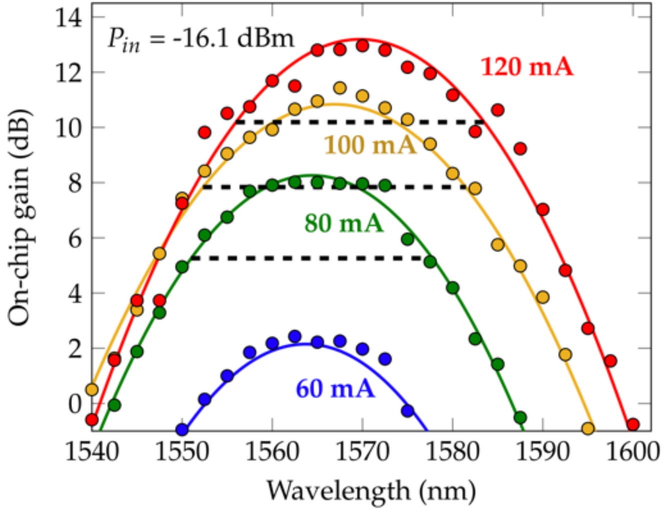


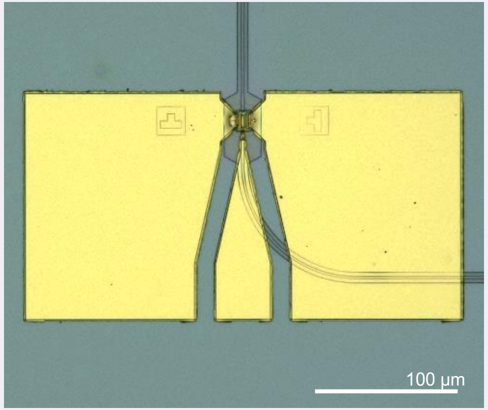
Fig. 1. (a) Schematic layout of the two-step taper from the Si_3N_4 waveguide to the InP/InAlGaAs amplifier. The fundamental TE mode is shown at different stages in the taper. The first two modal distributions are plotted with the same color scale to illustrate the mode matching at the a-Si:H tip interface. (b) SEM image of a cross-section of a micro-transfer printed III-V amplifier on an a-Si:H waveguide, overlaid with a schematic drawing of the stack. A lateral misalignment of ∼650 nm between the SOA and the a-Si:H waveguide is visible. (c) Optical microscope image of a micro-transfer printed SOA coupon on an a-Si:H waveguide coupling to the Si_3N_4 layer.



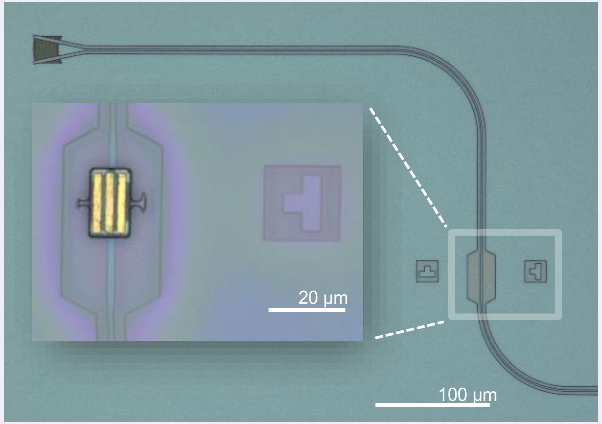
Transfer printed UTC

D. Maes et al., CLEO 2022

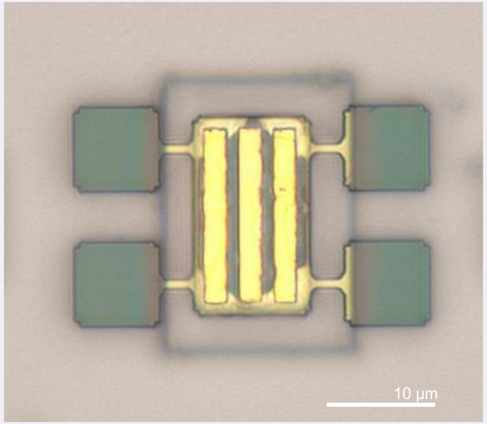
- 0.45 A/W responsivity
- 10 nA dark current
- > 100 GHz bandwidth



Coplanar waveguide for probe characterization



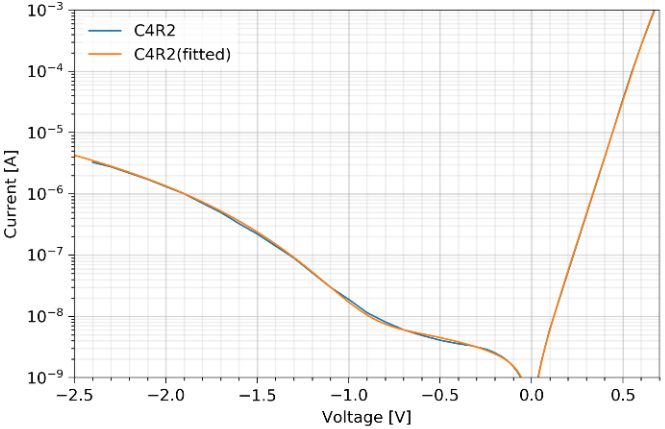
SiN waveguide with transfer-printed photodiode



Suspended UTC photodiode coupon

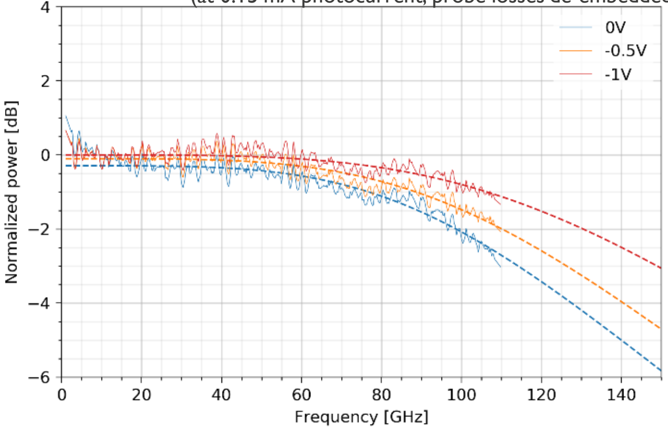
Dark current

(junction area = 2x16um²)



RF-response

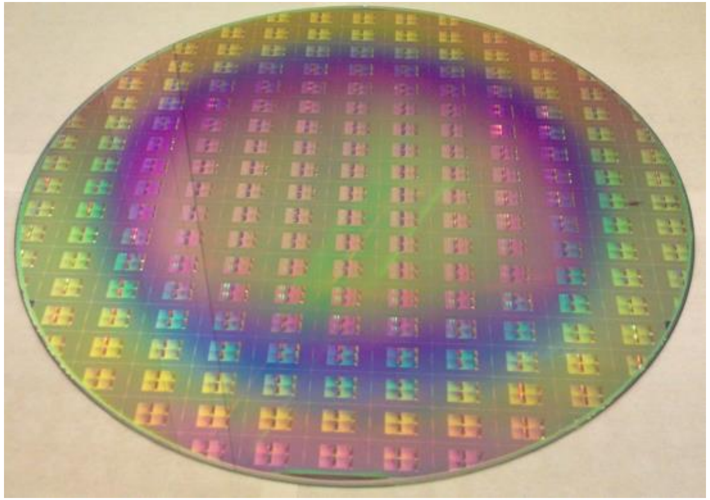
(at 0.15 mA photocurrent, probe losses de-embedded)

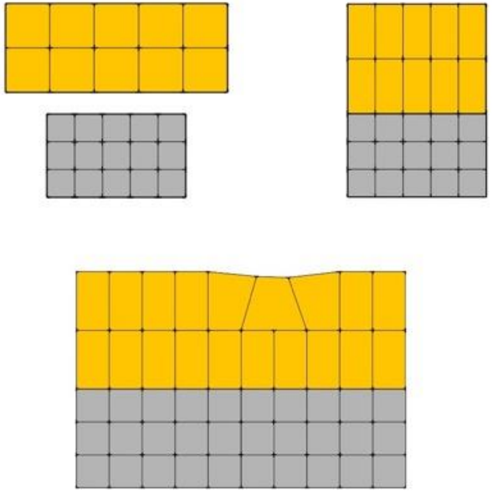


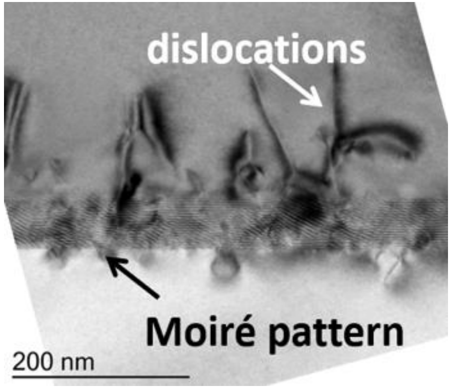
Hetero-epitaxial growth

Direct Epitaxy on Silicon

Promises & Challenges





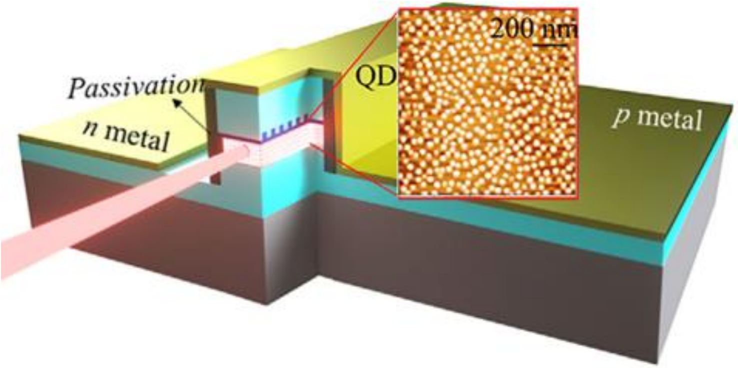


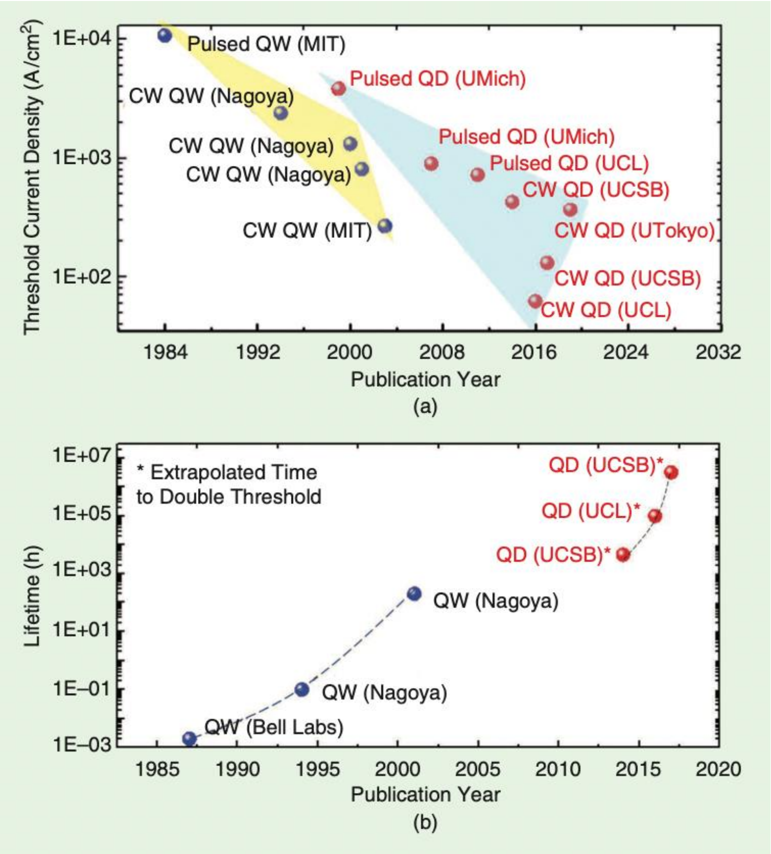
- Ultimate scalability: selective growth using MOCVD on 300mm wafers
- But: lattice mismatch, different polarity, different thermal expansion coefficients…

Direct Epitaxy on Silicon

Approach 1: Planar growth, quantum dot active layers

- Using QDot gain layers to minimize effect of dislocations
- Excellent performance & long lifetime demonstrated
- But: not trivial to integrate with standard silicon photonics platforms



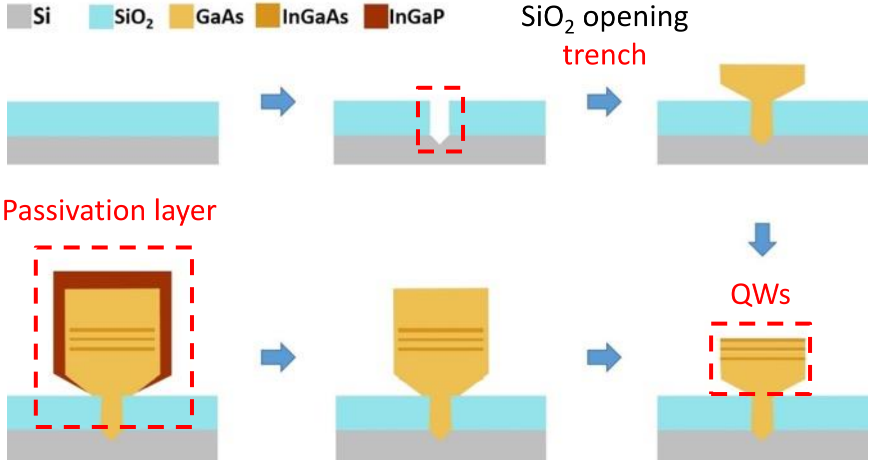


From Y. Wan e.a., IEEE Nanotechnology Magazine, 2021 (UCSB)

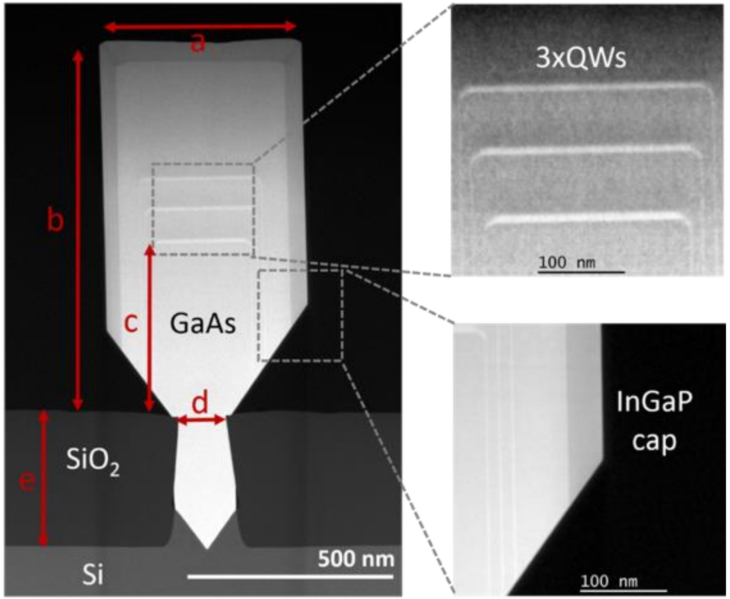
IMEC appproach

Aspect-Ratio-Trapping (ART) & Nanoridge Engineering

Basic processing scheme



Reference sample

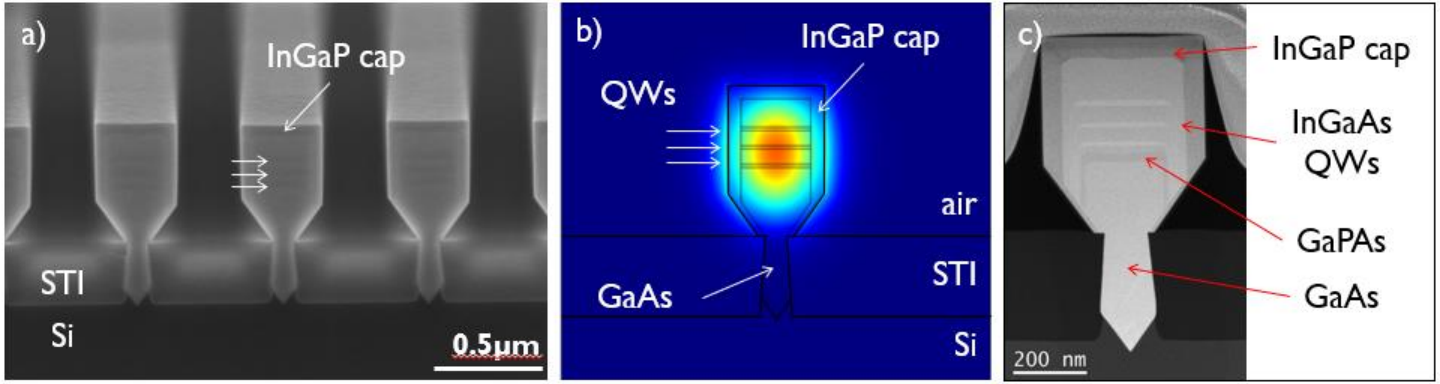


B. Kunert e.a. Applied Physics Letters, 109(9), doi:10.1063/1.4961936 (2016

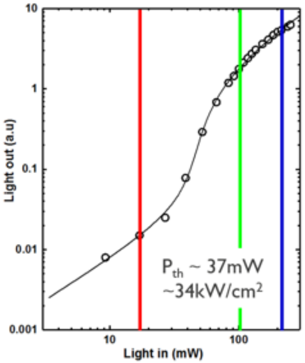
Nano-Ridge Engineering for III-V device

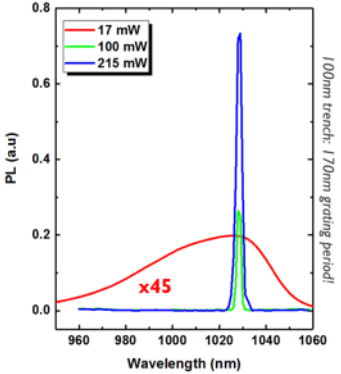
Novel integration concept on 300mm Si substrate

Nano-Ridge Engineering: Optically pumped InGaAs/GaAs DFB nano-ridge Laser

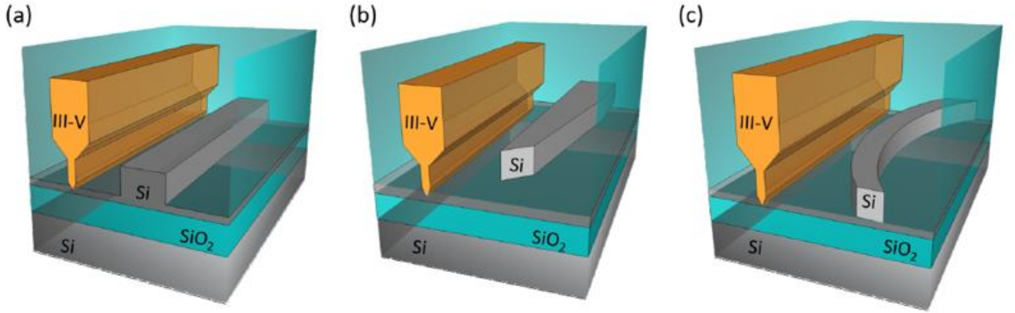


Y. Shi et al., Optica Vol. 4, No 12, 1468 (2017)
Y. Shi et al., Optics Express, 27, 26 (2019) 37781



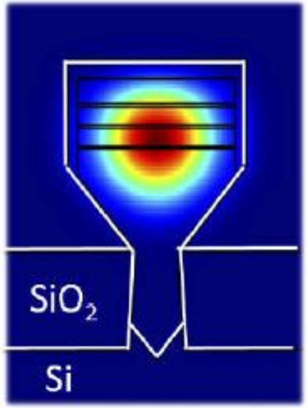


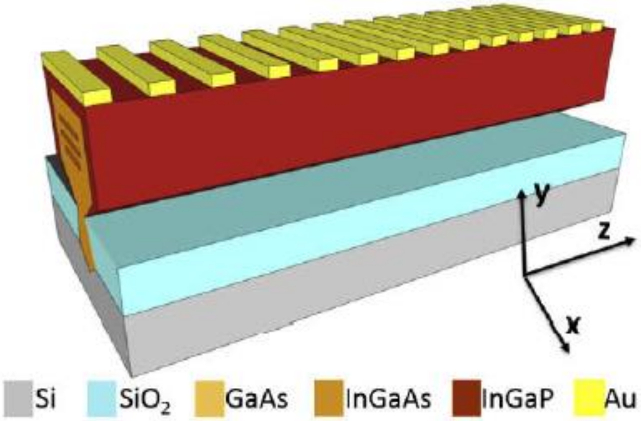
Novel adiabatic coupler for III-V nano-ridge laser

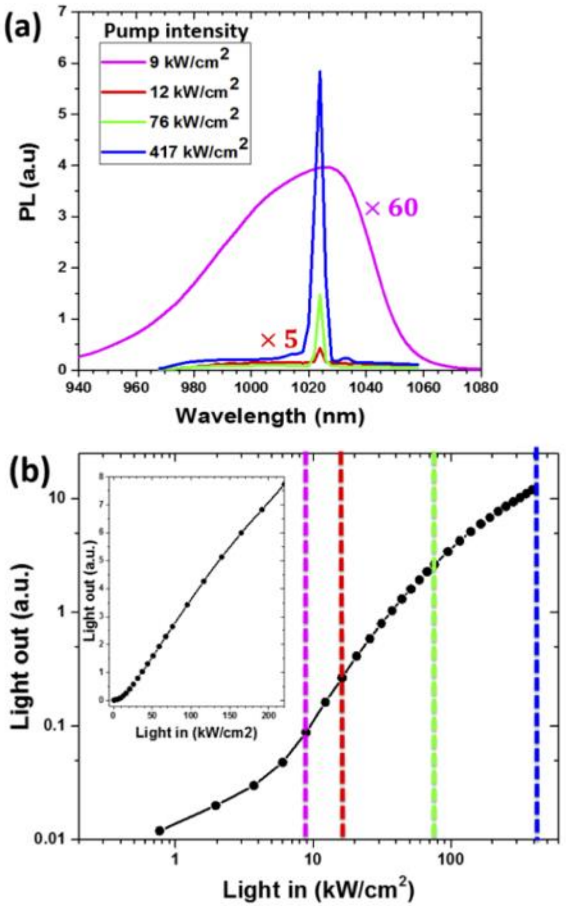


Loss-coupled DFB nano-ridge laser

Metal grating deposited on top of the nano-ridge





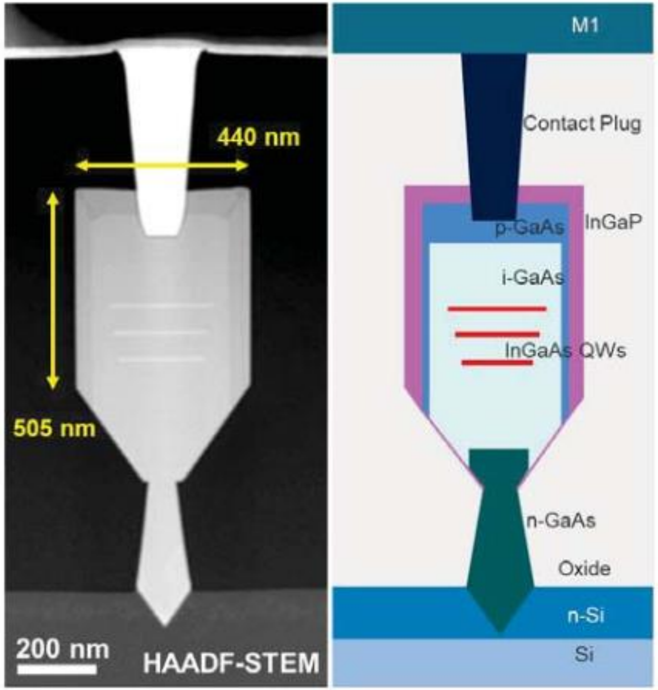


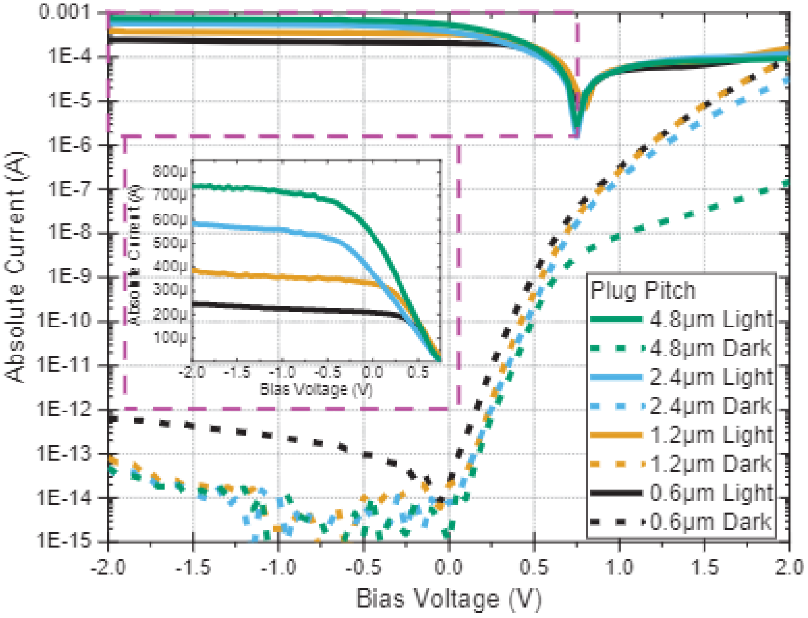
Y. Shi et al., Optics Express Vol. 29, No 10, 14649 (2021)

Next step: electrically injected lasers

InGaAs/GaAs nano-ridge photodetector

0.3pA Dark Current and 0.65A/W Responsivity at 1020nm



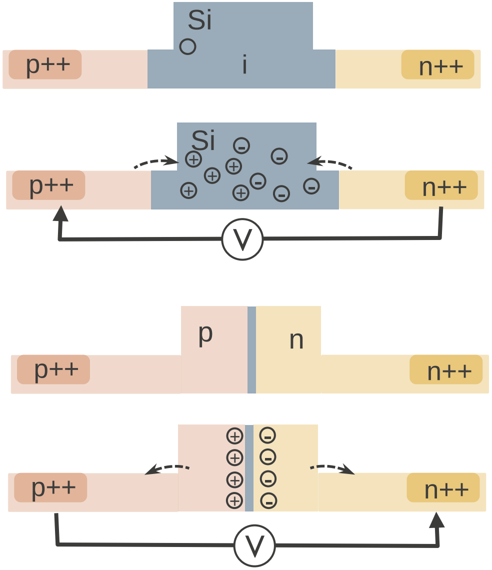


C. I. Ozdemir et al., 2020 ECOC, 20349509

Next Generation Modulators

Motivation

Why do we need alternative modulator approaches?

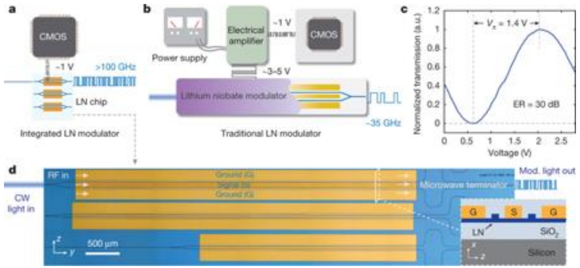


- The Silicon platform already has modulators and switches:
  - Exploiting carrier dispersion
    - Depletion (pn), injection (pin), accumulation devices
- Using native CMOS-processes
  - Highly mature
  - Very well understood, good models available
  - Very reliable processes
- BUT
  - Carrier dispersion show intrinsic trade-off between: efficiency – loss – speed
  - No pure phase modulation (AM/FM mixing)
  - Not compatible with cryogenic temperatures
  - Ge-based devices (FK): limited ratio ER/IL, limited operating wavelength range

ER: Extinction Ratio – IL: Insertion Loss

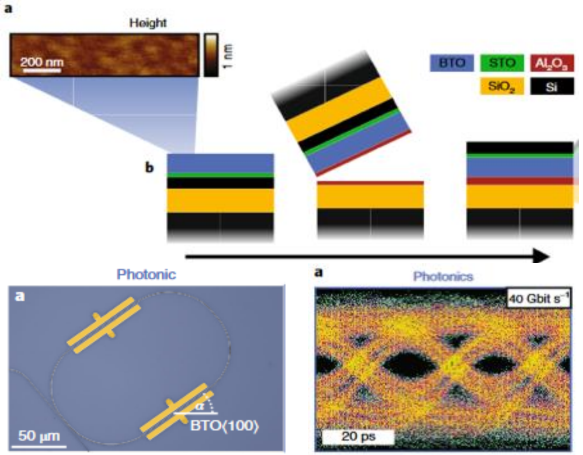
Explosion in new modulator materials

$LiNbO_3$ on Insulator



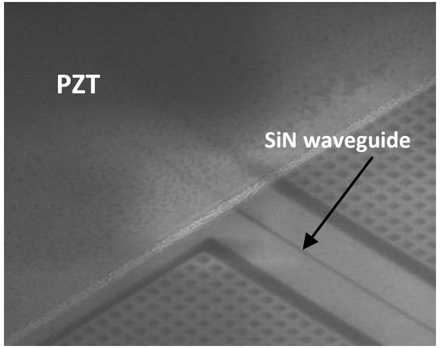
Wang e.a., Nature 2018

BTO on Silicon



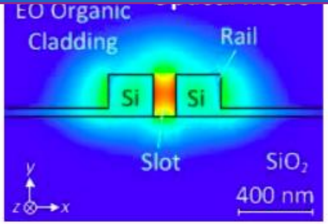
Stefan Abel et al, Nat. mat. 2018

PZT-on-anything

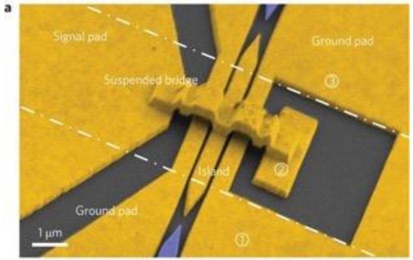


K. Alexander et al, Nat. Comm. 2018

Electro-optic Polymers

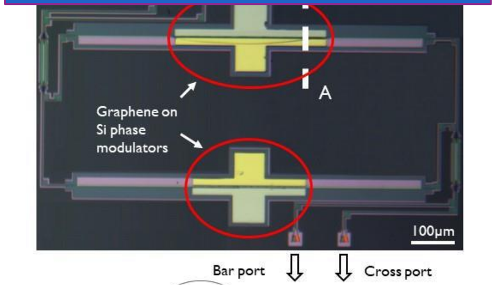


Koos e.a., Nature 2017



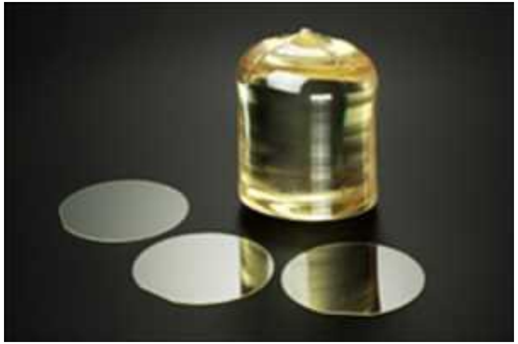
Leuthold e.a.

Graphene



Romagnoli e.a., Nature Photonics 12 40 44 (2018)

Lithium Niobate (LN)



From https://surfacingmagazine.net

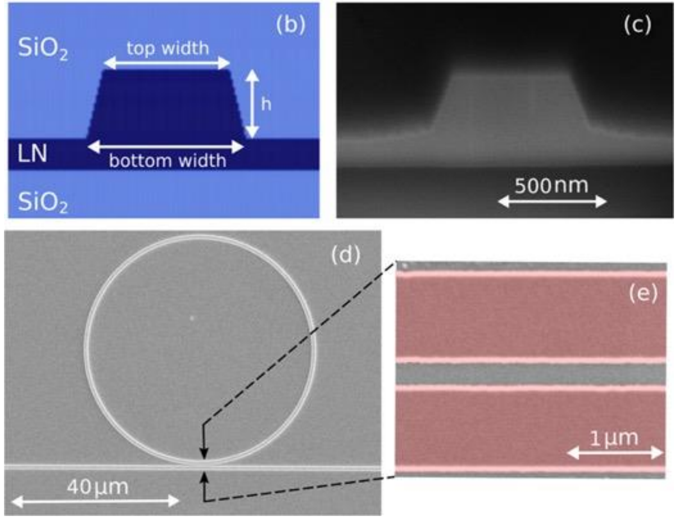
- Till recently the main modulator technology in telecom
  - Very well understood
  - Very good linearity
  - Decent performance (r_{eff} ~30pm/V)
- But how to integrate with Silicon ?
  - $LiNbO_3$ typically grown as bulk crystal
- Breakthrough:
  - Company NanoLN started providing thin film LN on Silicon substrates
  - Loncar-group (Harvard) demonstrated it is possible to etch low-loss WG in LN

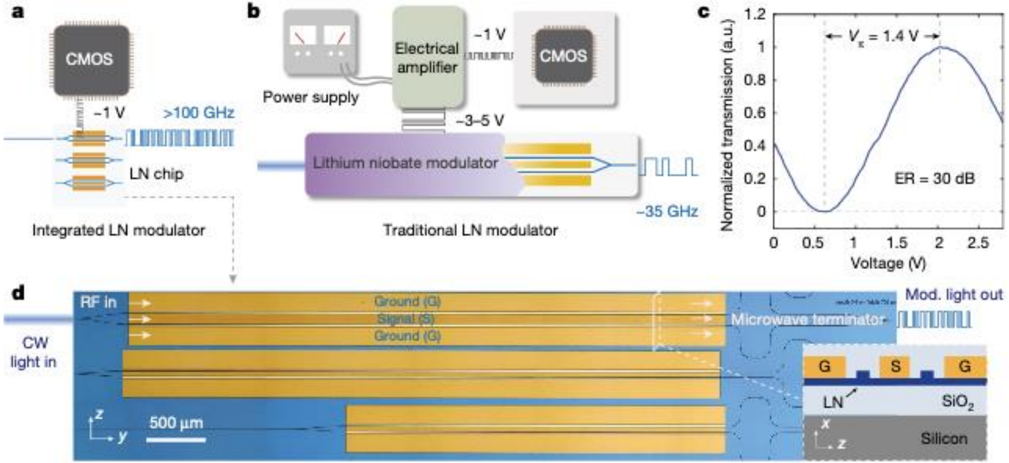

LETTER

https://doi.org/10.1038/s41586-018-0551-y

Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages

Cheng Wang[1,2,6], Mian Zhang[1,6], Xi Chen[3], Maxime Bertrand[1,4], Amirhassan Shams-Ansari[1,5], Sethumadhavan Chandrasekhar[3], Peter Winzer[3] & Marko Lončar[1]*



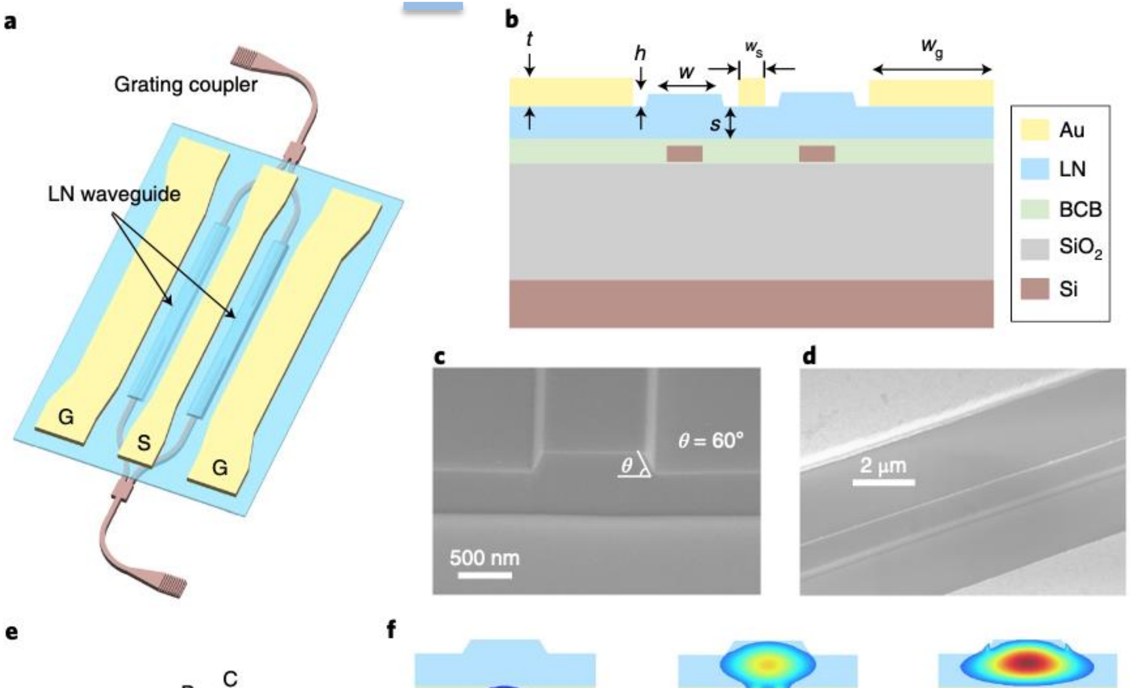


nature photonics
ARTICLES
https://doi.org/10.1038/s41566-019-0378-6

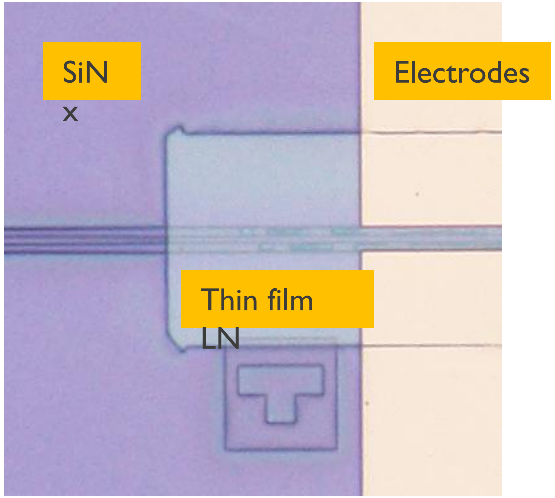
High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s^{-1} and beyond

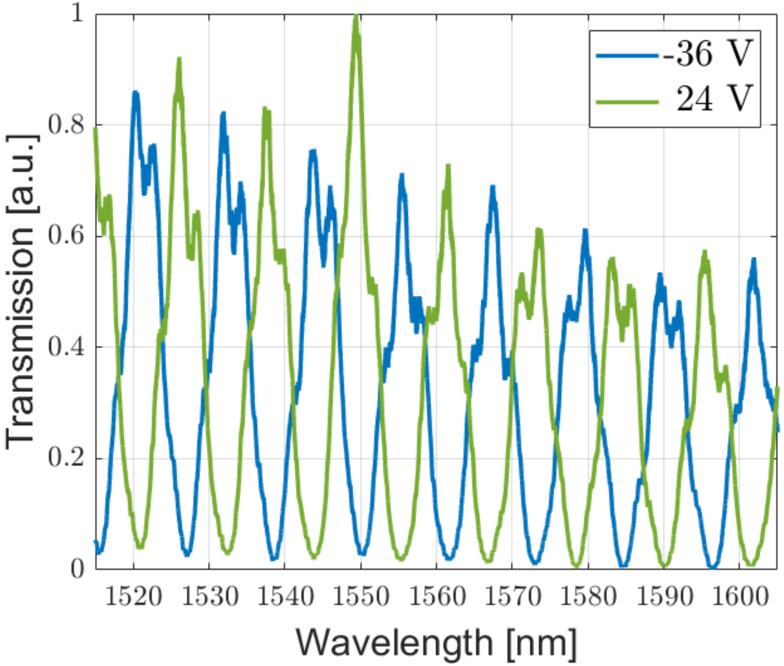
Mingbo He[1], Mengyue Xu[1], Yuxuan Ren[2], Jian Jian[1], Ziliang Ruan[2], Yongsheng Xu[2], Shengqian Gao[1], Shihao Sun[1], Xueqin Wen[2], Lidan Zhou[1], Lin Liu[1], Changjian Guo[2], Hui Chen[1], Siyuan Yu[1], Liu Liu[2]* and Xinlun Cai[1]*

State Key Laboratory of Optoelectronic Materials and Technologies and School of Electronics and Information Technology, Sun Yat-sen University, Guangzhou, China. 2Centre for Optical and Electromagnetic Research, Guangdong Provincial Key Laboratory of Optical Information Materials and Technology, South China Academy of Advanced Optoelectronics, South China Normal University, Higher-Education Mega-Center, Guangzhou, China.



Transfer printing of lithium niobate





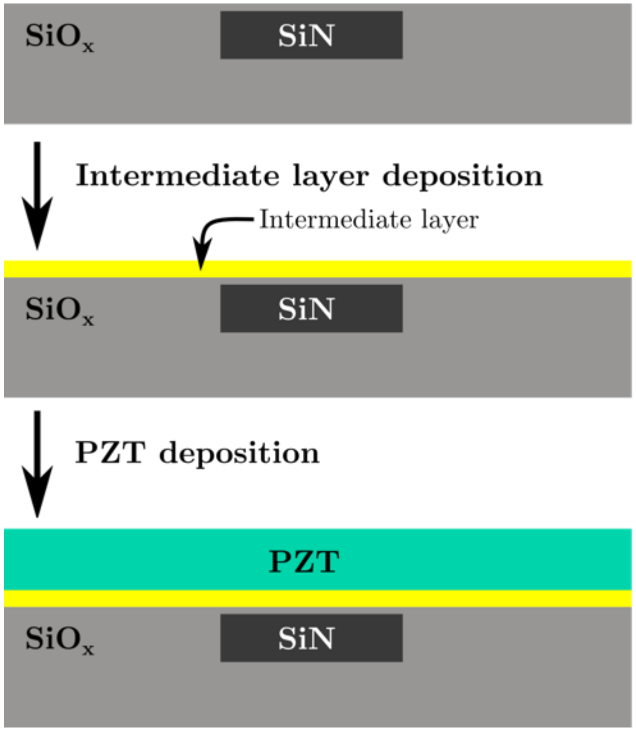
$$V_\pi L_\pi \approx 5.4\,Vcm$$

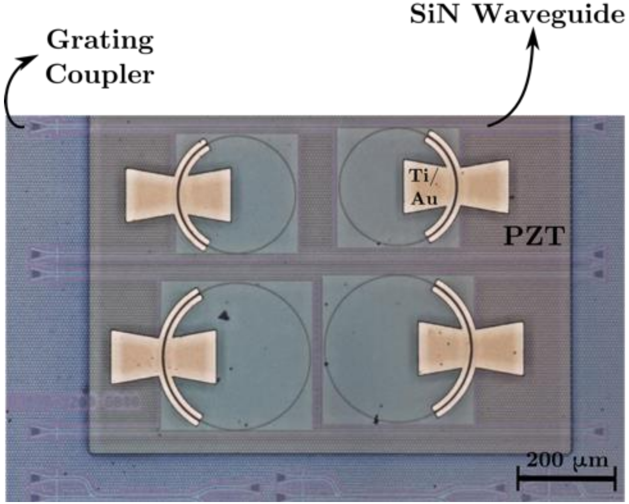
$$L_{LN} = 1.0\,mm$$

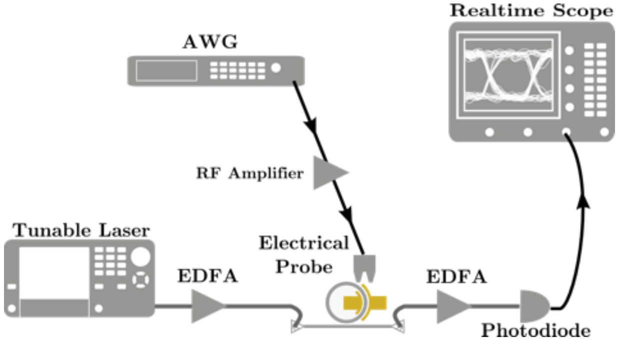
$$L_{Electrodes} = 0.9\,mm$$

T.Vanacker e.a., ECOC 2021

Alternative: PZT Sol-Gel integration







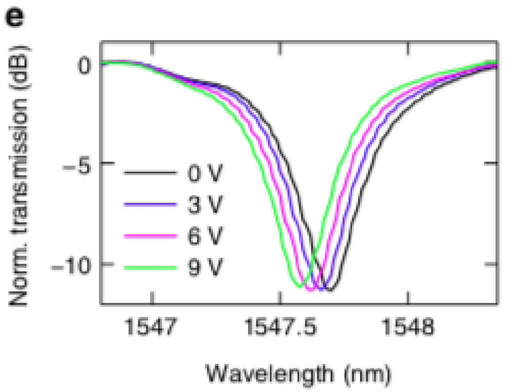
nature COMMUNICATIONS

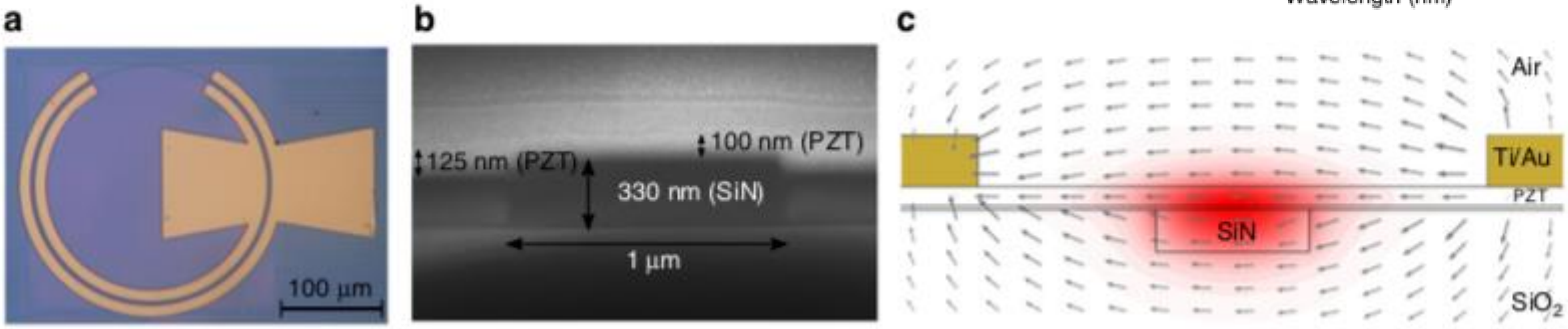
ARTICLE

DOI: 10.1038/s41467-018-05846-6

OPEN

Nanophotonic Pockels modulators on a silicon nitride platform

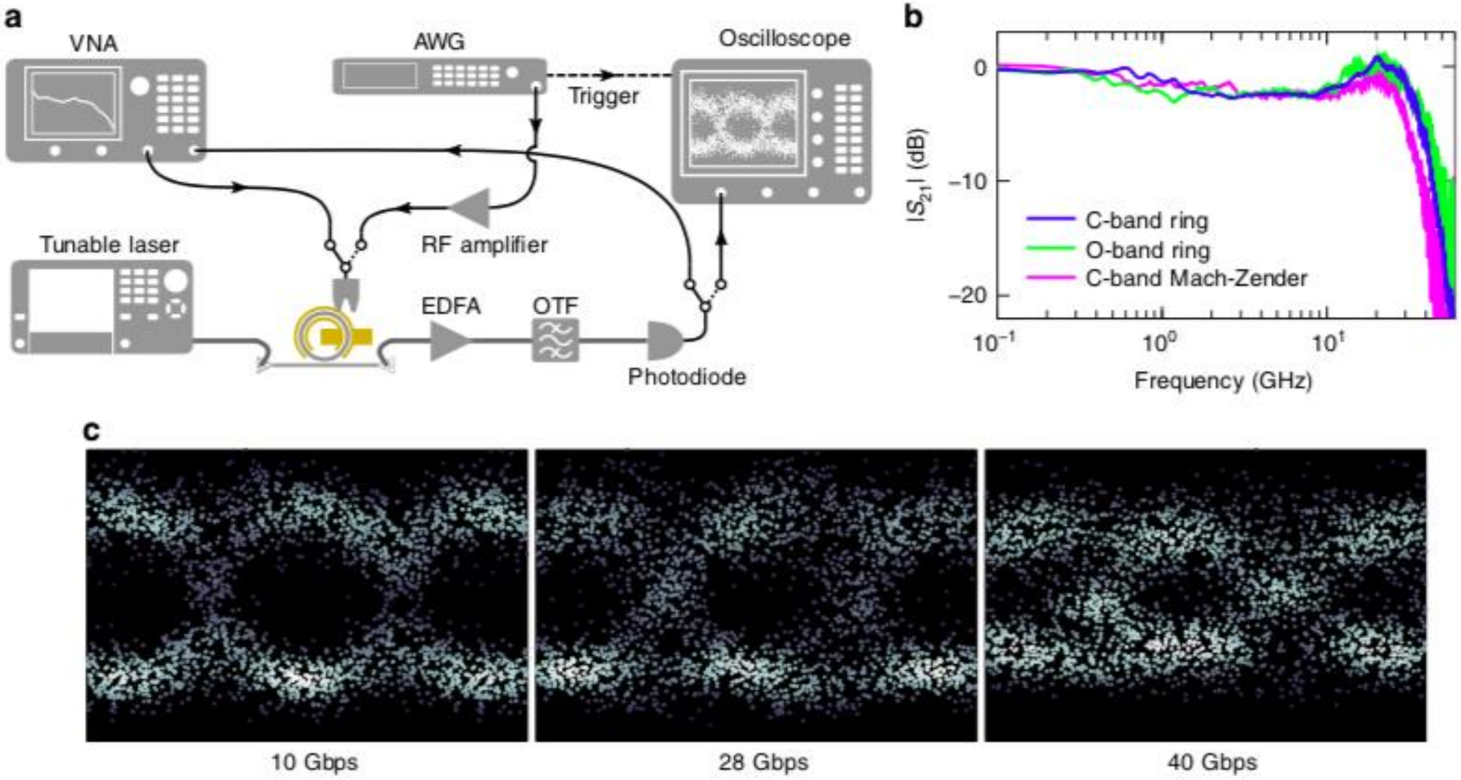




$V_{\pi}L = 3.2$ V.cm - $\alpha \approx 1$ dB cm^{-1}

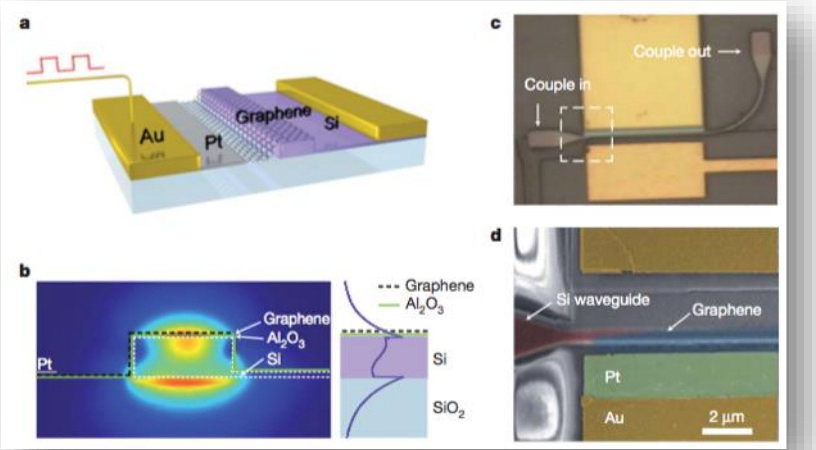
PZT On Silicon Nitride

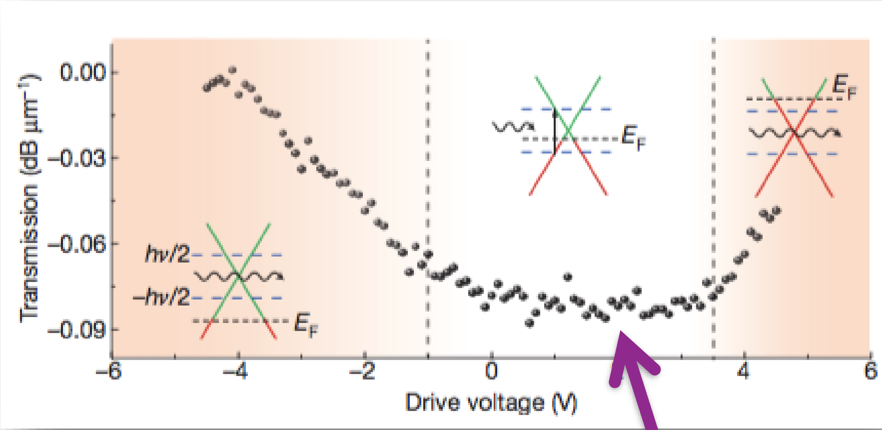
$V_{\pi}L = 3.2$ V.cm - $\alpha \approx 1$ dB cm^{-1} – BW = 33GHz



Graphene based modulators

- Shifting graphene's Fermi level changes its absorption (and refr. index)
- The effect is broadband and intrinsically very fast



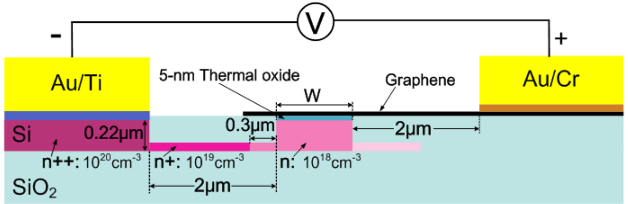


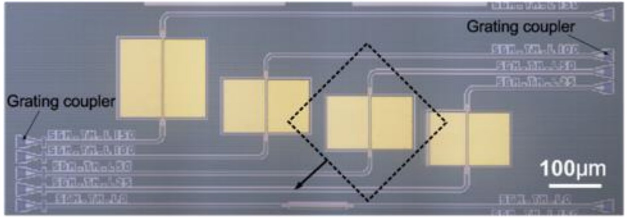
Also:
- Operation from 1300nm to 1600nm
- 1.2GHz 3dB BW

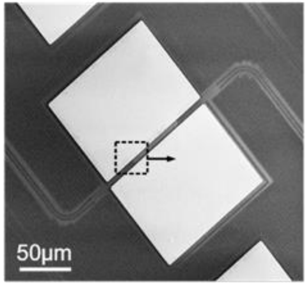
~0.1dB/µm

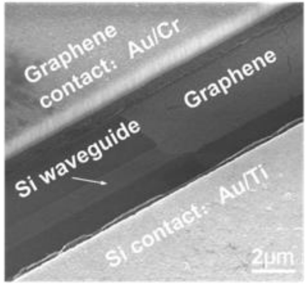
Liu e.a., Nature 2011

Graphene Based modulators









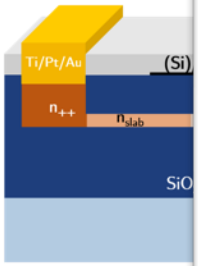
(Eye Diagrams measured at 1560nm. 2.5Vpp and 1.75V bias)

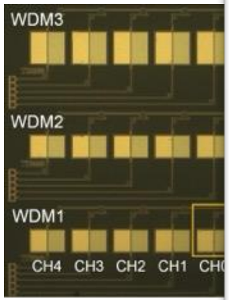
- First demonstration high quality eye diagrams from graphene modulator
- Bit Rates from 6GB/s to 10GB/s
- Dynamic ER > 2.6dB, low jitter
- Signal-to-Noise ratio beyond SNR=7

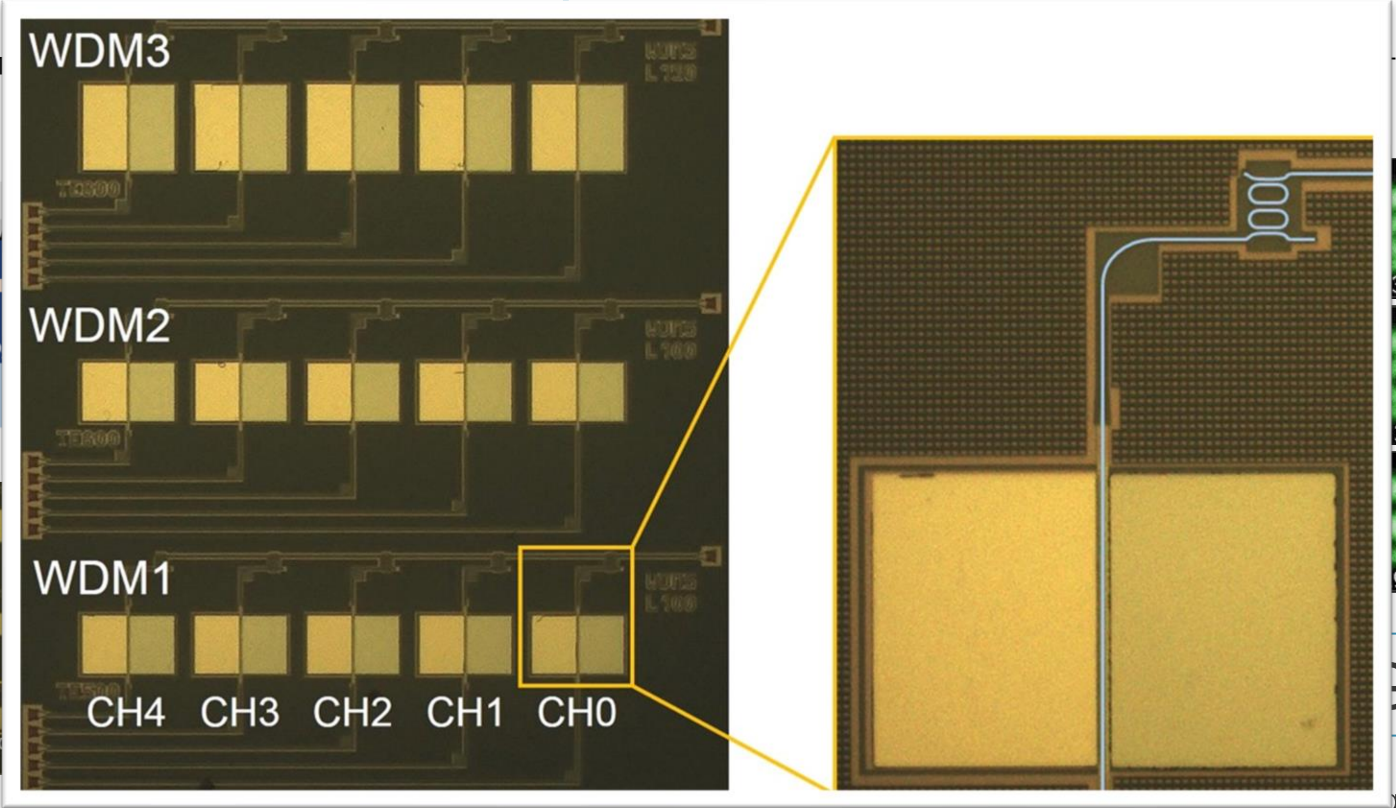
IEDM 2014, Y. Hu et al.

WDM Transmitters with n-doped Si EAMs

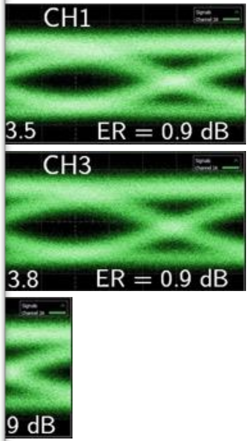
CROSS SECT



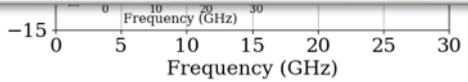




ERISATION



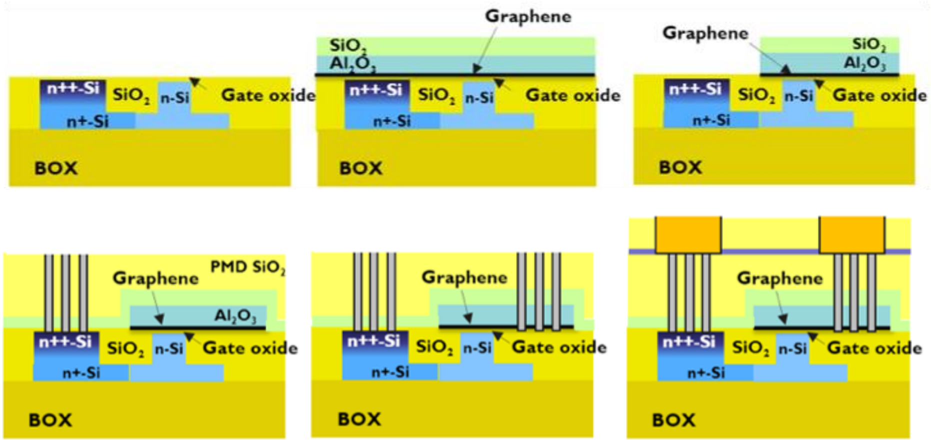
Gbit/s

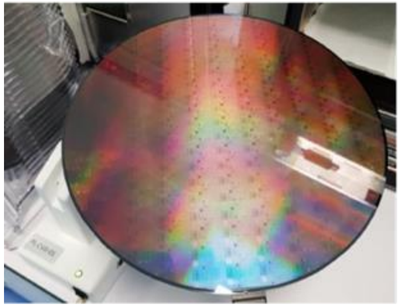


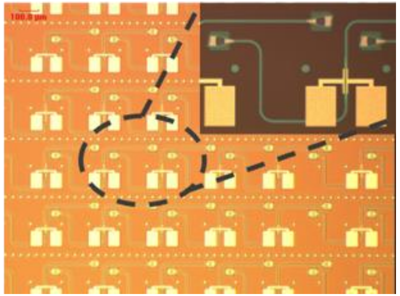
- Reproducible static and high-speed measurements on all 15 graphene EAMs
- Three WDM transmitters at 5 x 25 Gbit/s

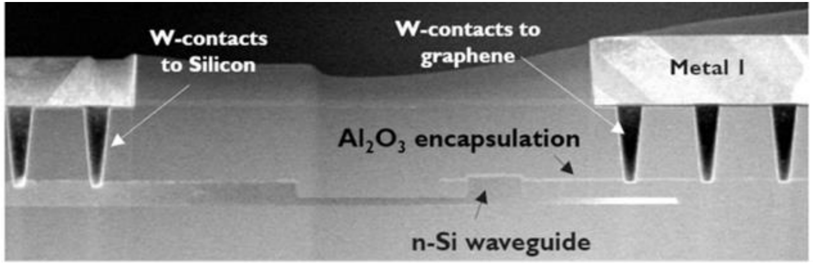
C. Alessandri e.a, Applied Optics, 2020, 59(4)

Wafer-scale Graphene EAM

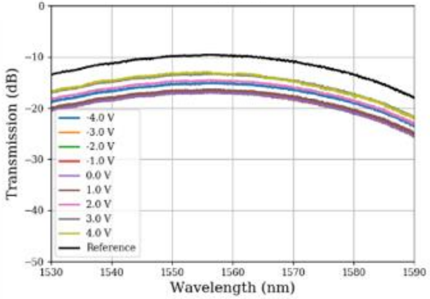




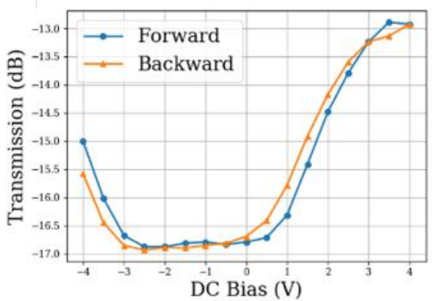




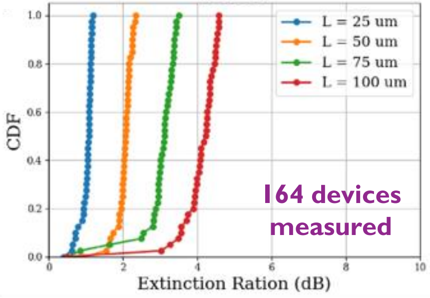
Transmission



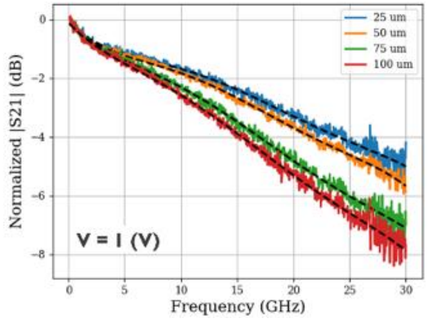
Transmission modulation



Cumulative distribution function



S-parameter



Summary & Conclusion

- Silicon Photonics is booming
  - Widely used in telecom and datacom
  - New application rapidly emerging (biomedical sensing, environmental sensing, spectroscopy, artificial intelligence, quantum computing…
  - Available from major fabs all over the world
- Remaining challenges:
  - Waferscale integration of lasers, phase modulators …
  - Need for integration of new materials to enhance functionality

Acknowledgements


Photonics Research Group

PRG Team: Profs. Baets, Roelkens, Kuyken, Bogaerts, Bienstman, Le Thomas, Clemmen, Morthier
Ugent LCP Prof. Beeckman
IMEC: Joris Van Campenhout, Marianna Pantouvaki, Cedric Huyghebaert, Inge Asselberghs, Bernardette Kunert and their respective teams

Spice

ACT PHAST

HOT

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