GHENT UNIVERSITY

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

September 2nd, 2024

III-V Photodetectors Monolithically Integrated on Silicon for Interconnect Applications

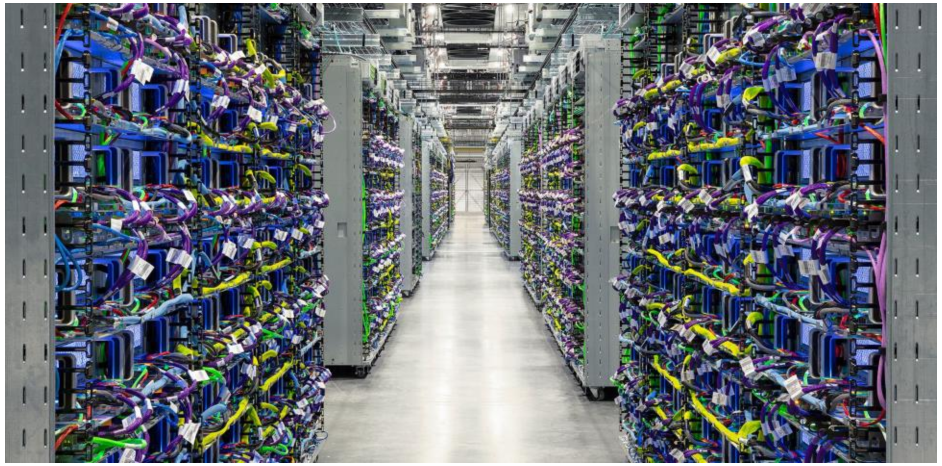
Ph.D. Public Defense

Cenk Ibrahim Özdemir

imec

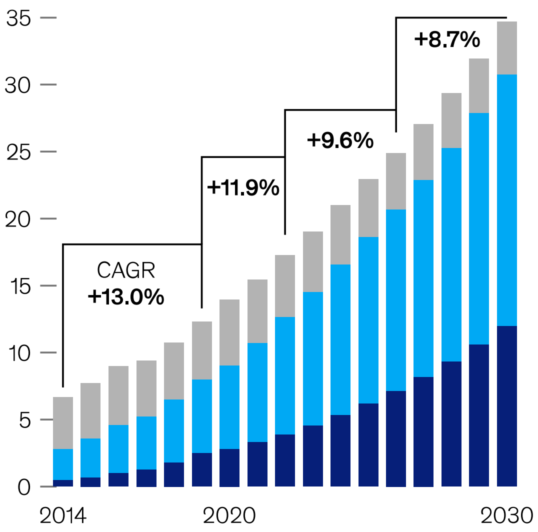
New Trends

- Information age is evolving beyond communicating and computing the information, but also <u>generating</u> the information now
- Most of these happens at data centers
  - Adding more resources quantitatively to keep up with the demand
  - Yet all components operating at high speeds need to connect somehow
- **Most of the connectivity ('interconnect') happens on optical domain**
- **Optical connectivity solutions will follow this growth trend and are needed to be cost-/power-efficient, while offering higher speeds**

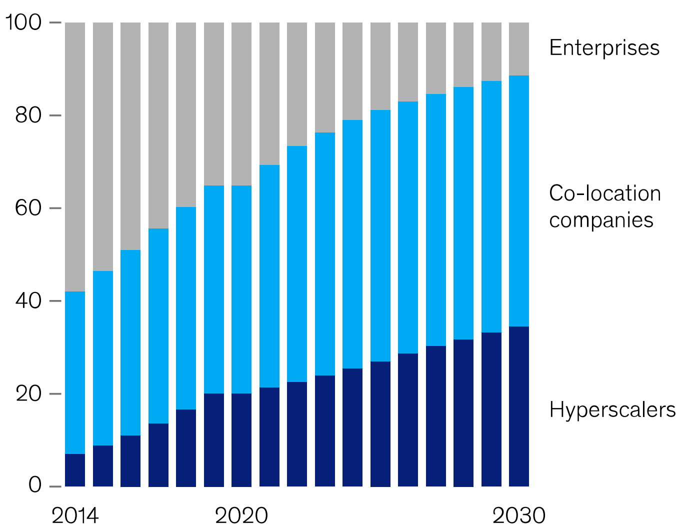


Google

Data center power consumption, by providers/enterprises,[1] gigawatts



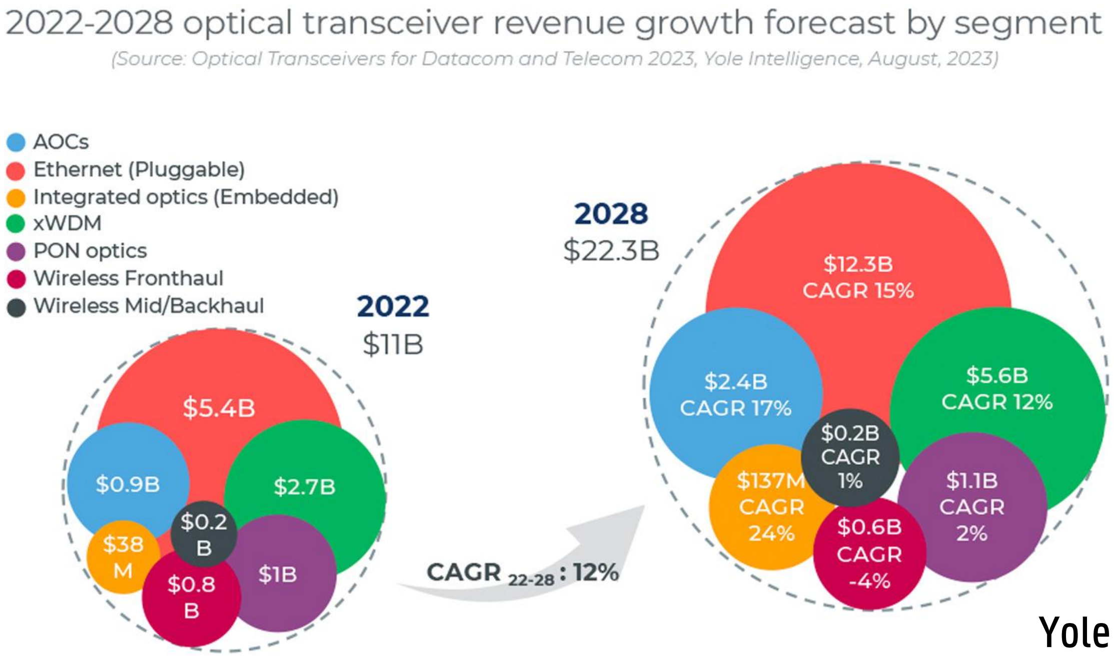
Data center power consumption, by providers/enterprises,[1] % share



[1]Demand is measured by power consumption to reflect the number of servers a data center can house. Demand includes megawatts for storage, servers, and networks.

McKinsey

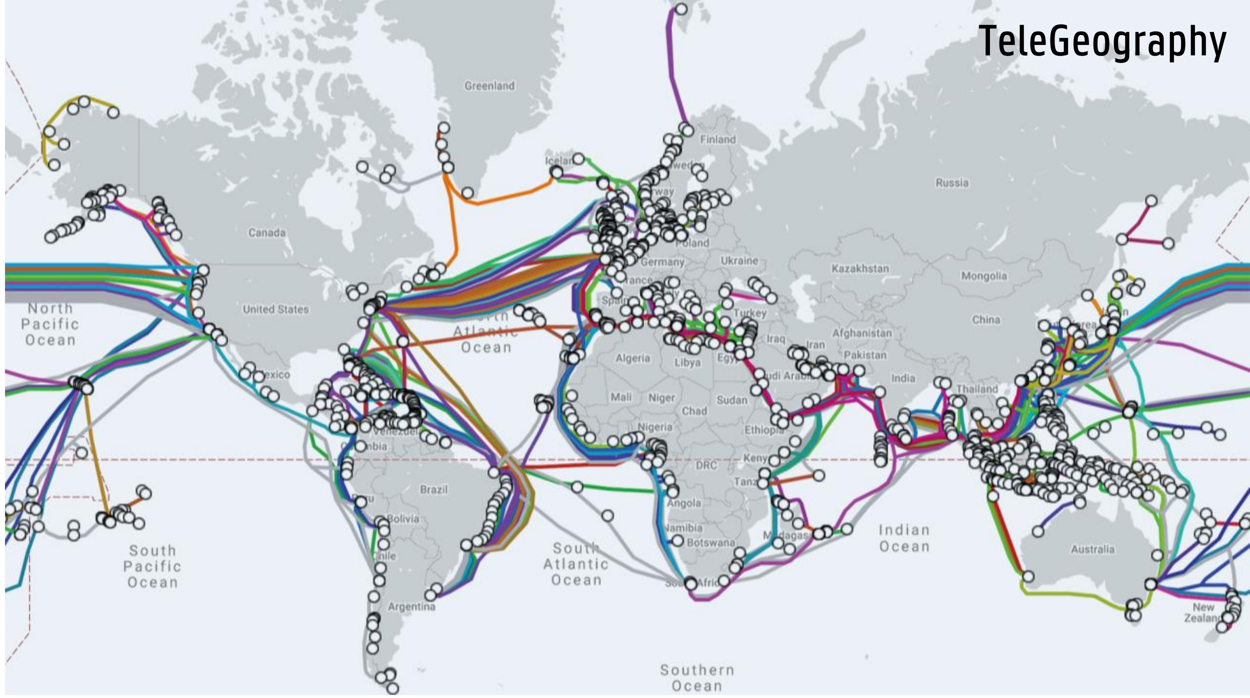
McKinsey & Company



Yole

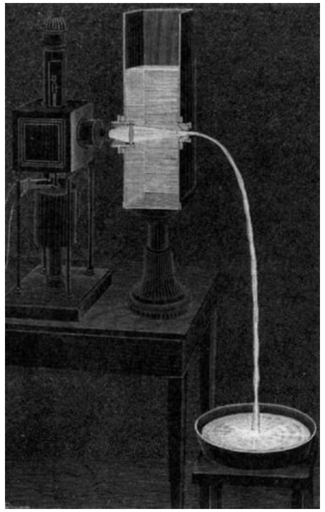
Optical communications

- Light confinement in high index materials, e.g. glass fibers
- Enabled optical transport, fiber optic networks all around the globe
- Recently optical communication is also used in free space (Starlink)

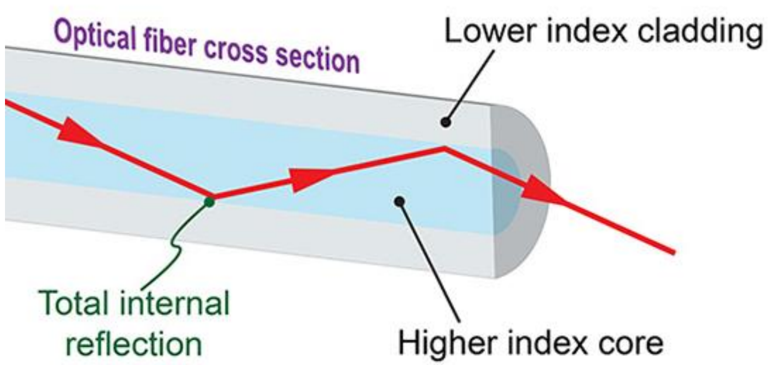


TeleGeography

Subsea and also on land!



D. Colladon, 1842, Paris



Coherent


PCMag

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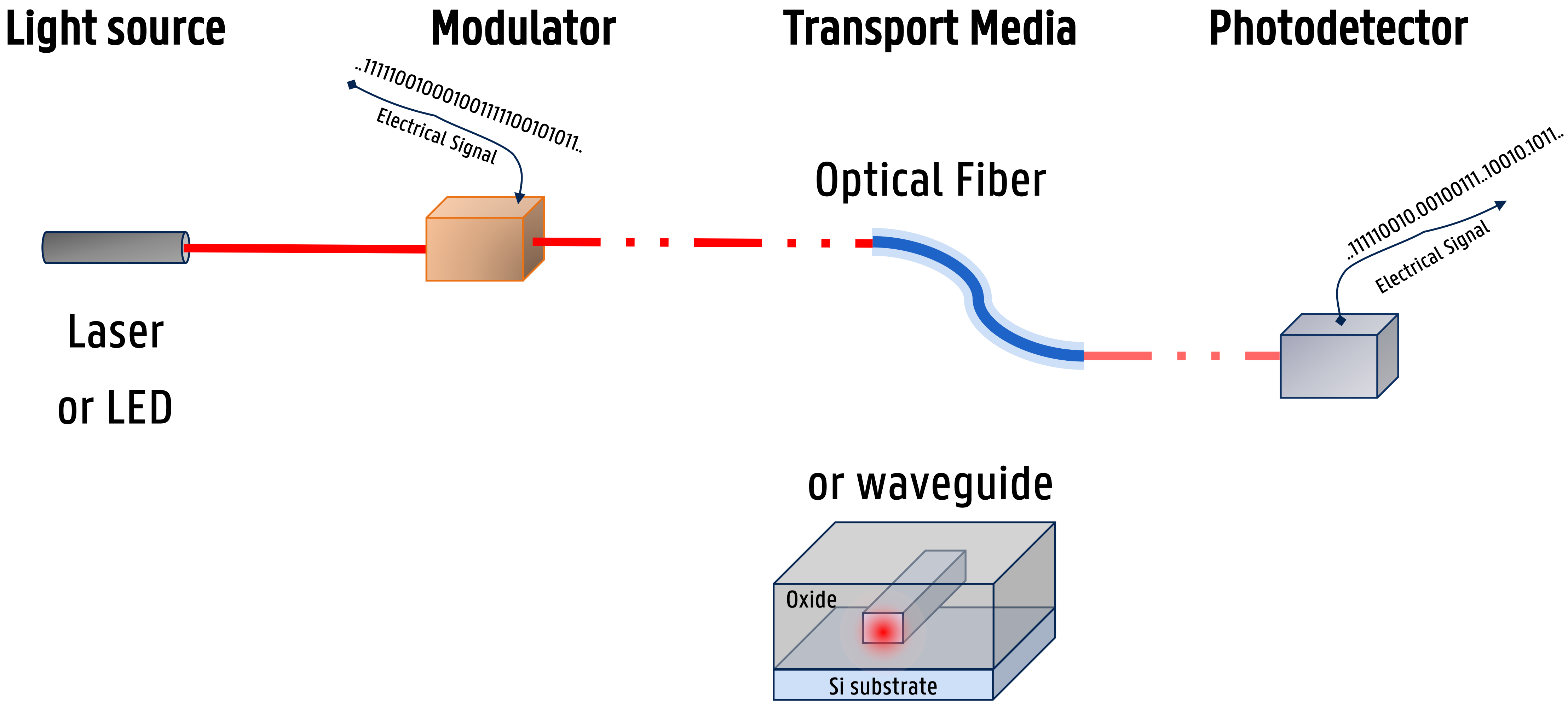
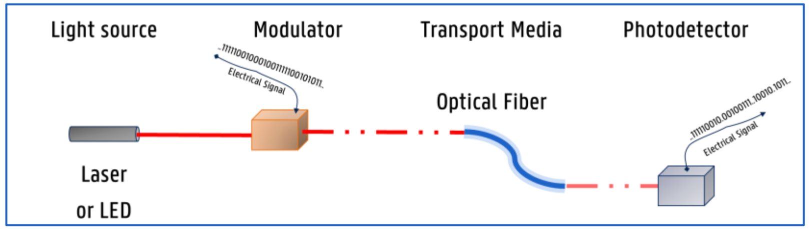
A simple optical link

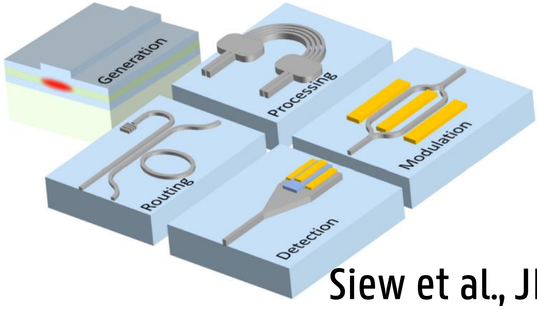


Photonic Integrated Circuits

Discrete Components

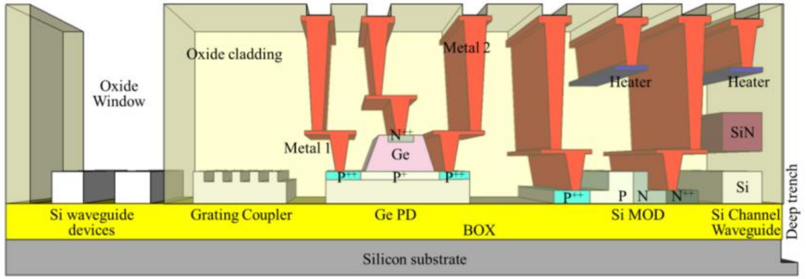


Integrated Components (on chip)



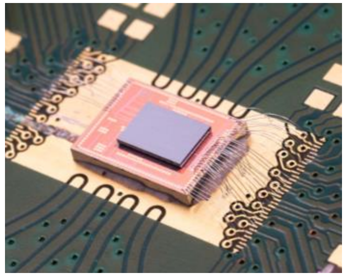
Siew et al., JLT, 2021

Photonic Integrated Circuit (PIC)



Siew et al., JLT, 2021

a PIC Chip



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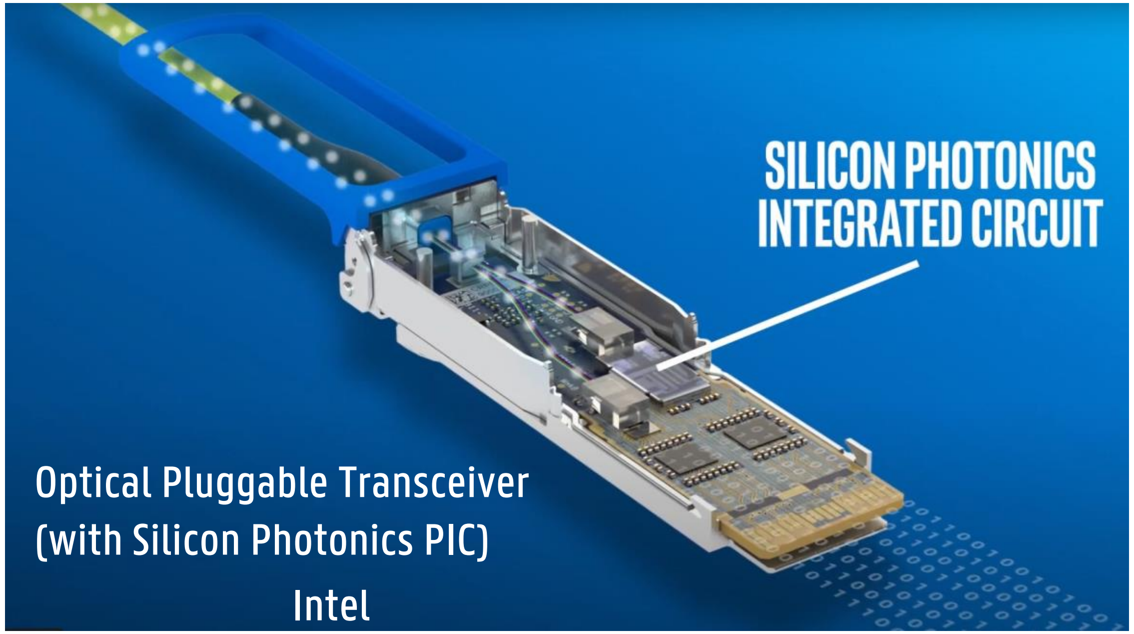
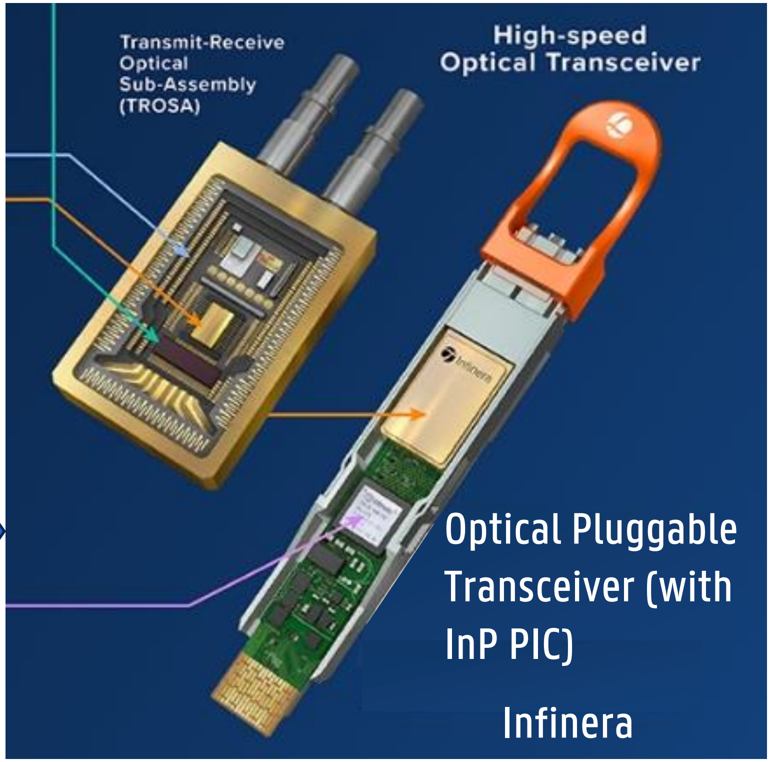


Optical Pluggable Transceiver (with Silicon Photonics PIC)

Intel



Optical Pluggable Transceiver (with InP PIC)

Infinera

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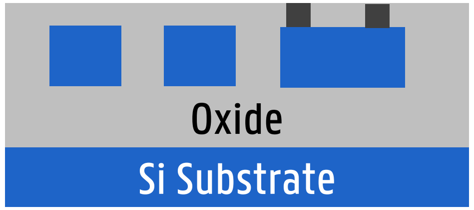
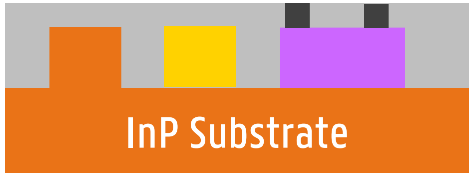
Two main material Platforms for PICs

Silicon is basis of everything in electronics, and (almost) in photonics, but we need III-V devices for photonics.



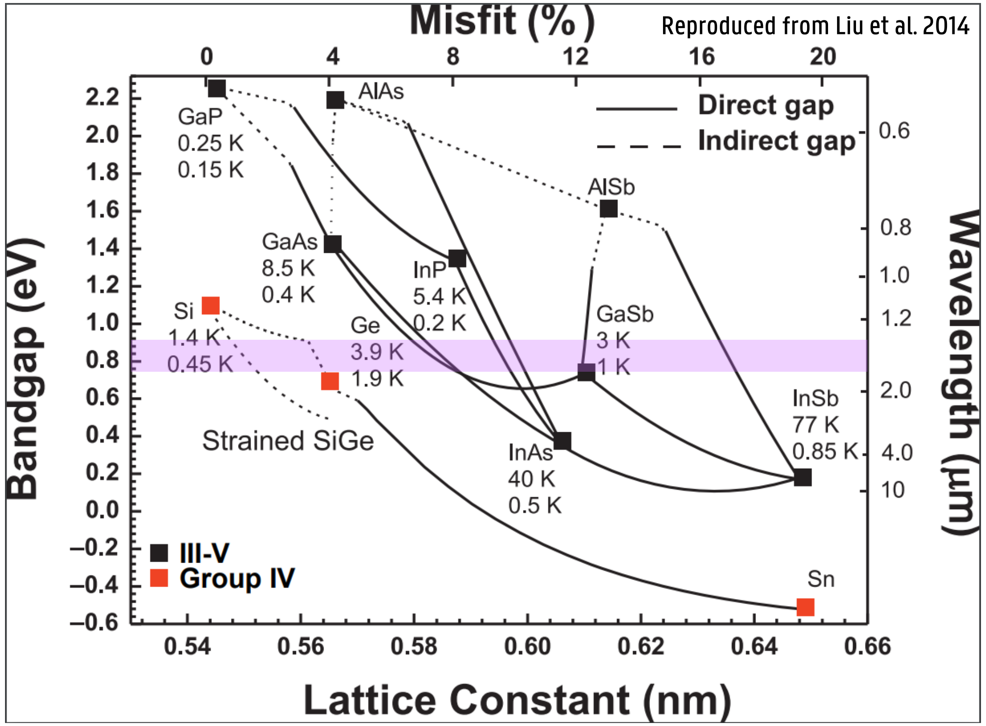
Different active devices

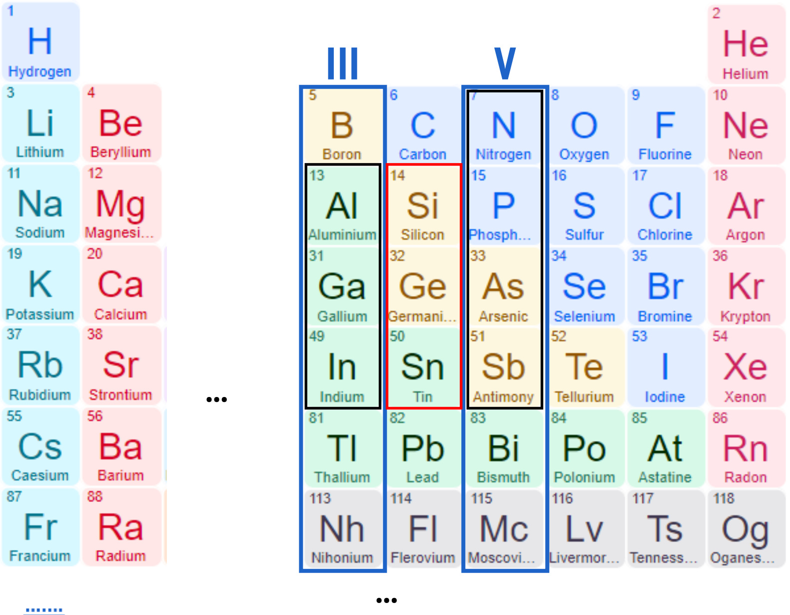


Capabilities	Silicon	III-V
Light Source (laser, LED, SOA)	Incapable – requires external components or materials	Capable
Modulators	Capable	Capable
Waveguides	Capable	Capable
Photodetectors (at telecom)	Incapable – requires external components or materials (Ge)	Capable
Circuit Complexity / Size	Very capable	Limited
Cost	Low	Moderate

III-V Compounds

- III and V group columns of periodic table
  - III-V compounds are combinations of elements on these columns (binary, ternary or quaternary)
- Why III-V in photonics?
  - Direct bandgap, can easily emit and detect light
  - Bandgap tunable with different combinations
    - Can work at telecom wavelengths defined by the minimum loss wavelengths of glass fibers





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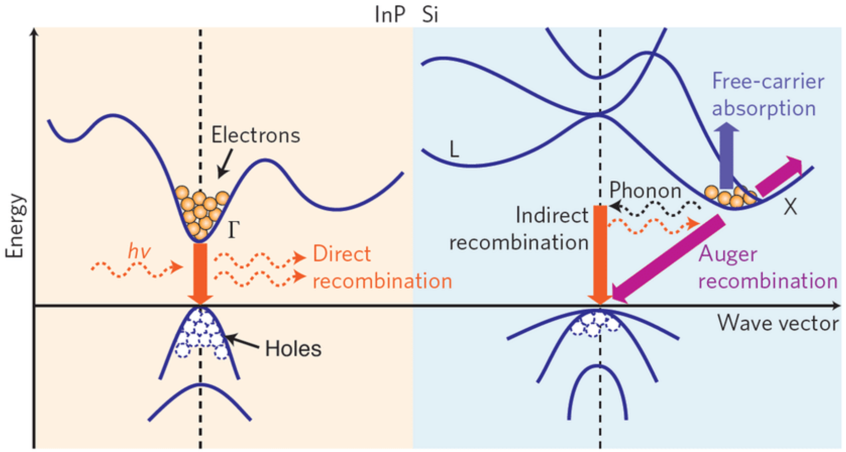
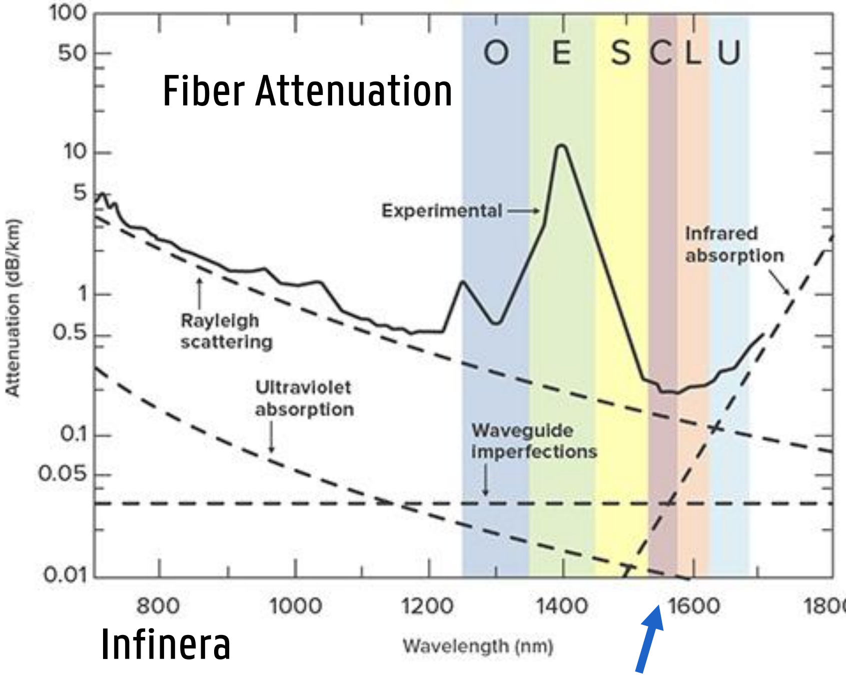


B. Romain, 2015



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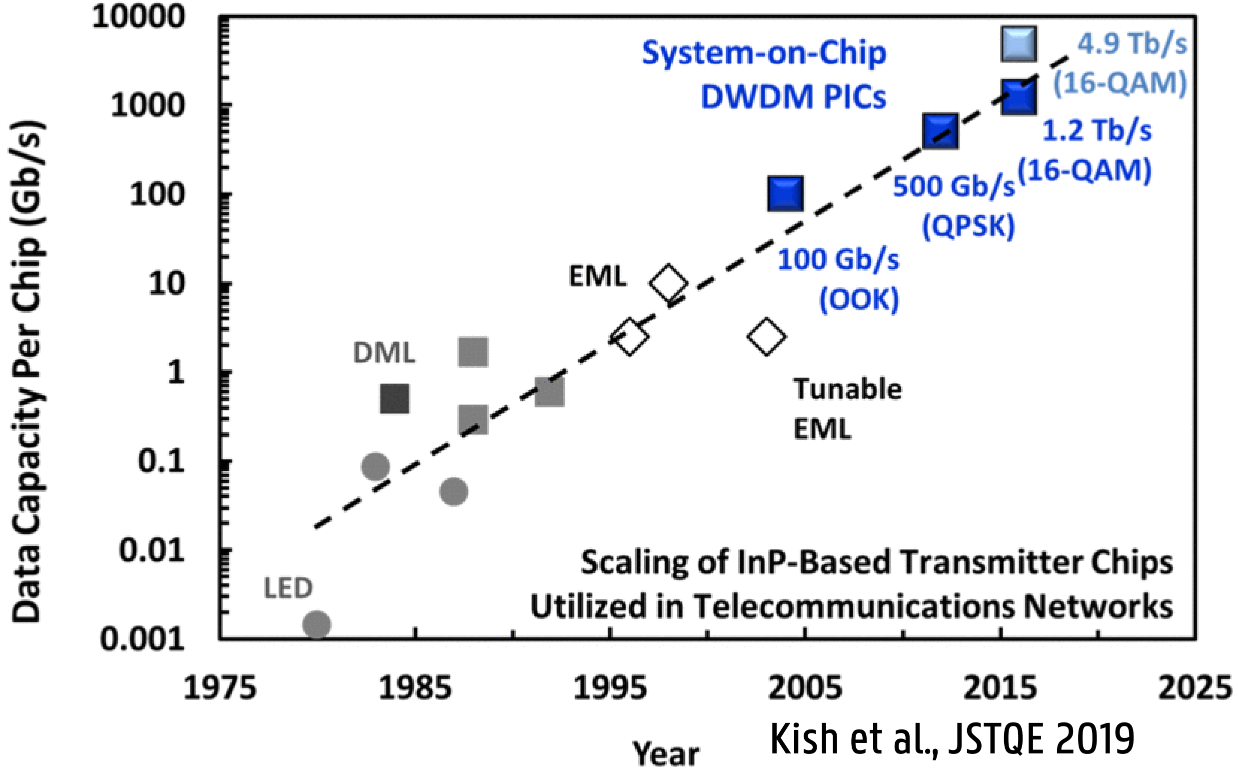
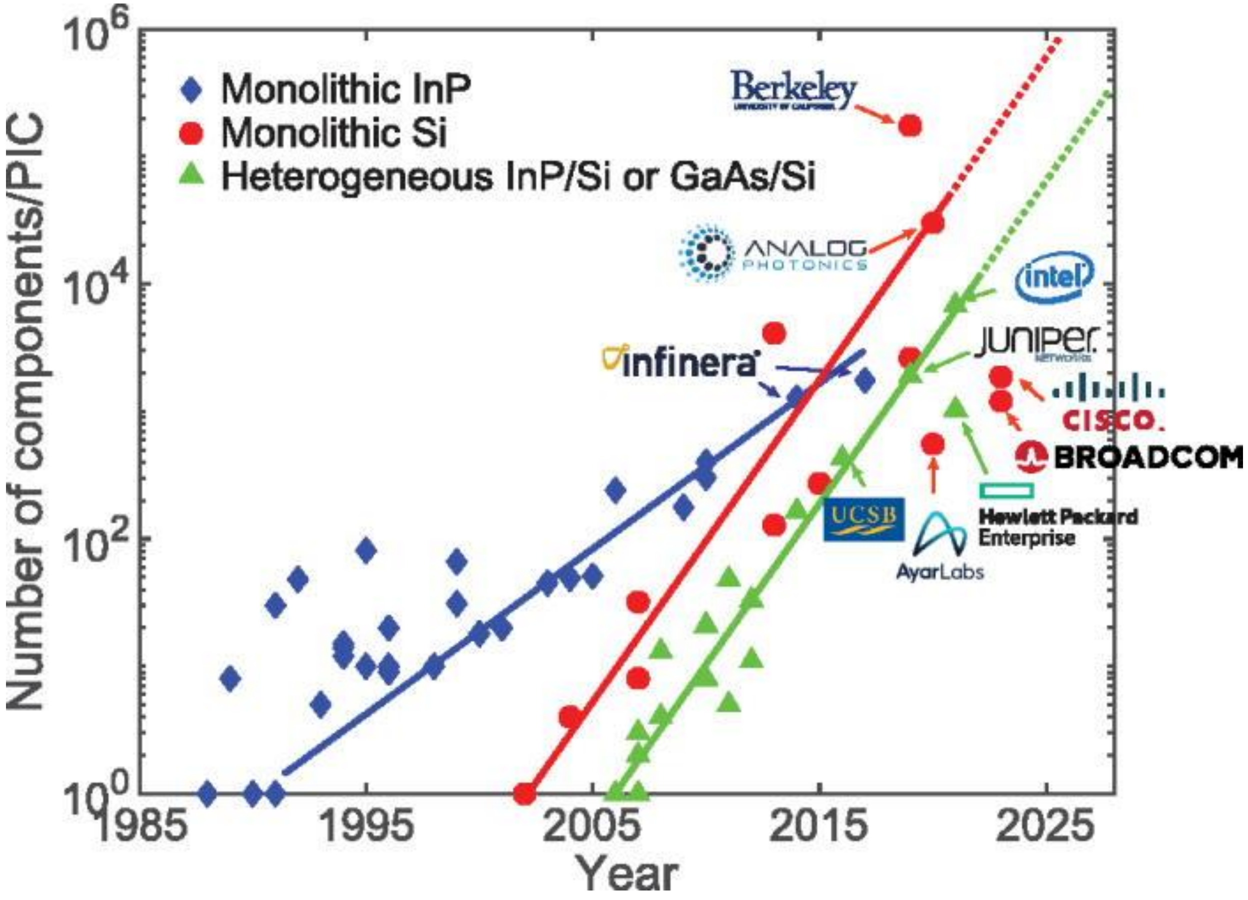
Integrated Photonics Evolution

Started with III-V based components and PICs …

… Later Si photonics era emerged



Kish et al., JSTQE 2019



Margalit et al., Appl. Phys. Lett. 2021

DML Directly-modulated laser
EML Externally-modulated laser
DWDM dense wavelength division multiplexing
OOK, QPSK, 16-QAM are different modulation formats

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III-V on Si

Capabilities	Silicon	Co-integration	III-V
Light Source (laser, LED, SOA)	Incapable – requires other components or materials	Capable	Capable
Modulators	Capable	Capable	Capable
Waveguides	Capable	Capable	Capable
Photodetectors (at telecom)	Incapable – requires other components or materials (Ge)	Capable	Capable
Circuit Complexity / Size	Very capable	Very capable	Limited
Cost	Low	Low	Moderate

Missing capabilities in Silicon Photonics can be overcome by introducing additional material systems:

- III-V materials for light modulation and detection, also generation

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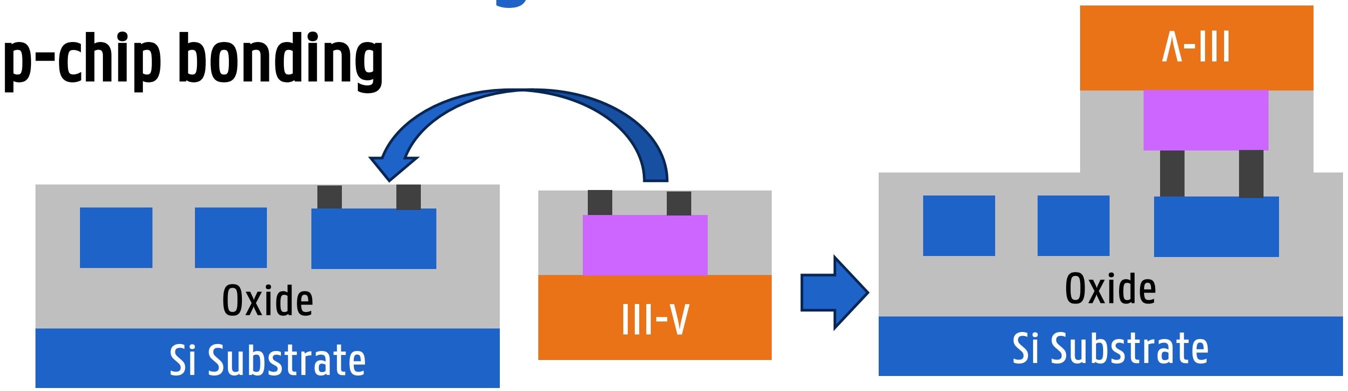
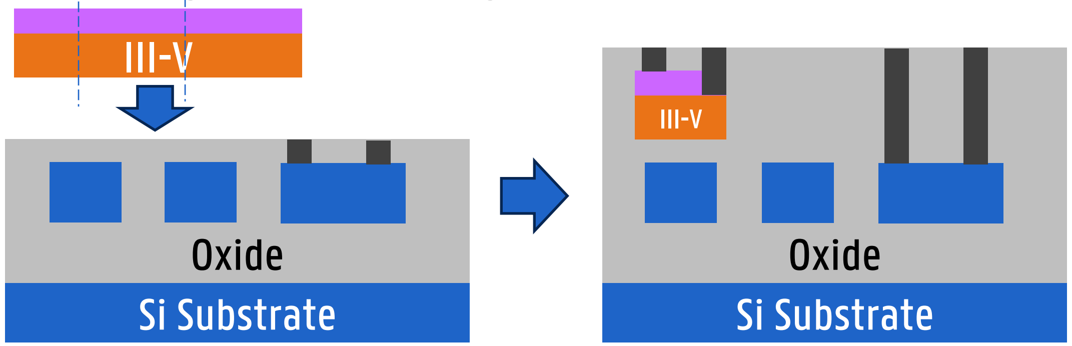
III-V on Si Integration Methods

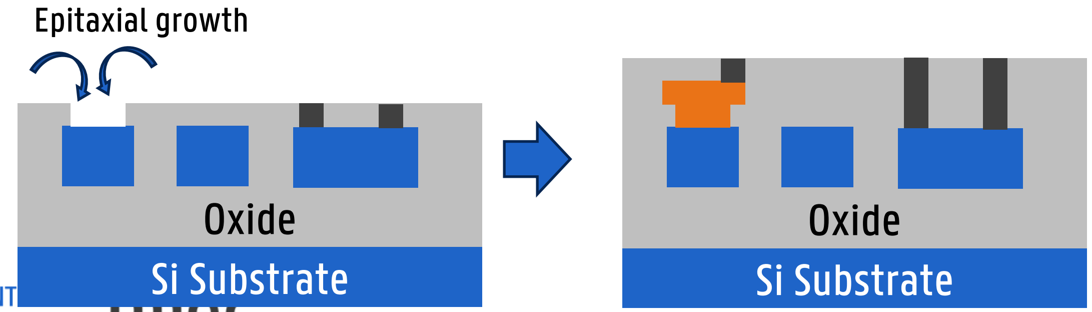
Flip-chip bonding



Heterogenous integration



Monolithic integration



Capabilities	Flip-chip	Heterogenous	Monolithic
Throughput	Low	Low-Moderate	High
Cost	High	High	Low-Moderate
Yield	Moderate	Moderate	Moderate-High

Monolithic integration of III-V on Si can offer the highest production throughput and lowest cost

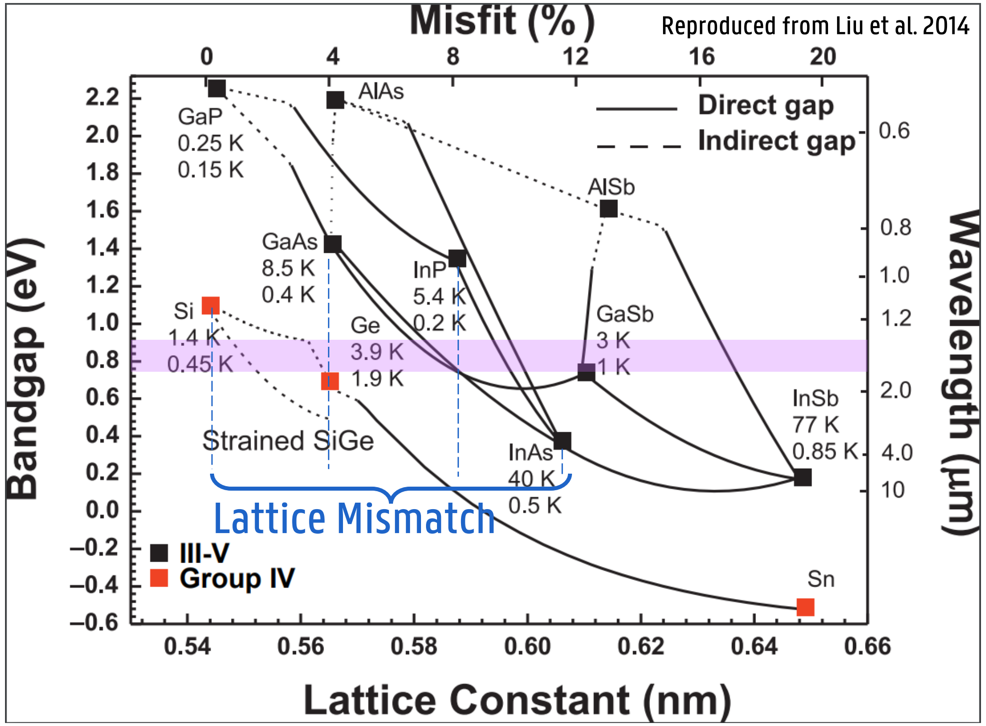
Monolithic III-V on Si

Difficult to grow III-V on Si with high crystal quality due to mismatch in lattice constant & thermal expansion coefficient (CTE), and polarity

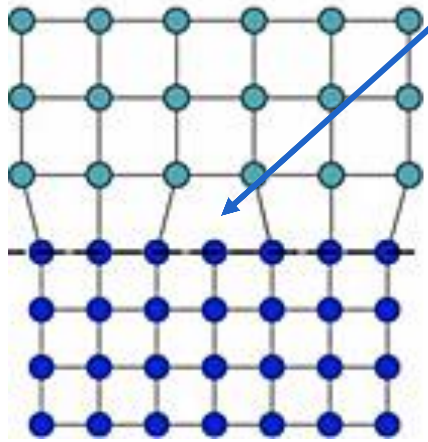
<u>Lattice constant mismatch</u>: Crystal configuration (atom spacing) is different and higher for most of III-V compounds than Si

<u>CTE</u>: Si and III-V compounds expand/contract differently

<u>Polarity</u>: Si is non-polar, while III-V is polar



Misfit Defect



Wanlass et al., 2004

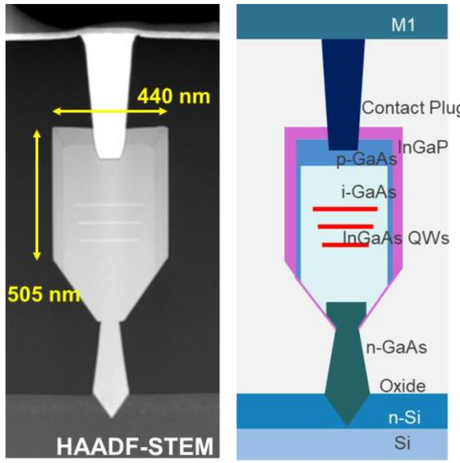
Objectives

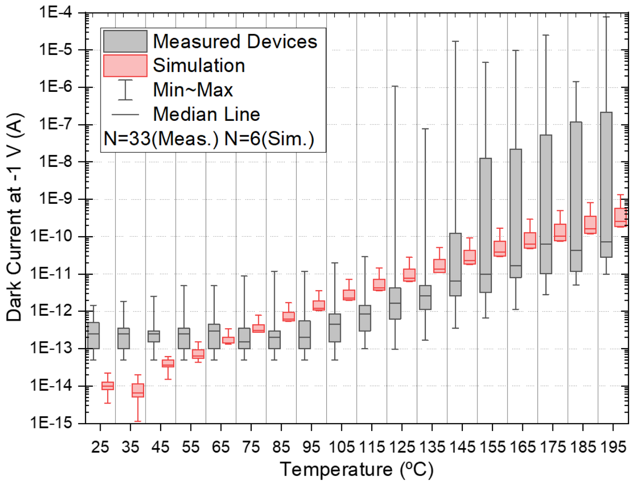
The objective of this thesis was to enhance the capabilities of silicon photonics platforms by integrating active III-V devices.

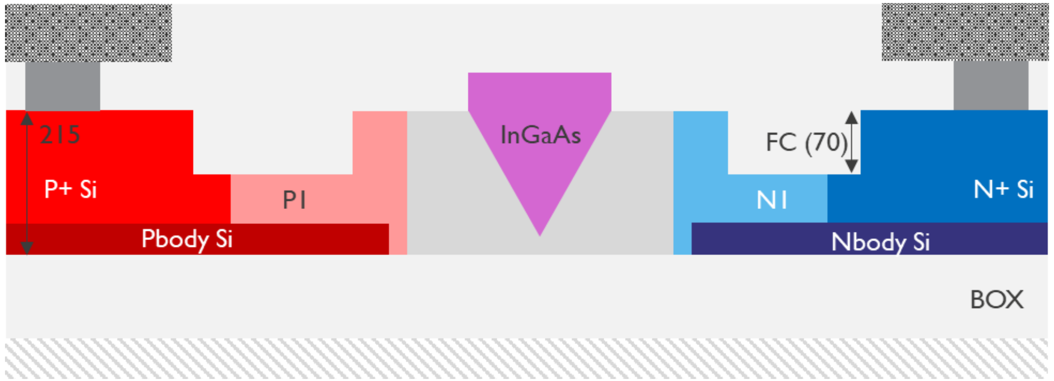
- Monolithic Integration of nano-ridge waveguide devices
  - Co-design and co-integration of photodetectors (NRWPD) with GaAs NR lasers
- Assessment of the quality of the grown NRWPD material via extracting various leakage mechanisms through elevated temperature studies
- Experimenting selective area grown InGaAs on Si photonics platform to achieve modulation and photodetection capabilities directly on the same platform

… In this thesis:

1. Introduction
2. III-V on Si Nano-Ridge Photodetectors
    1. What is a nano-ridge? How does a nano-ridge work?
    2. How are nano-ridges made?
    3. How do they perform?
3. Leakage Mechanisms of Nano-Ridge Photodetectors
4. Wide-field grown III-V Photodetectors
5. Conclusions and Future







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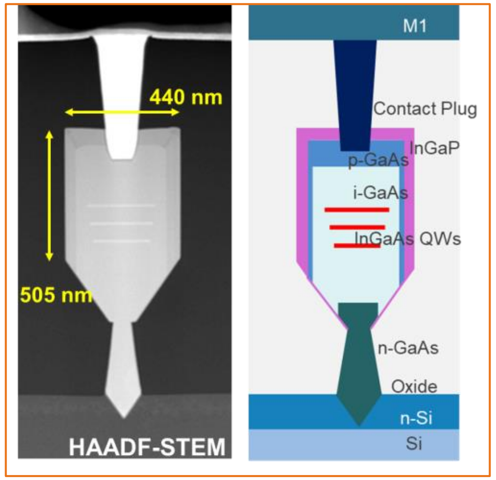
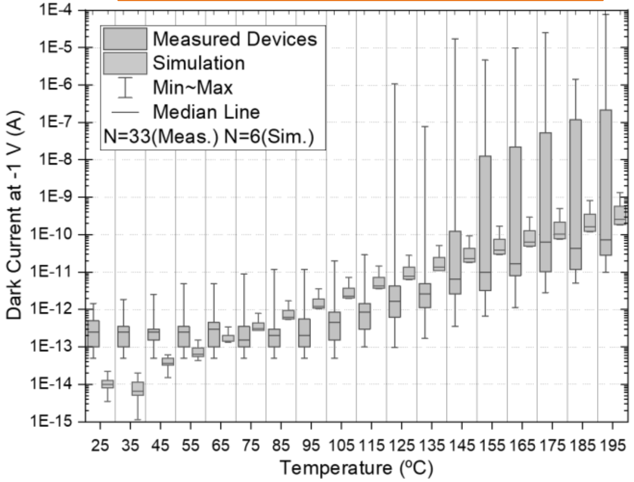
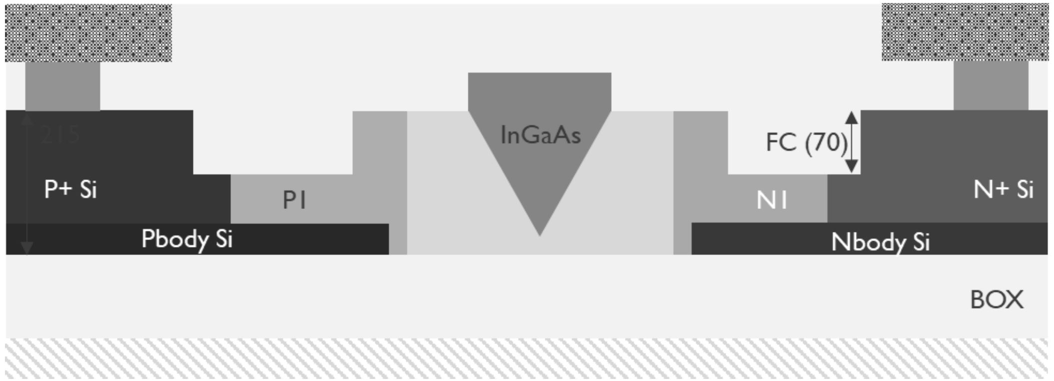
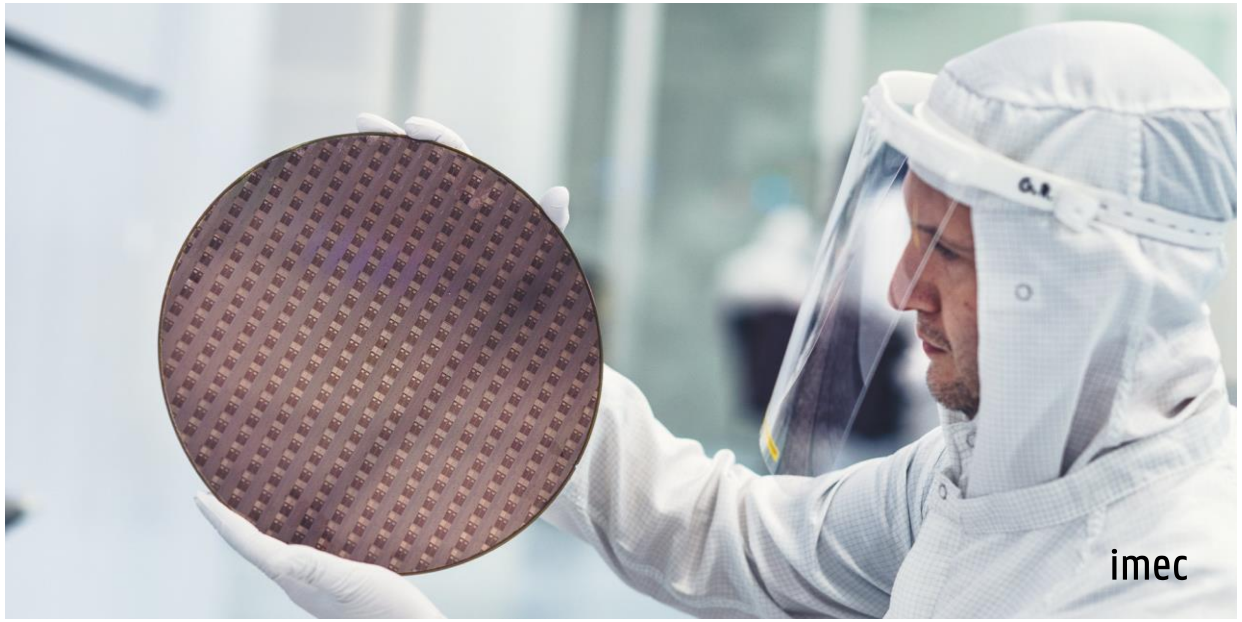


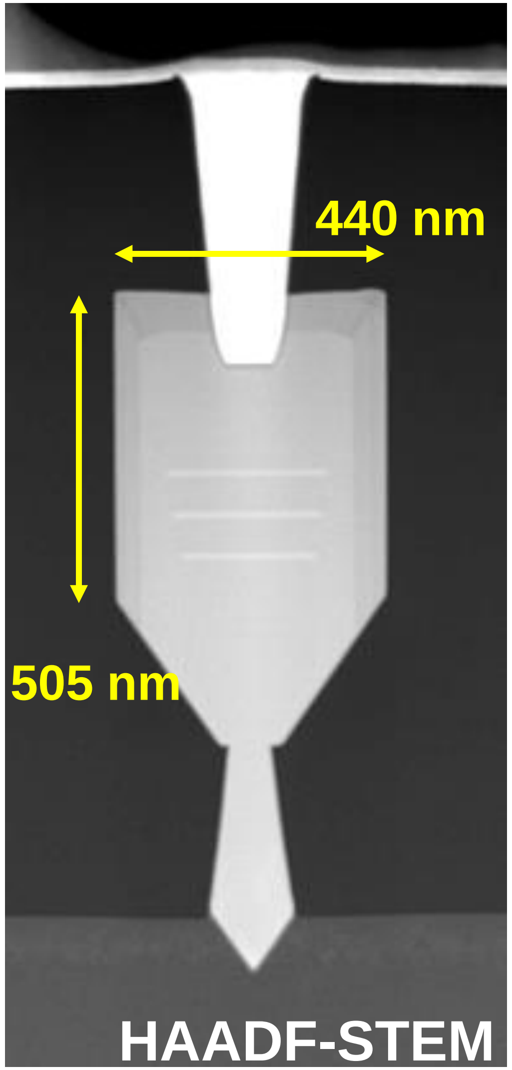


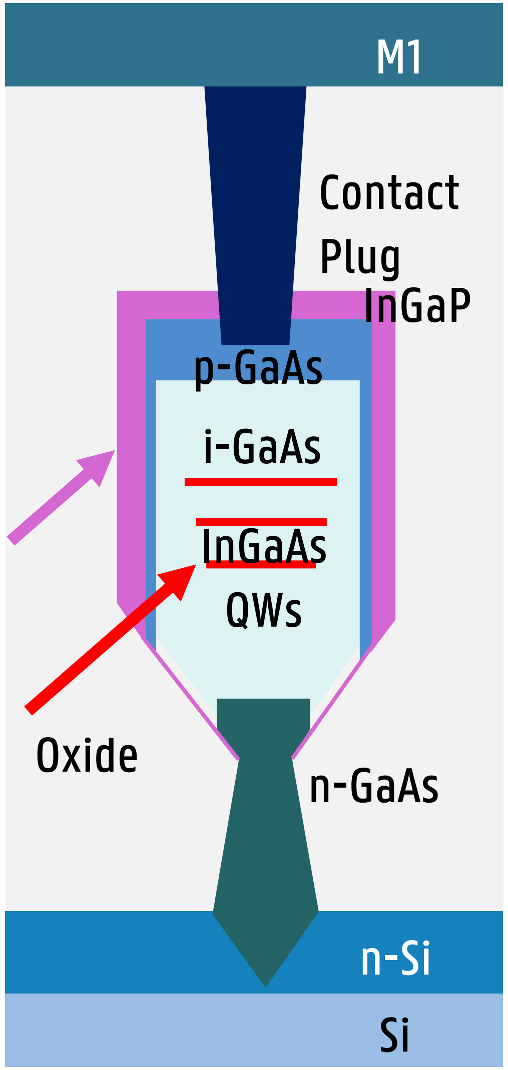


InGaAs/GaAs on Si Nano-ridge Waveguide Photodetector (NRWPD)

- By applying ART and NRE methods, p-i-n InGaAs/GaAs diode is grown on a 300-mm standard Si wafer
- Three InGaAs quantum wells embedded in i-GaAs, as active material, with ~22% In composition
- Nano-ridge is capped with InGaP for passivation, with contacts plugs accessing p-GaAs

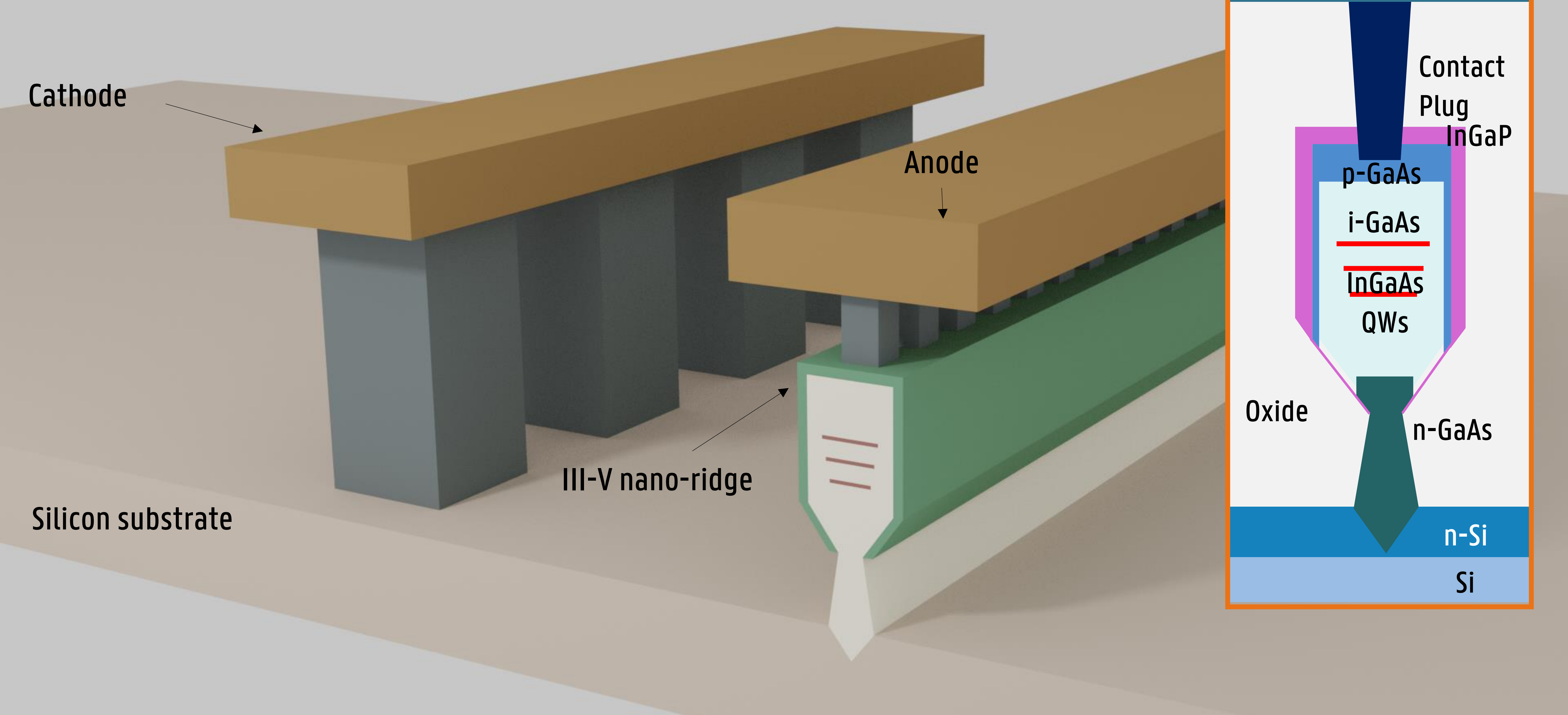




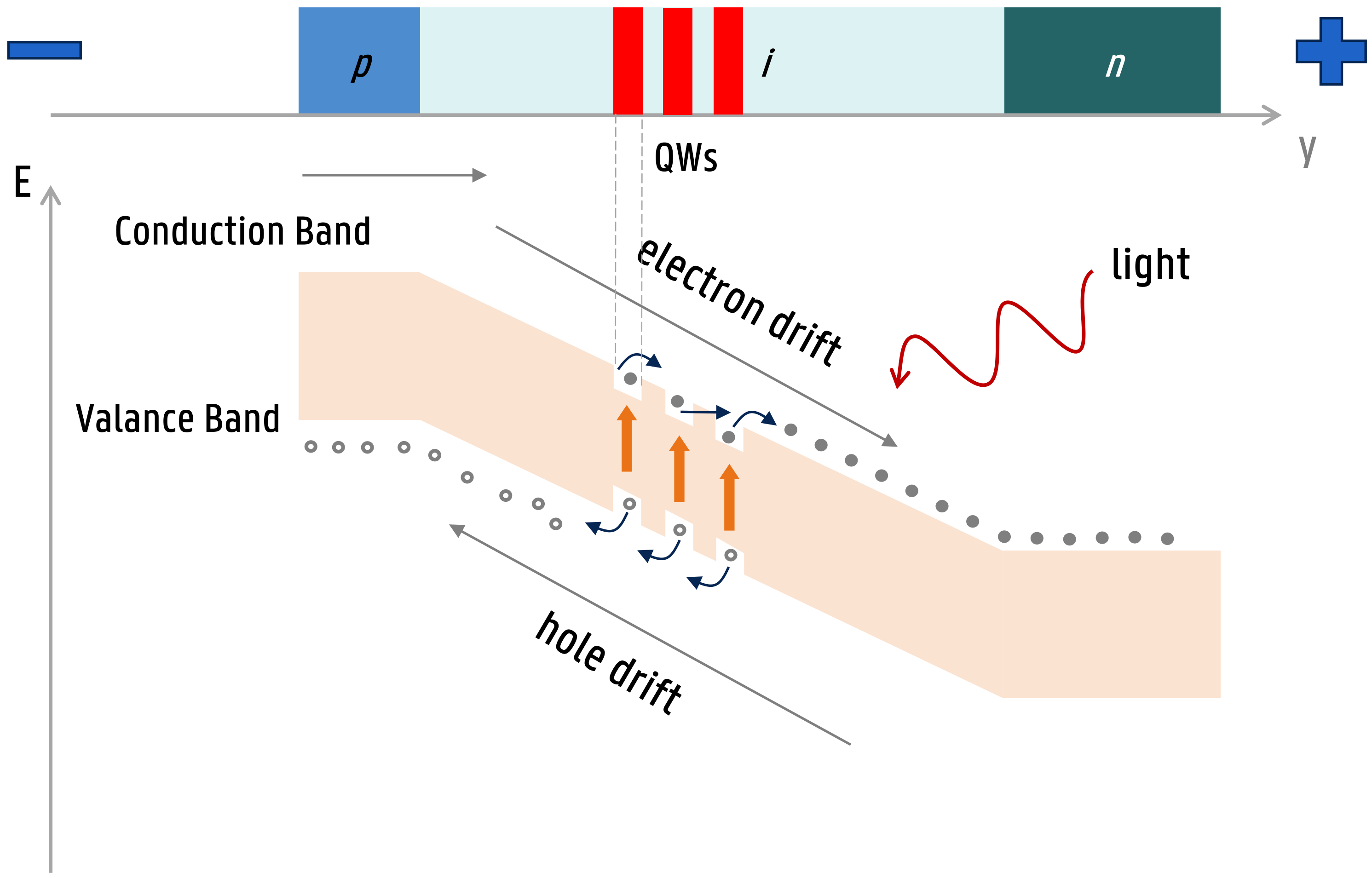


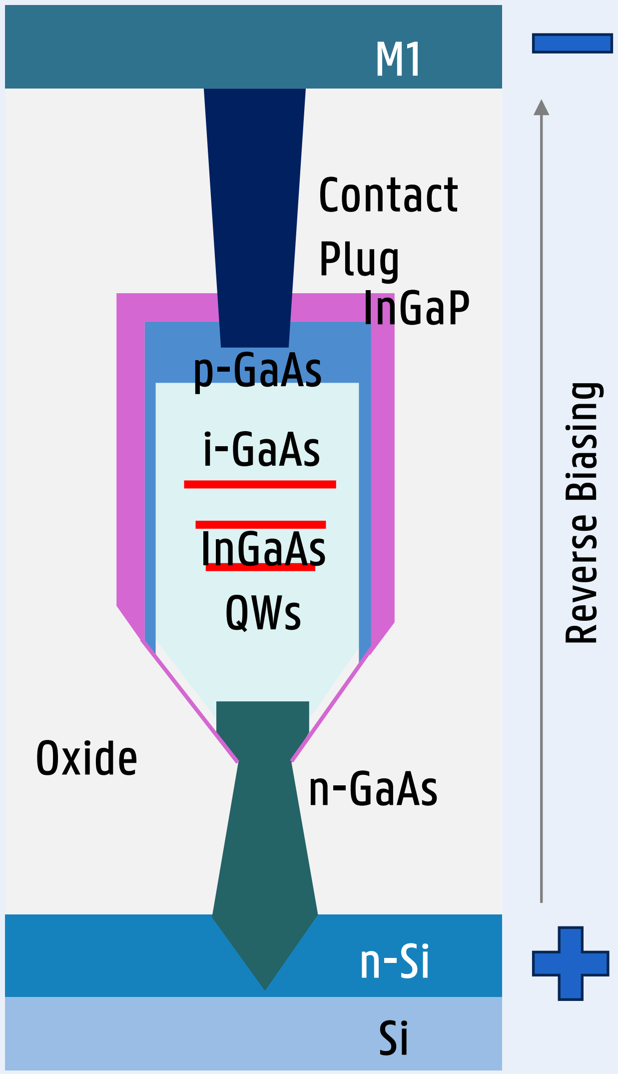
HAADF-STEM: High-angle annular dark-field scanning transmission electron microscope

III-V on Si Nano-Ridge Photodetectors



GaAs PIN Photodiode with InGaAs Quantum Wells





○ Hole (+)
● Electron (-)

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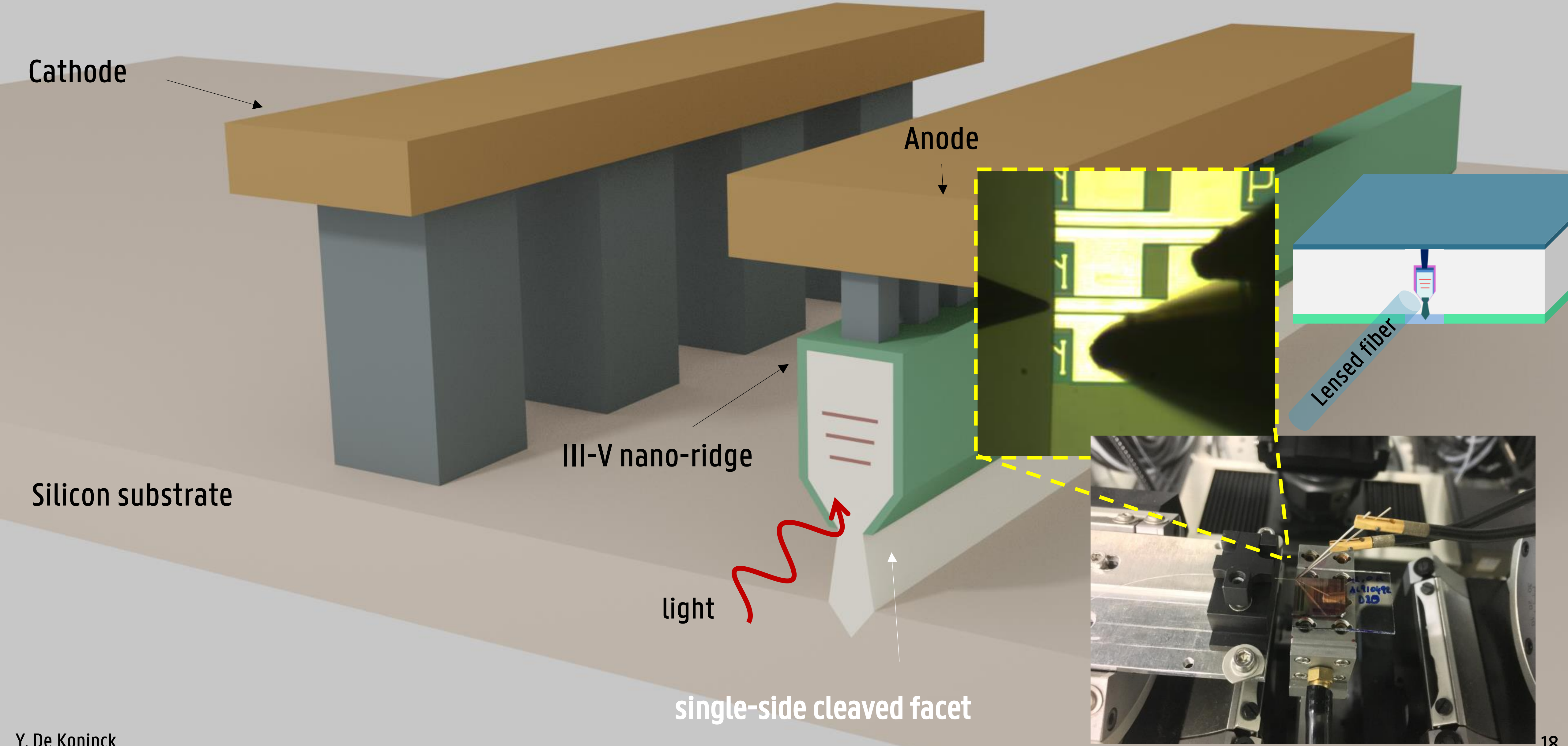
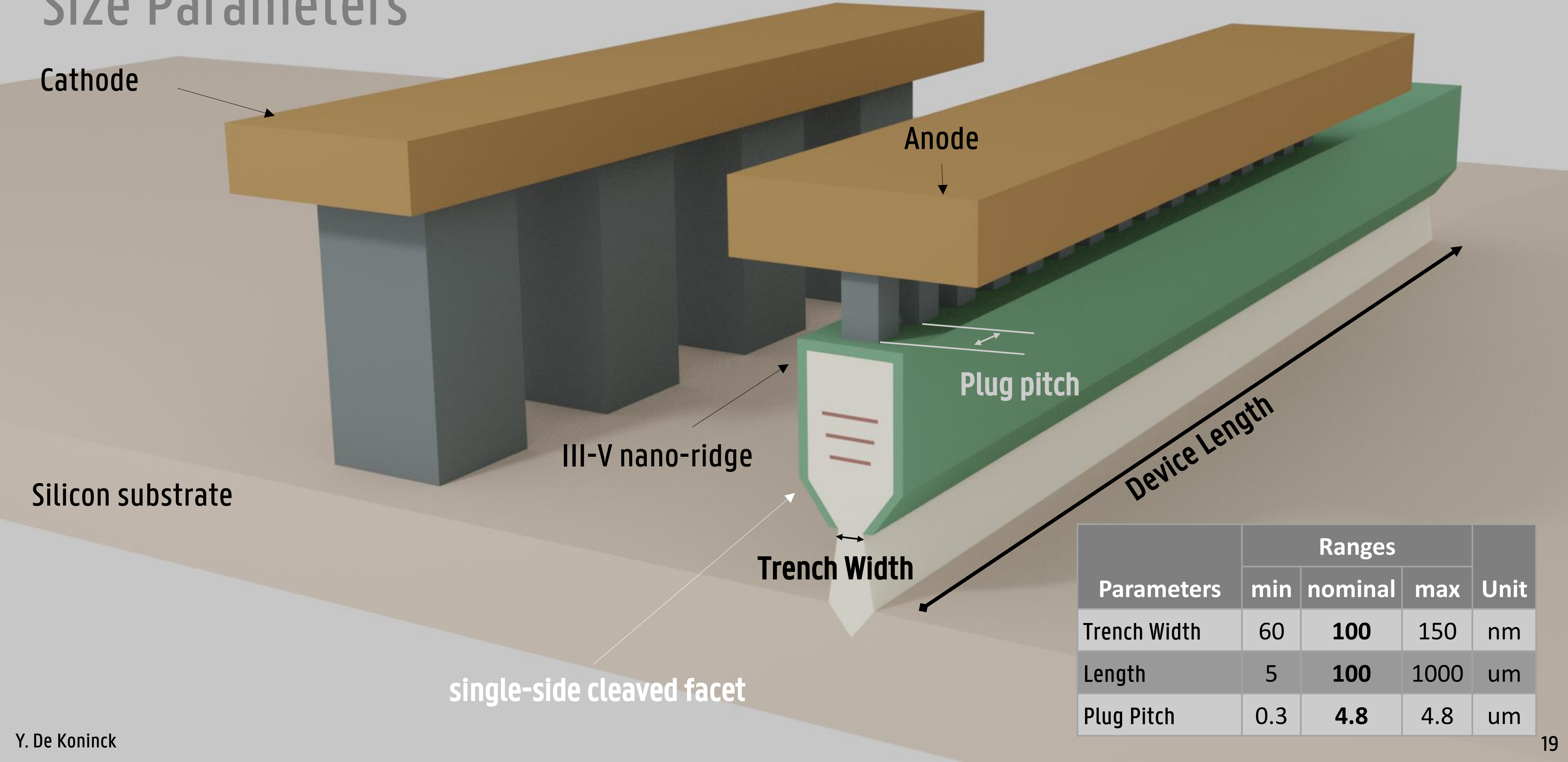
How will this work?



III-V on Si Nano-Ridge Waveguide Photodetectors

Size Parameters



Parameters	Ranges			Unit
	min	nominal	max	
Trench Width	60	**100**	150	nm
Length	5	**100**	1000	um
Plug Pitch	0.3	**4.8**	4.8	um

Aspect Ratio Trapping (ART)

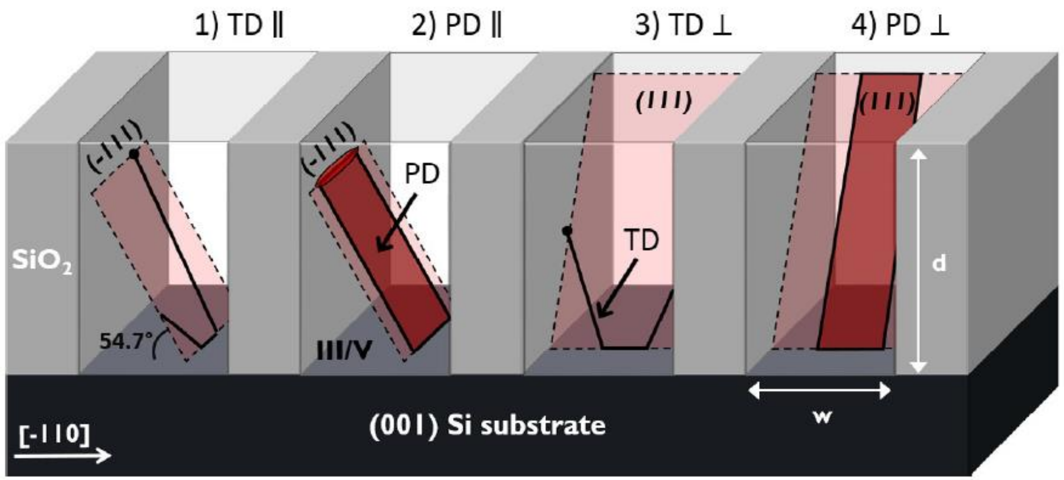
ART enables:

- Trapping threading (TD) dislocations parallel and perpendicular to the trench axis (TD|| and TD⊥) (**cases 1 & 3**)
- Trapping planar defects on parallel {111} plane (**case 2**)

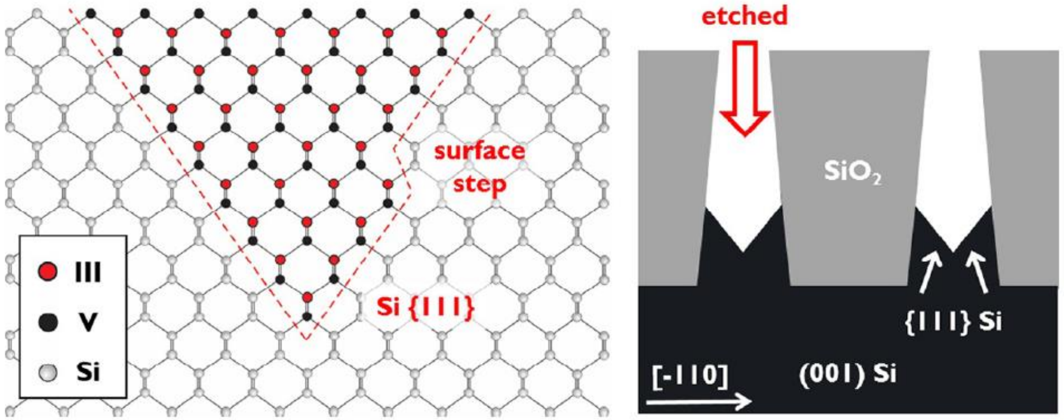
Formation of planar (PD) defects on perpendicular {111} plane are reduced via seed optimization, cleaning and surface pre-treatment (**case 4**)

Anti-phase domains are avoided by starting growth on {111} Si surface

Effective trapping depends on the aspect ratio (depth/width) and applied growth conditions



Van Thourhout et al., 2019



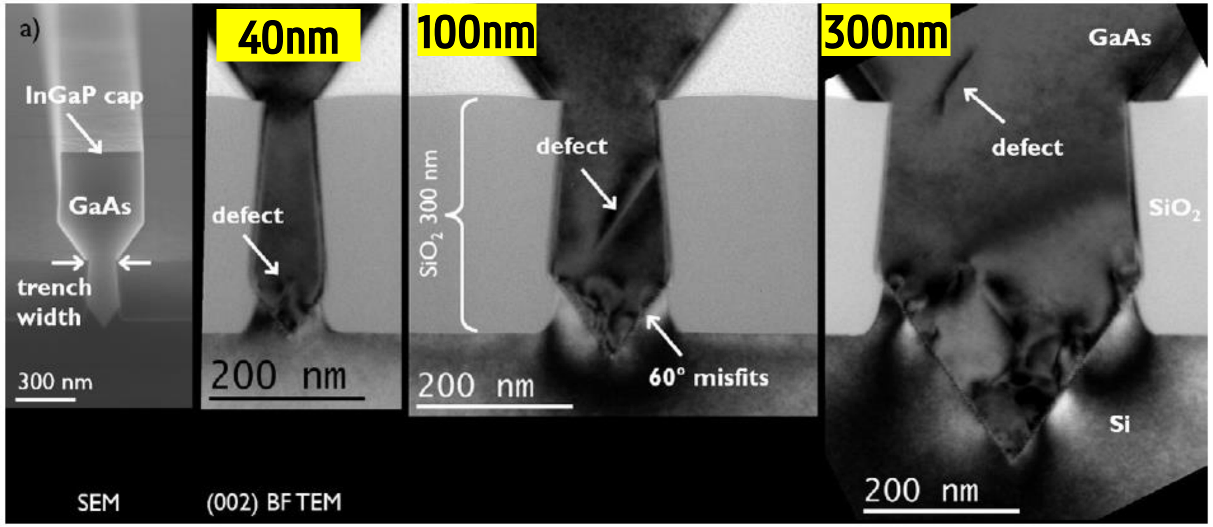
Kunert et al., 2018

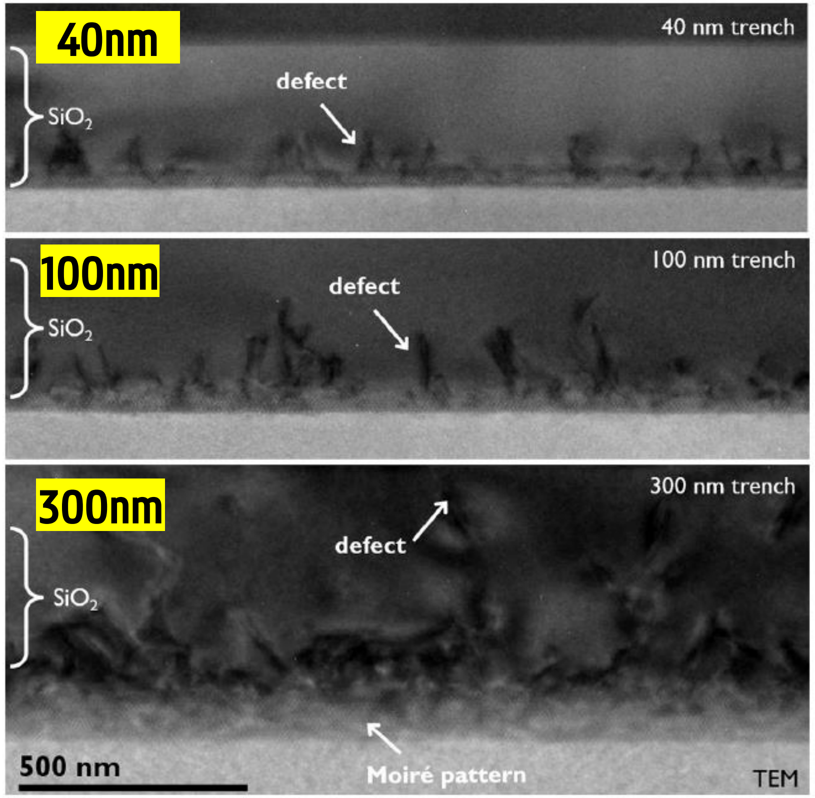
Effect of Aspect Ratio in ART

Aspect ratio (AR) (depth/width) of the trench becomes important for effective defect trapping

For fixed depth (300nm), narrower trench widths (higher AR) trap more defects arising from the heterointerface

40 nm trench width has minimum number of defects propagating to the top, compared to 100 nm & 300 nm trench widths

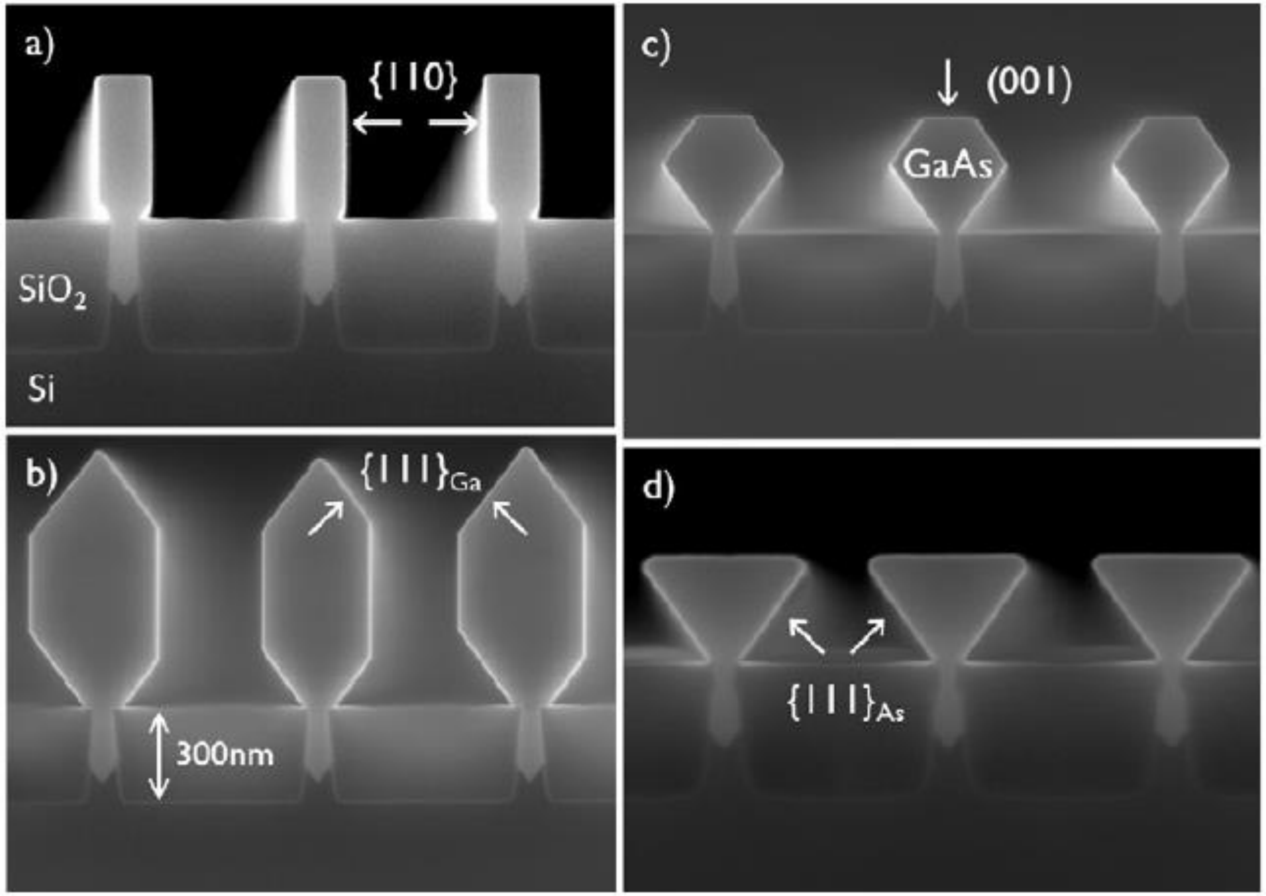




Kunert et al., 2018

Nano-Ridge Engineering (NRE)

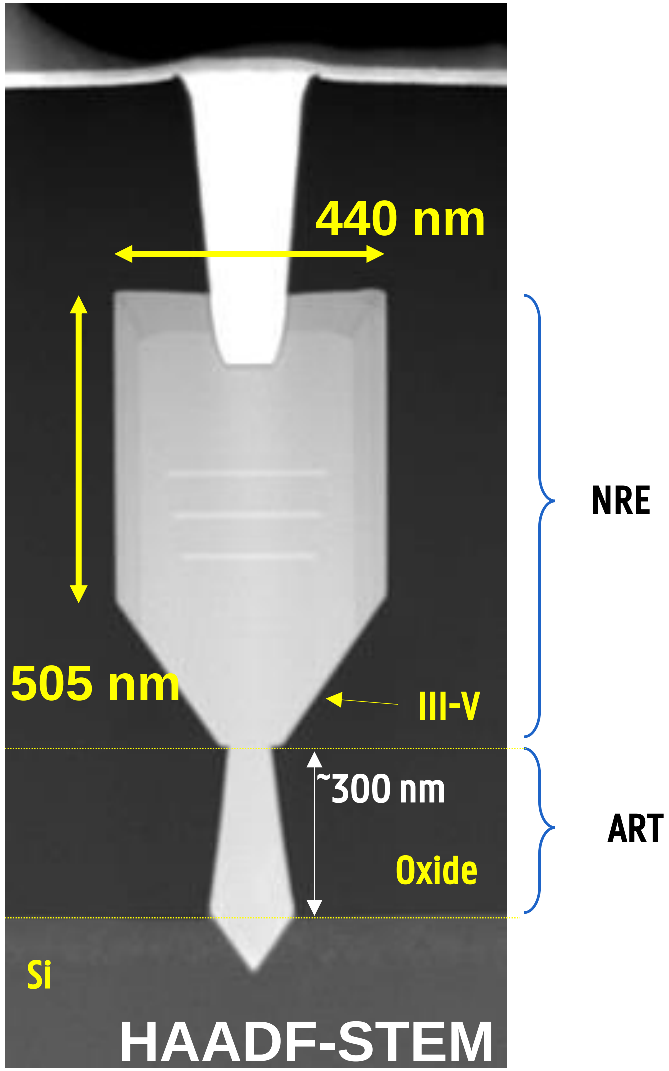
- NRE facilitates desired geometry, device and active material cross-section by:
  - Appropriate growth conditions for different facets
    - Such as growth temperature, reactor pressure, precursor partial pressure and gas phase ratio
  - Introduction of dopants for diode device formation
  - Introduction of In forming active InGaAs medium

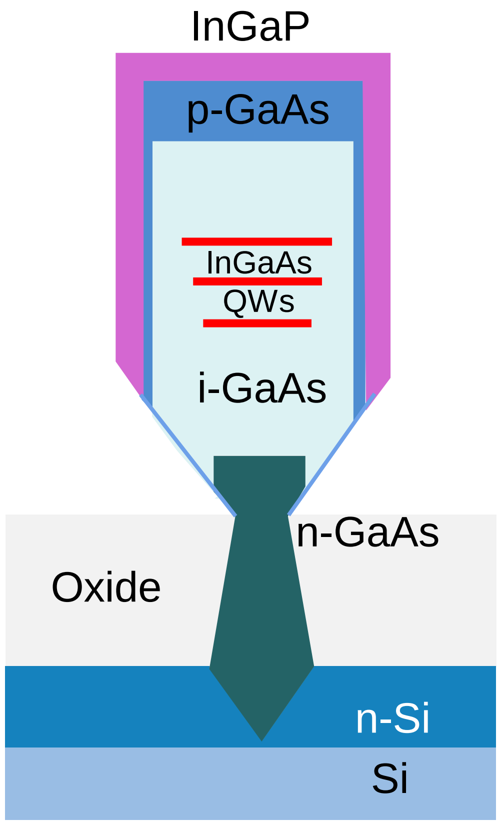


Kunert et al., 2018

Nano-Ridge Engineering

- Now we will make our active device with NRE:
  - ✓ Waveguide with a rectangular profile
    - Appropriate deposition conditions for different facets forming the desired shape
  - ✓ Consisting active volume, e.g. quantum wells
    - Introducing In during growth with the controlled composition
  - ✓ Forming p-i-n diode junction
    - Introducing dopants at given growth steps
  - ✓ Passivating external boundary to suppress surface recombination
    - with InGaP



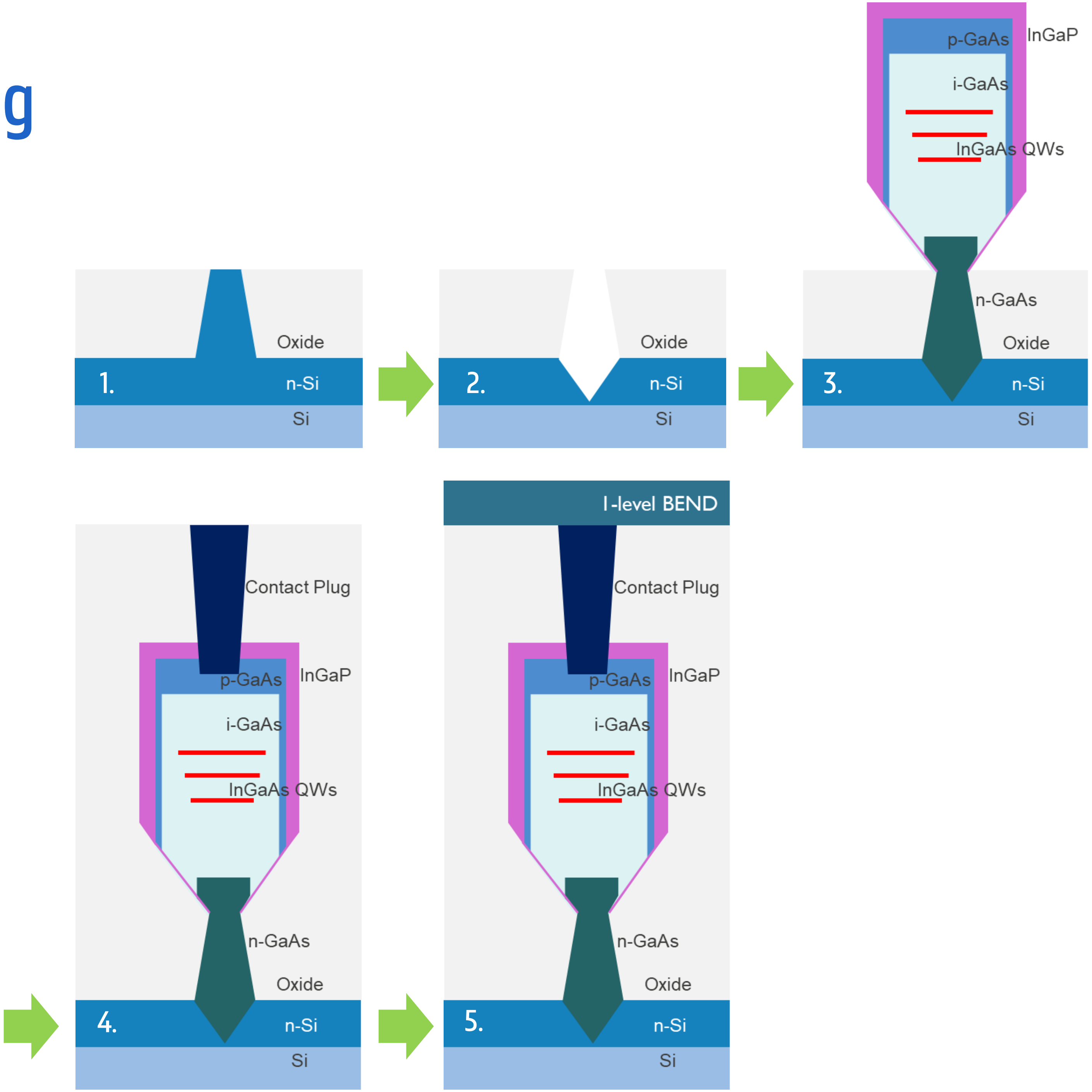


HAADF-STEM: High-angle annular dark-field scanning transmission electron microscope

NRWPD Device Processing

Completed in imec's 300-mm CMOS line

1. Shallow trench isolation
2. Anisotropic Si etching
3. Epitaxial growth of NRWPD
4. Planarization and tungsten contact plug addition
5. Copper damascene metal interconnect layer



Performance Metrics of Photodetectors

Dark Current (A)	Responsivity (A/W)	Bandwidth (3 dB bandwidth) (GHz)
Leakage current at dark condition Due to defects and impurities Increasing power consumption and noise As minimum as desired	Amount of photocurrent generated (A) per unit input optical power (W) Indicator of how efficient the photodetector	Metric for how fast the photodetector can operate

Dark Currents of Nano-Ridge Waveguide Photodetectors

The devices exhibit extremely low dark current of:

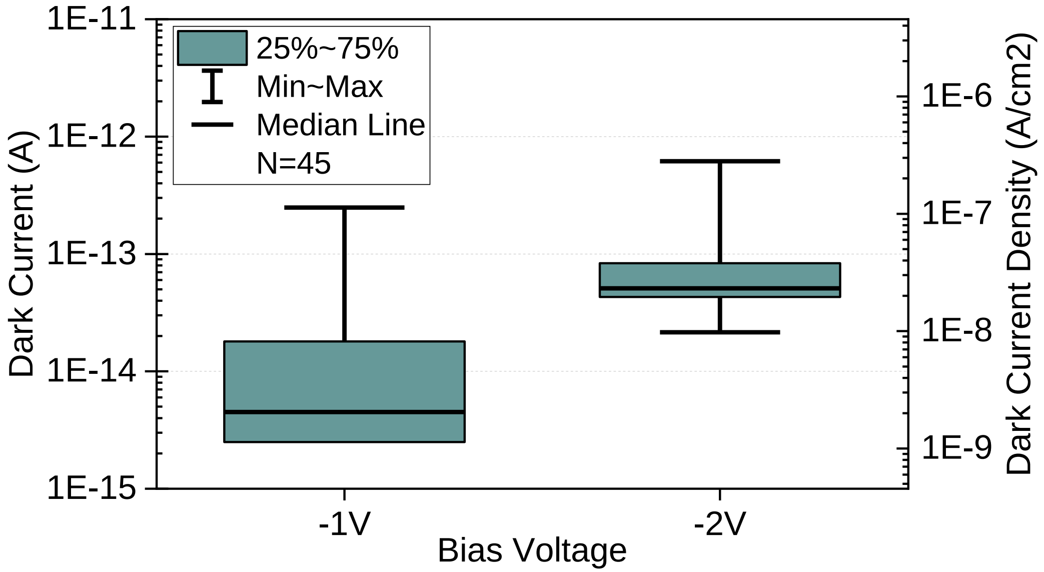
At -1 V:

median 7.3E-15 A, **maximum 0.25 pA**

At -2 V:

median 5.1E-14 A, **maximum 0.62 pA**

Considering the 440 nm width and 500 µm length, this corresponds to a **1.98×10^{-8} A/cm^2** equivalent dark current density at -1 V



Internal responsivities

How do they operate under light?

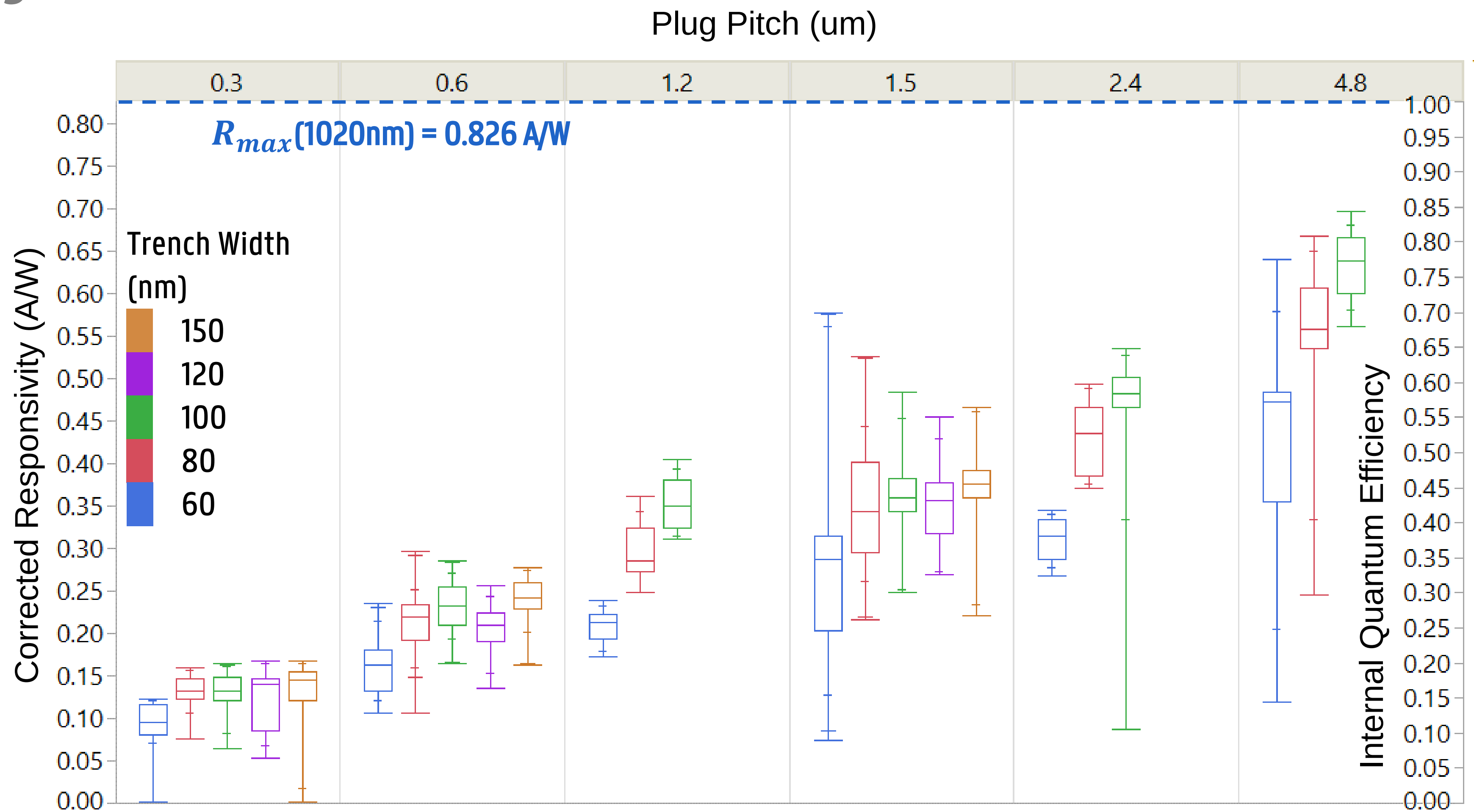
Coupling-efficiency correction is made with fiber to chip simulation:

$$P_{coupled} = P_{incident} \times \eta_{coupling}$$
$$\boldsymbol{R_{corr} = I_{ph}/P_{coupled}}$$

Median Responsivity of **0.65 A/W (max 0.68 A/W)** at -1V

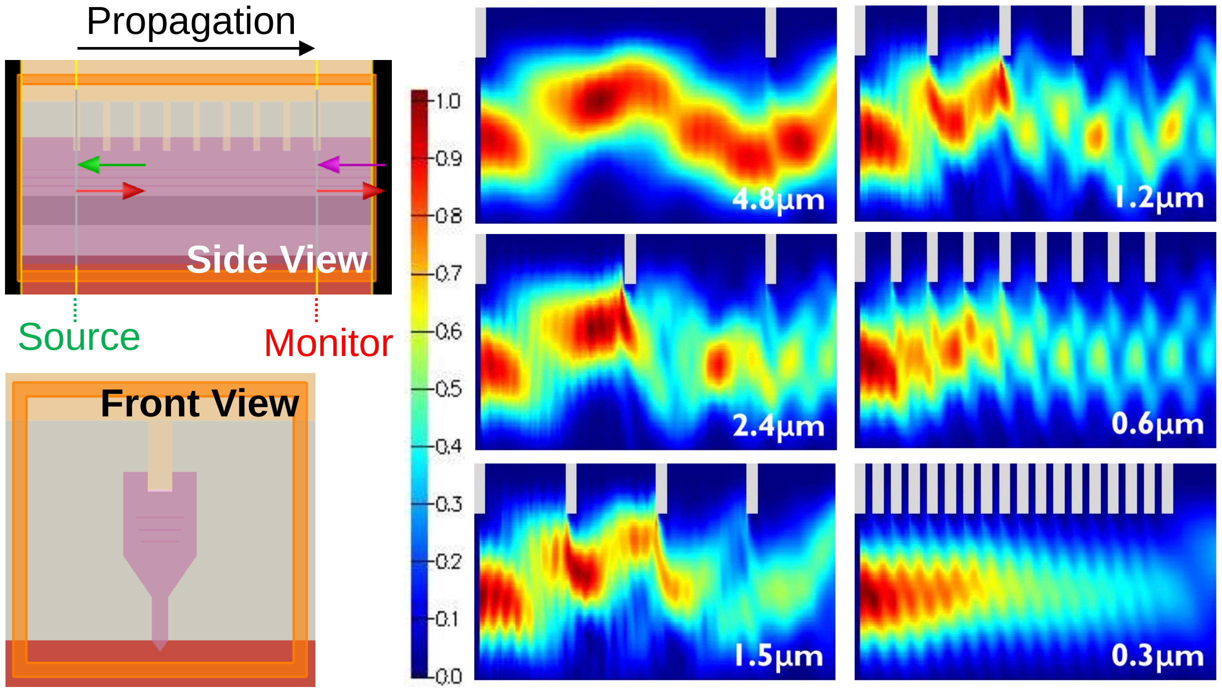
Equivalent of **79% (max 83%) internal quantum efficiency**

(of device with TW=*100nm, length=500um, CON35 pitch=4.8um)*



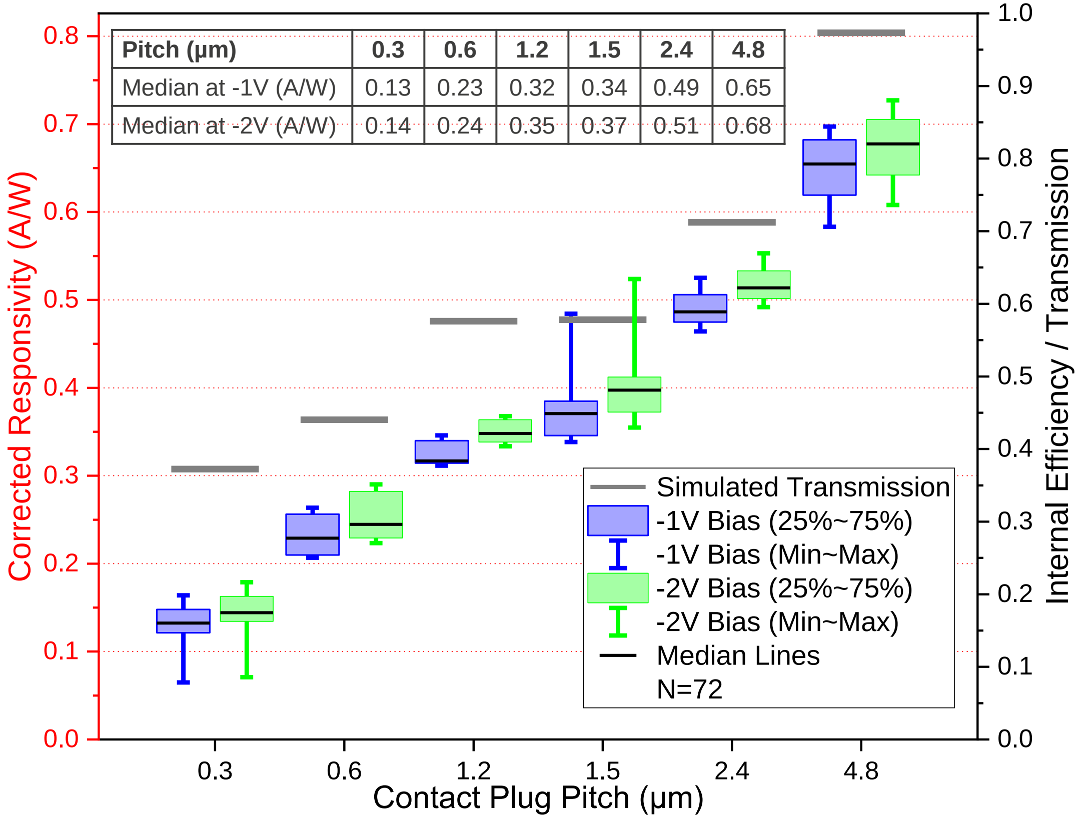
I_{ph} : photocurrent
I_l : light current
I_d : dark current

FDTD simulation for plug losses



Coupling corrected responsivities at -1 and -2V

w/ simulated transmissions for different plug pitches (aligned to right y-axis)



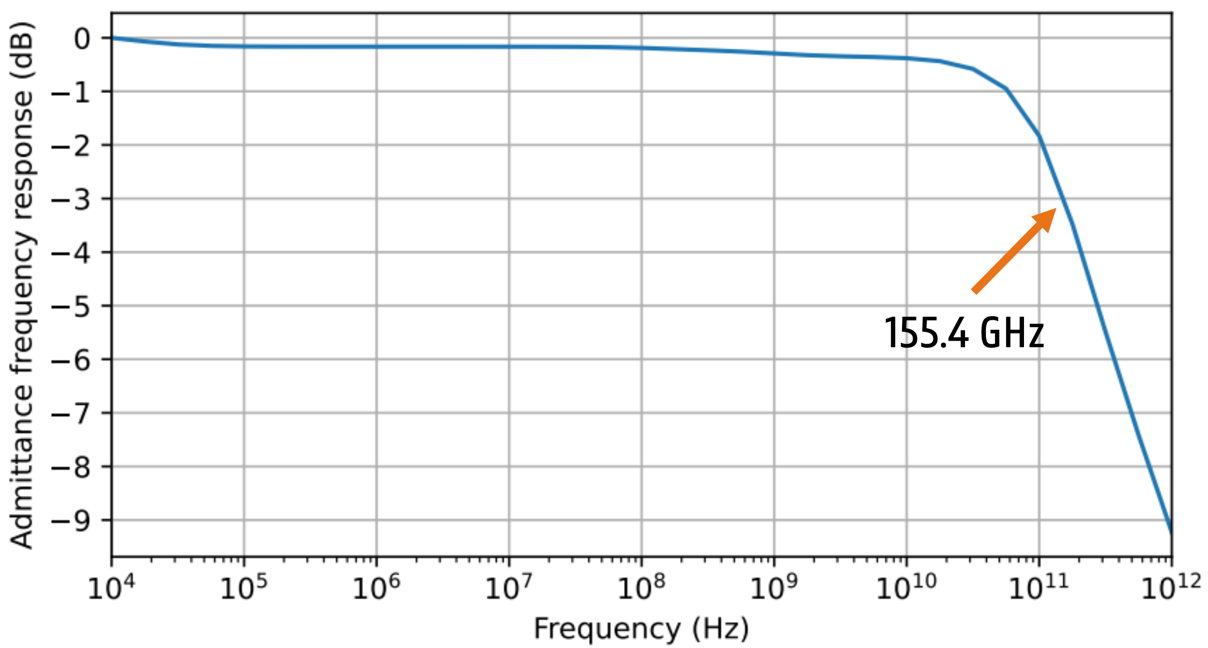
Pitch (µm)	0.3	0.6	1.2	1.5	2.4	4.8
Median at -1V (A/W)	0.13	0.23	0.32	0.34	0.49	0.65
Median at -2V (A/W)	0.14	0.24	0.35	0.37	0.51	0.68

High Speed Performance

$$f_{3dB} \sim \frac{1}{2\pi}\sqrt{\frac{1}{\tau_{RC}^2 + \tau_{transit}^2}} = \sqrt{\frac{1}{\frac{1}{f_{RC}^2} + \frac{1}{f_{transit}^2}}}$$

High speed performance of PIN photodiodes mainly depend on two factors:

- Carrier transit time bandwidth
  - How fast carriers can exit the intrinsic volume
- Resistance-Capacitance bandwidth
  - How fast the electrical circuit can operate



Simulated transit time bandwidth was found to be 155.4 GHz

High Speed Performance (2)

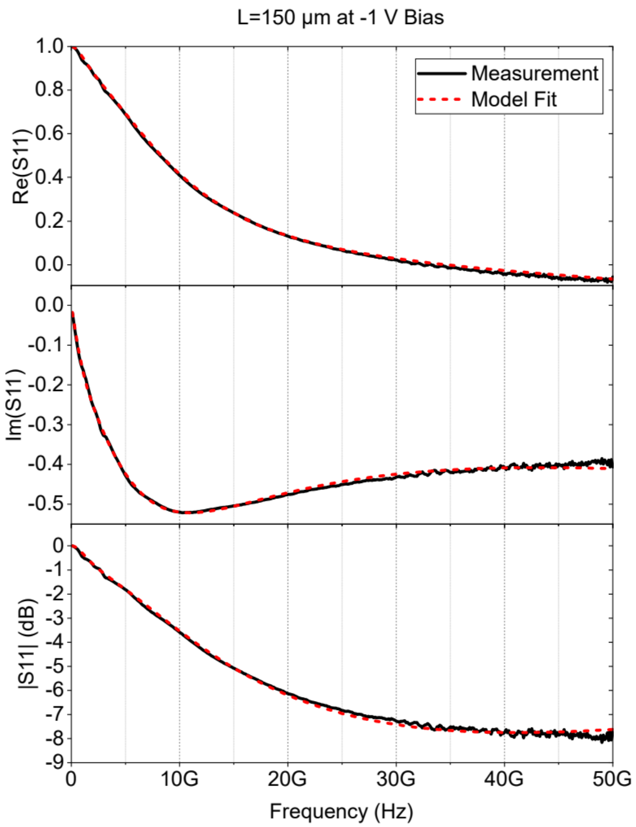
$$f_{3dB} \sim \frac{1}{2\pi}\sqrt{\frac{1}{\tau_{RC}^2 + \tau_{transit}^2}} = \sqrt{\frac{1}{\frac{1}{f_{RC}^2} + \frac{1}{f_{transit}^2}}}$$

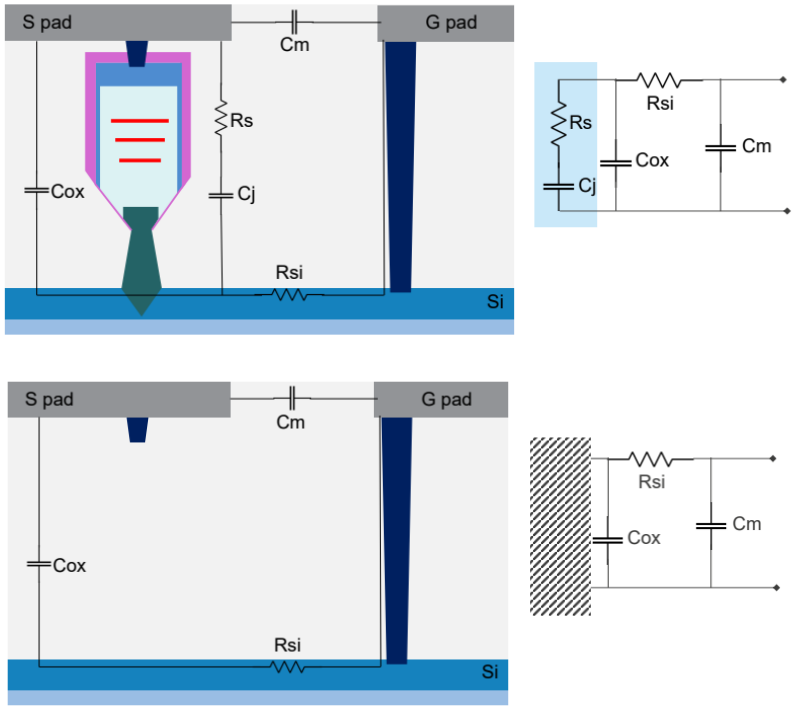
S11 parameter measurements were completed for extracting device RC parameters

RC bandwidth is found 1.1-1.9 GHz

NRWPDs are RC bandwidth limited

Parameter	Unit	Min	Typical	Max
C_{ox}	fF	102	122	162
C_m	fF	17	22	33
R_{Si}	Ohm	56	72	86
C_j	fF	55	91	105
R_s	Ohm	760	880	2300
f_{RC}	**GHz**	**1.1**	**1.9**	**2.5**





Benchmark

Ref.	Year	Mat.	V_{op} (V)	λ_{op} (nm)	BW_{op} (GHz)	R (A/W)	η	J_{dark} (A/cm^2)
[8]	2016	Ge	-1	1310	67	0.93	88%	3.4×10^{-2}
[9]	2017	III-V	-1	1250	2.3	0.9	89%	0.8×10^{-4}
[10]	2018	III-V	-3	1310	5.5	0.08	7%	1.3×10^{-4}
[11]	2018	III-V	-3	1550	9	0.79	63%	8.0×10^{-4}
[12]	2019	III-V	-1	1300	N\A	0.26	25%	3.5×10^{-7}
[13]	2020	III-V	-5	1310	2.3	0.234	22%	6.6×10^{-5}
[14]	2020	III-V	-3	1550	28	0.27	22%	1.0×10^{-1}
[15]	2020	III-V	-2	850	N\A	0.17	34%	4.5×10^{-7}
[16]	2020	III-V	-1.5	1346	25	0.4	37%	1.4×10^{0}
[17]	2020	III-V	-2	1346	25	0.68	47%	2.8×10^{0}
[18]	2020	III-V	-0.5	1550	N\A	1.06	85%	3.3×10^{-2}
[19]	2020	III-V	-1	1020	N\A	0.25	30%	1.4×10^{-5}
[20]	2021	III-V	-1	1310	40	0.8	32%	1.1×10^{-2}
[21, 22]	2022	III-V	-1	1310	52	0.4	16%	4.8×10^{-4}
[23]	2022	III-V	-1	1320	70	0.2	19%	4.8×10^{-2}
This study: [24, 25]	'20,'21	III-V	-2	1020	1.9	0.68	**83%**	$\mathbf{1.9\times10^{-8}}$

Advanced performances on responsivity (IQE), and dark current densities compared to literature

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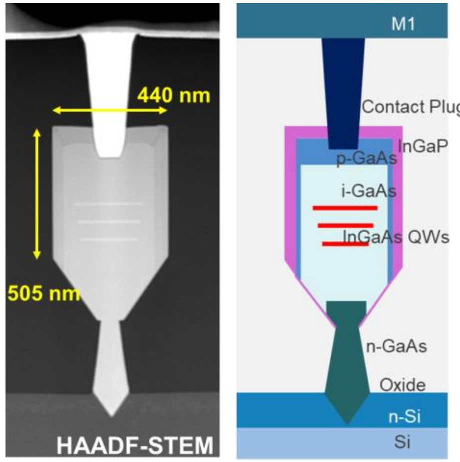
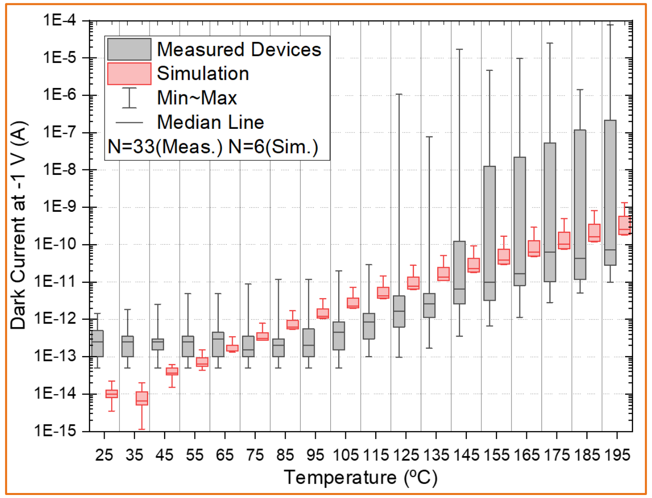
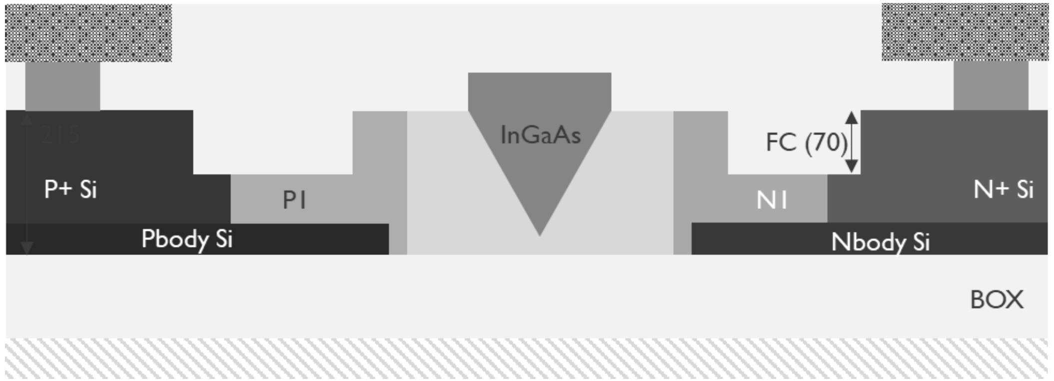
   2. How are nano-ridges made?
   3. How do they perform?
3. **Leakage Mechanisms of Nano-Ridge Photodetectors**
4. Wide-field grown III-V Photodetectors
5. Conclusions and Future

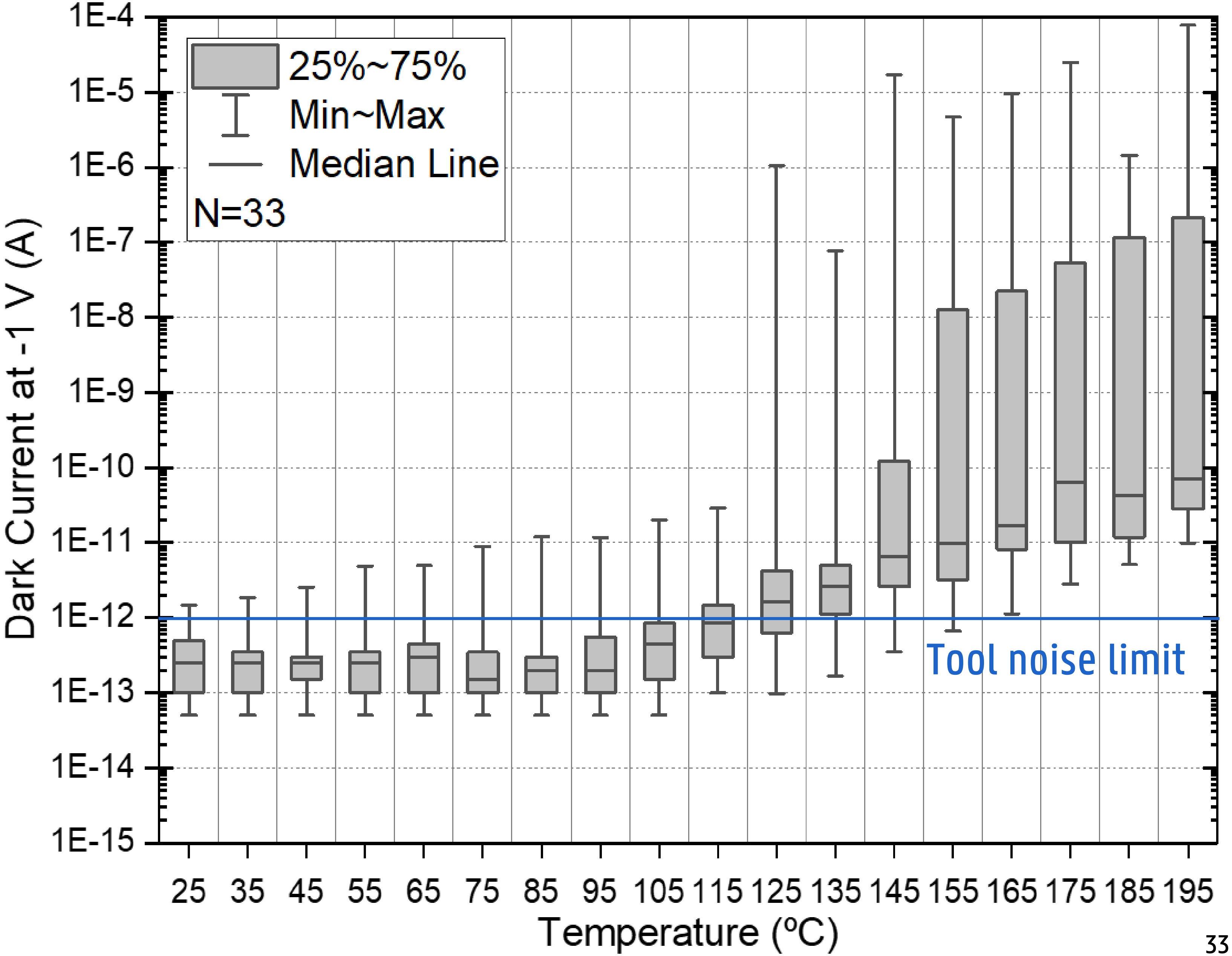






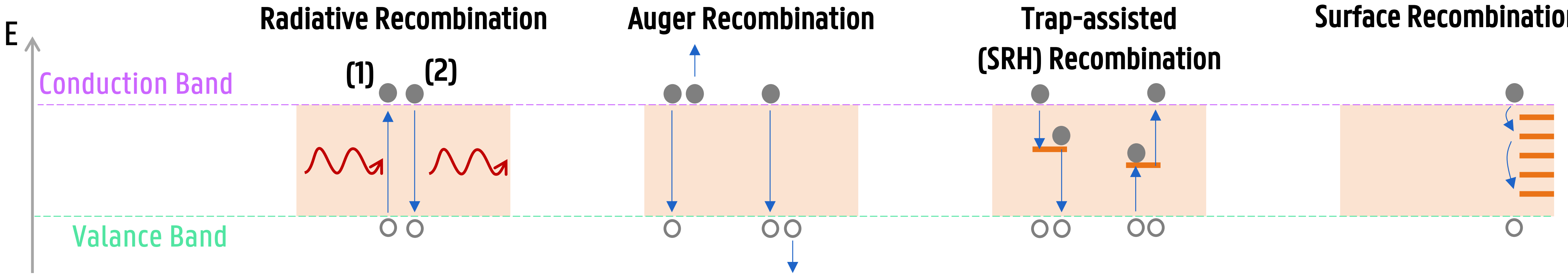
Leakage Mechanisms at Elevated Temperatures of NRs

- Extremely low dark currents (leakages)
- How can we assess the source of extremely low dark currents and the quality of grown material? *By heating it up!*
- We increase the temperature from 25°C to 195°C to resolve underlying leakage mechanisms



Studied Models for Leakages (Carrier Recombination – Generation)

$$R_{BulkSRH,net} = \frac{np - n_{i,eff}^2}{\tau_p(n+n_1) + \tau_n(p+p_1)} \quad R_{SurfSRH,net} = \frac{np - n_{i,eff}^2}{(n+n_1)/s_p + (p+p_1)/s_n}$$



- **Radiative:** resulting carrier generation after light absorption (1), or resulting a radiation after a recombination (2)
- **Auger:** moving carriers to higher energy levels
- **Trap-assisted (or Shockley-Read-Hall (SRH)):** Existing dopants or defects creating states (or traps), facilitating lower energy recombination-generation events
- **Surface:** traps due to sudden discontinuation of crystal (dangling bonds) act as traps

Bulk and surface SRH recombination are not desired

○ Hole (+)
● Electron (-)
— Traps

SRH: Shockley-Read-Hall

Studied Leakage Model Parameters

$$R_{BulkSRH,net} = \frac{np - n_{i,eff}^2}{\tau_p(n+n_1) + \tau_n(p+p_1)} \quad R_{SurfSRH,net} = \frac{np - n_{i,eff}^2}{(n+n_1)/s_p + (p+p_1)/s_n}$$

- Earlier activation energy and ideality factor extractions suggest SRH type recombination
- SRH
  - Bulk tau (τ) parameters needs to be extracted for GaAs and InGaAs (material in intrinsic volume)
  - Surface recombination velocity (S) for GaAs/oxide InGaP/oxide interface surfaces
- Auger and Radiative models were also included (but expected to be ineffective at reverse bias operation)

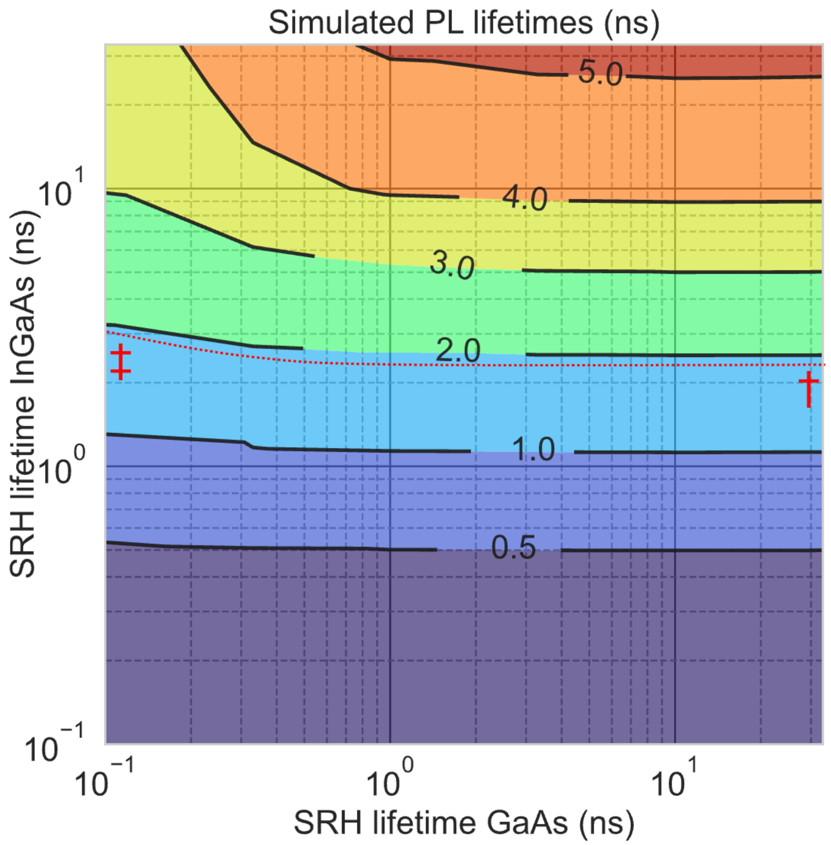
Model	Subcomponents	Parameter	Value	Unit	Reference
SRH Bulk	Main	$\tau_{SRH,GaAs}$	$0.1^{\ddagger}$ 0.33 1 3.3 10 $33^{\dagger}$	ns	-
		$\tau_{SRH,InGaAs}$	$3.2^{\ddagger}$ 2.7 2.6 2.5 2.5 $2.5^{\dagger}$	ns	Sim.
	Temperature Dependence	α	-1.5	-	[11]
SRH Surface	GaAs/Oxide	$S_{GaAs/Oxide}$	1×10^6 (PL simulation)	cm/s	[12]
			$5 \times 10^5 - 1 \times 10^7$ (electrical simulation)	cm/s	[12]
		ΔE_{trap}	-0.3	eV	[13]
	InGaP/Oxide	$S_{InGaP/Oxide}$	5×10^4	cm/s	[14]
Auger	GaAs	C_{GaAs}	1×10^{-30}	cm^6/s	[15]
	InGaAs	C_{GaAs}	1×10^{-29}	cm^6/s	[16]
Radiative	GaAs	B_{GaAs}	7.2×10^{-10}	cm^3/s	[15]
	InGaAs	B_{GaAs}	3×10^{-10}	cm^3/s	[15]

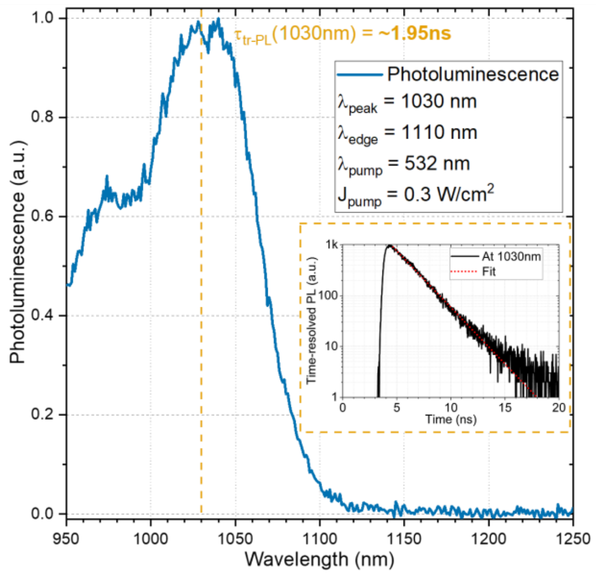
Extracting Bulk carrier SRH lifetimes

There are two materials in intrinsic volume (InGaAs QWs and i-GaAs) that can have different tau values

Tau parameters were extracted on a separate simulation study which emulates the PL response of the NRs

- Carrier recombination lifetime was extracted for various tau values of GaAs and InGaAs materials in the devices after an artificial radiation
- Real PL lifetime corresponding tau value pairs (along ‡-† curve, where lifetime is 1.95ns) were found





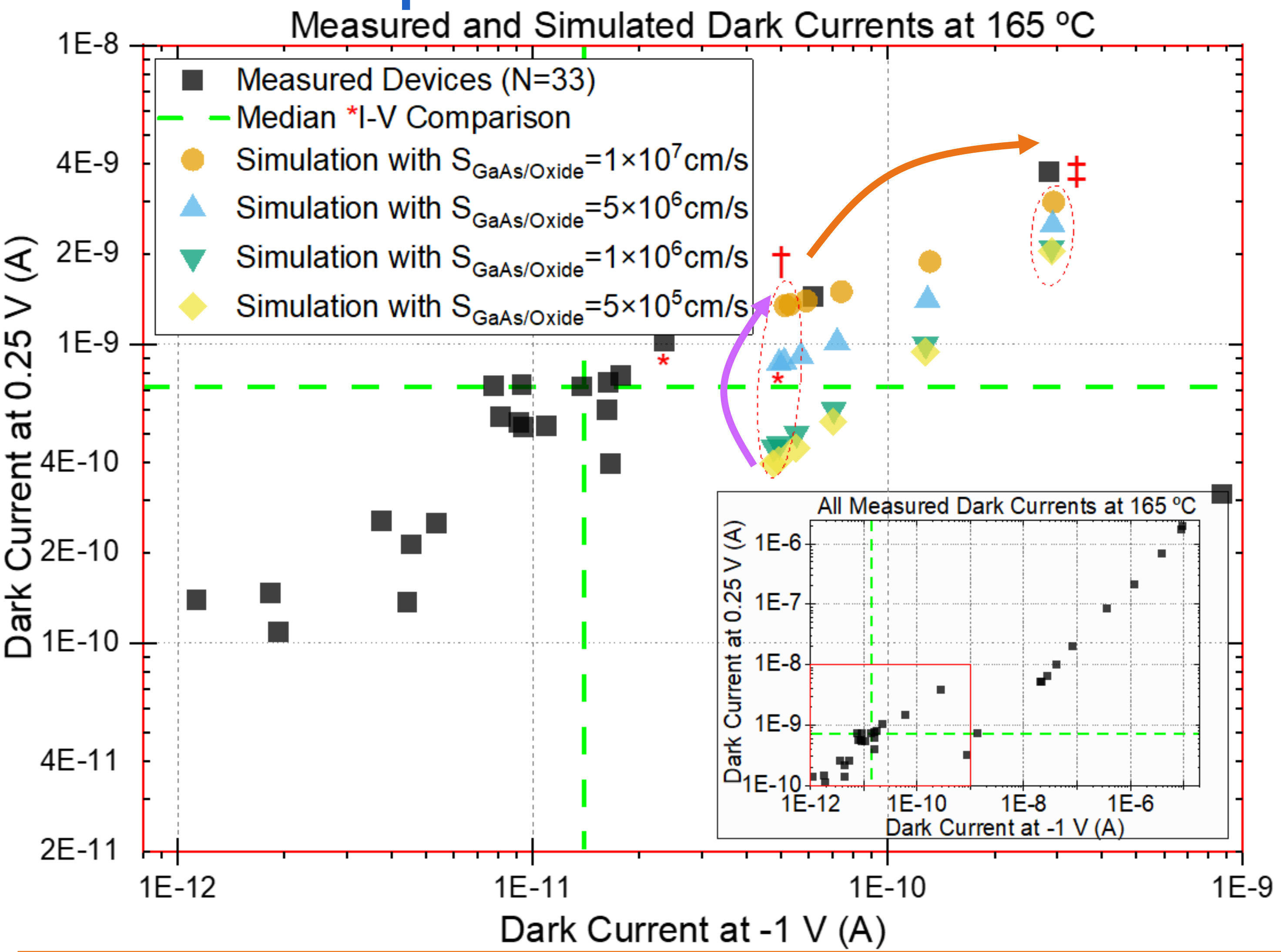
Forward / Reverse Leakage Current Comparison of Simulation Space vs. Measurement

Dark currents at -1 V and +0.25 V bias points at 165C measured and simulated were compared with the extracted tau pairs, along with literature surface SRH parameters

$S_{GaAs/Oxide}$ sweep

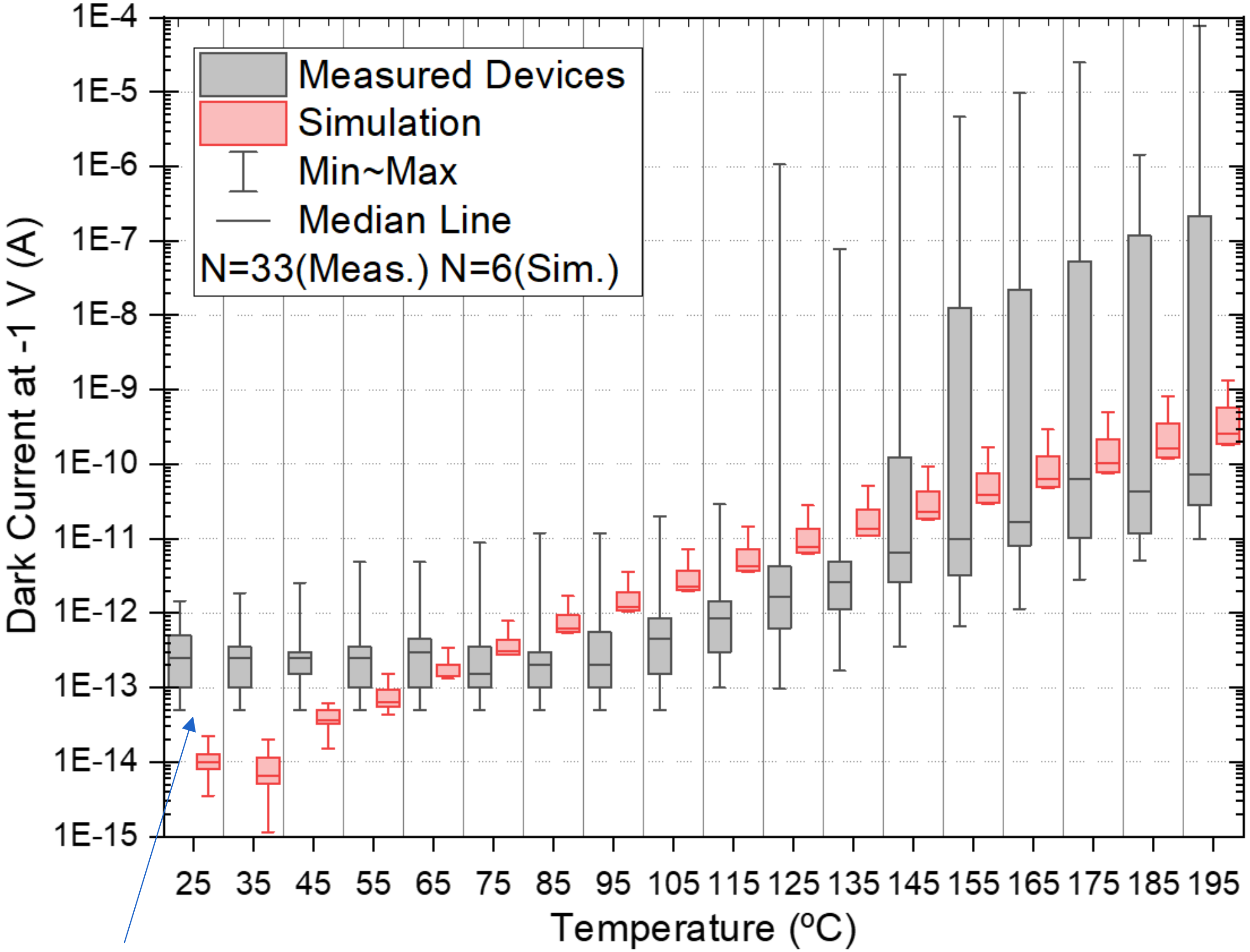
Tau pair sweep

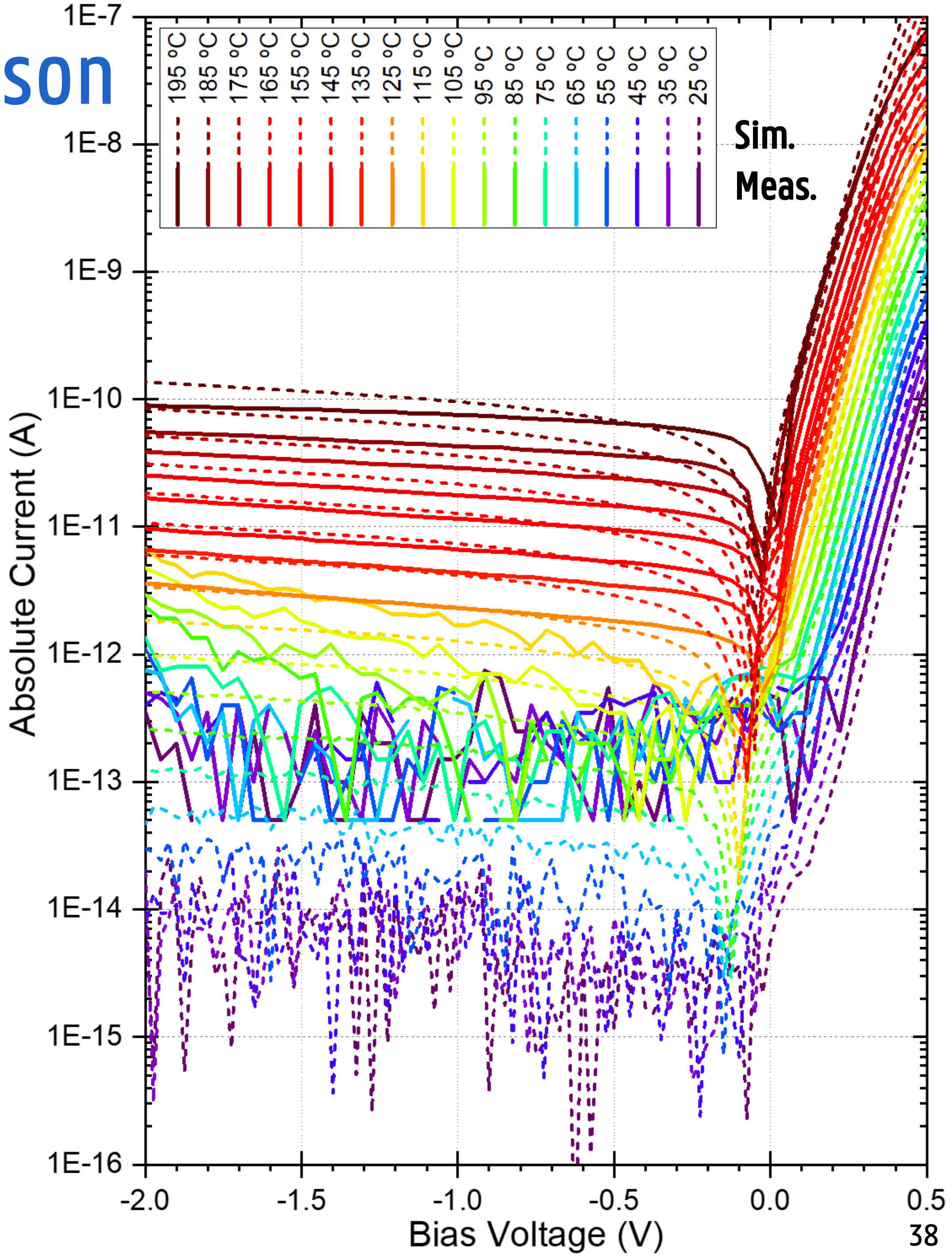
Effects of surface SRH was observed for +0.25 V bias



Parameter	Value						Unit	Reference
$\tau_{SRH,GaAs}$	0.1‡	0.33	1	3.3	10	33†	ns	-
$\tau_{SRH,InGaAs}$	3.2‡	2.7	2.6	2.5	2.5	2.5†	ns	Sim.

Device Model vs. Measurement Comparison

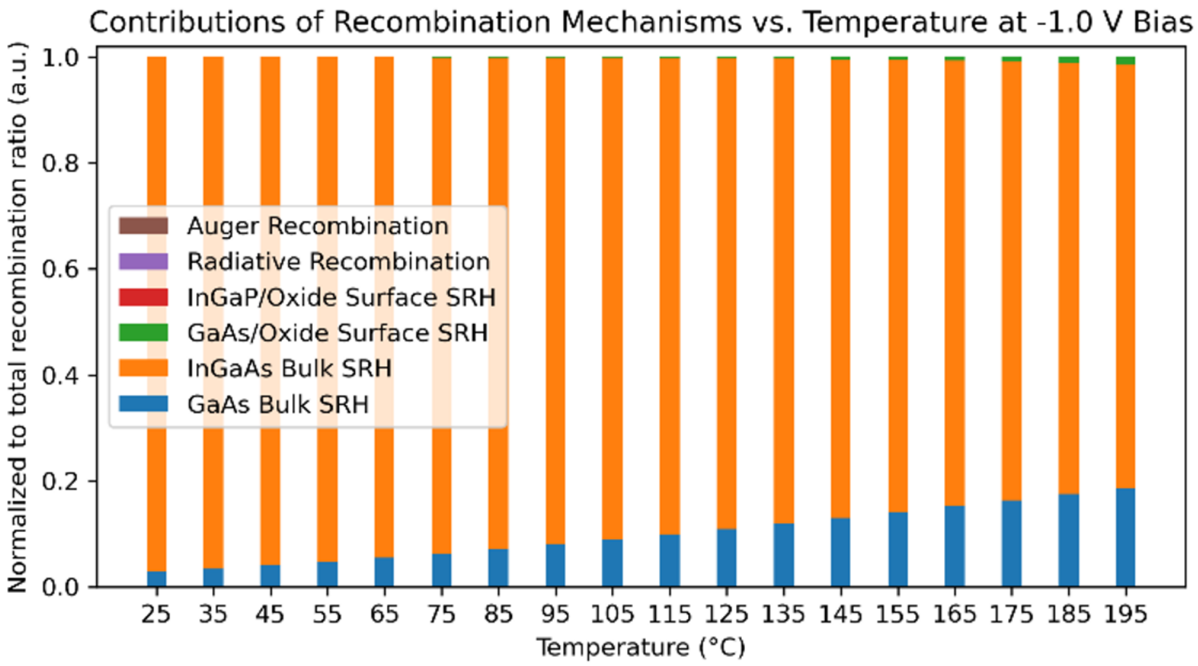




Our simulations show dark currents we measured at room temperature can be more than 10x smaller than what we measured!

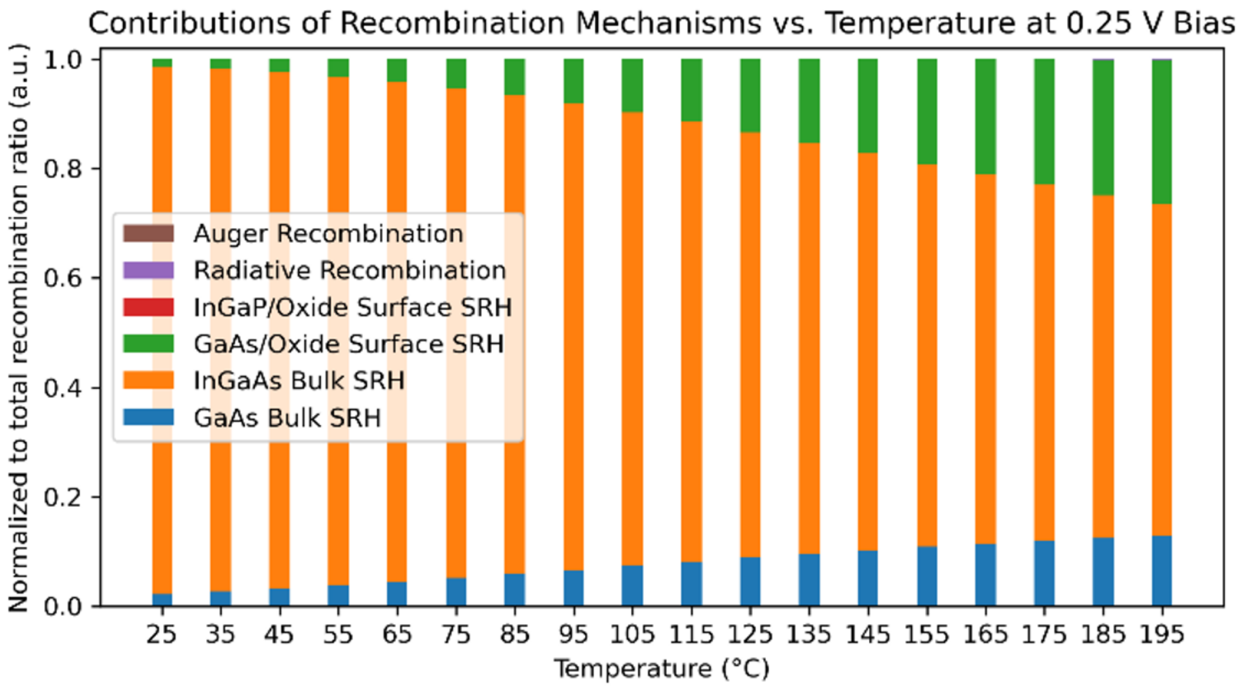
Percentile contributions at forward and reverse bias

-1 V



InGaAs SRH (defectivity levels in QW) plays an important role

+0.25 V



Surface SRH leakages were observed to be more prominent at forward subthreshold bias voltages

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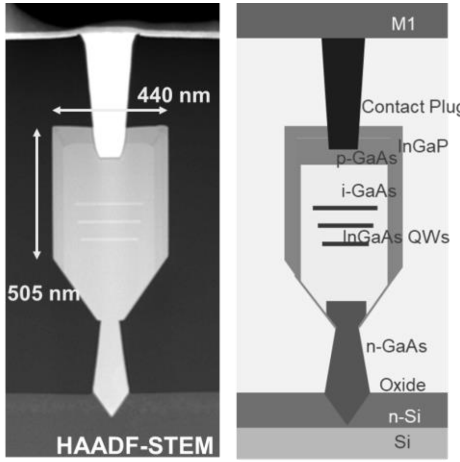
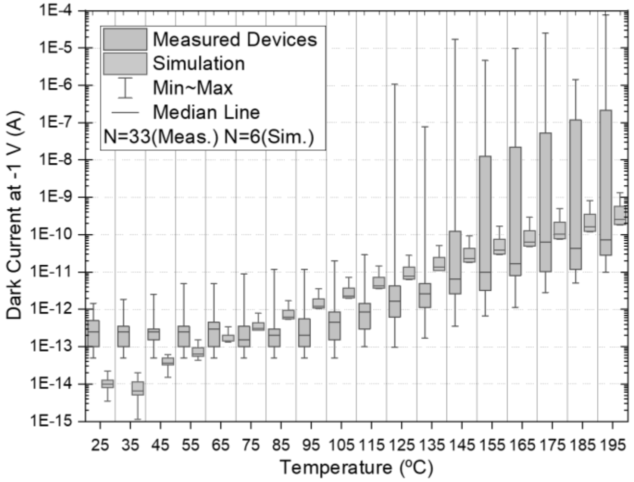
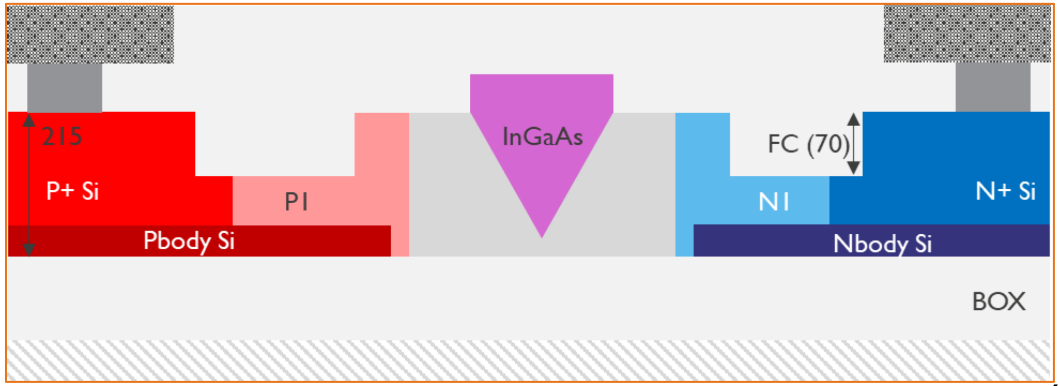


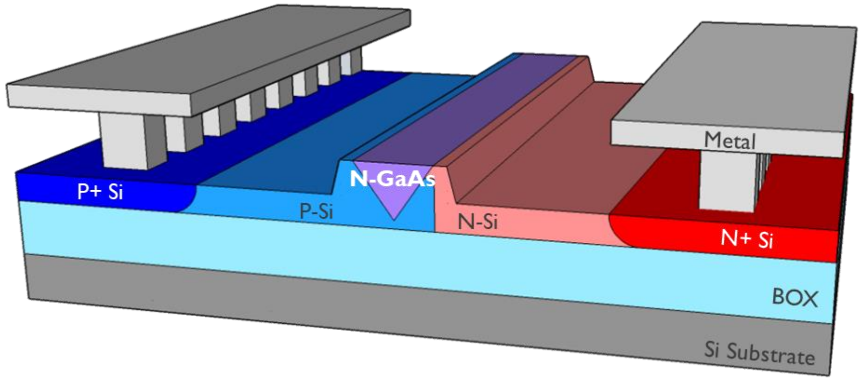




Wide-field grown III-V on Si devices

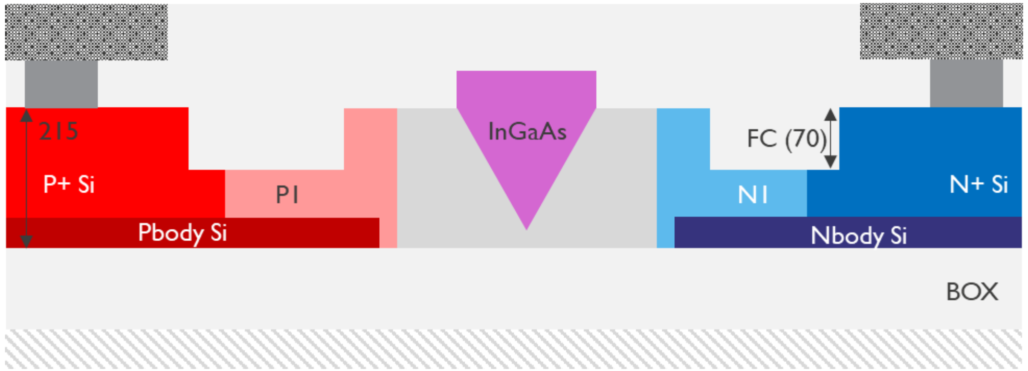
- Direct integration on Si with the Wide-field approach
- Objectives
  - Implementing on an existing silicon photonics platform to eliminate
    - Coupling difficulties in nano-ridges
    - Problems arising from III-V to metal contacting
  - Offering integration flexibility & wafer scalability, and fast prototyping

GaAs on Si for Carrier Depletion Phase Shifters / Modulators (PSM)



Y. Kim

InGaAs on Si for Electro-Absorption Devices



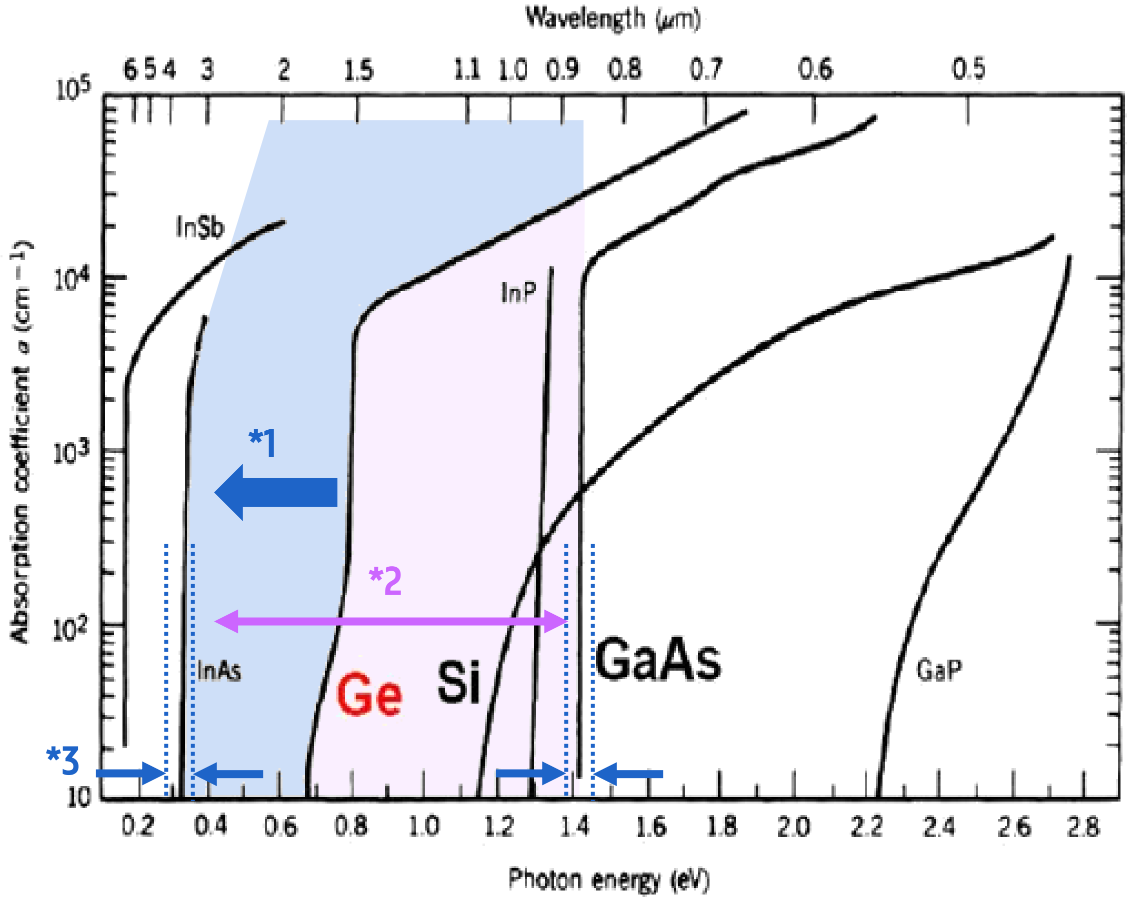
Advantages of InGaAs for electro-absorption devices

InGaAs offers:

1. Extension of operation wavelength beyond Ge bandgap
2. Bandgap engineering via material composition
3. Sharper band-edge at operated telecom wavelengths

Also:

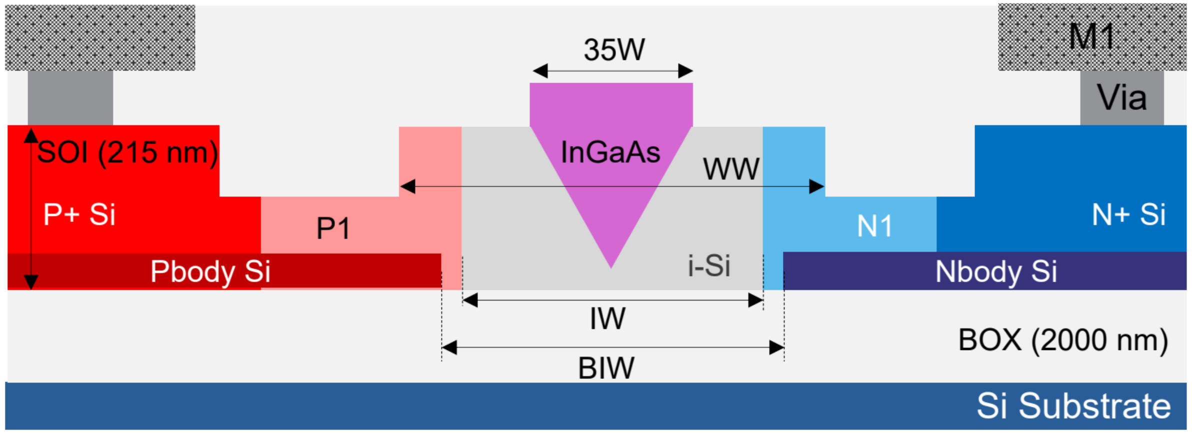
Higher mobilities and absorption coefficients



***1** – Wavelength extendibility
***2** – Bandgap tunability
***3** – Sharper band-edge

Kuo, 2006

Wide-field Grown InGaAs



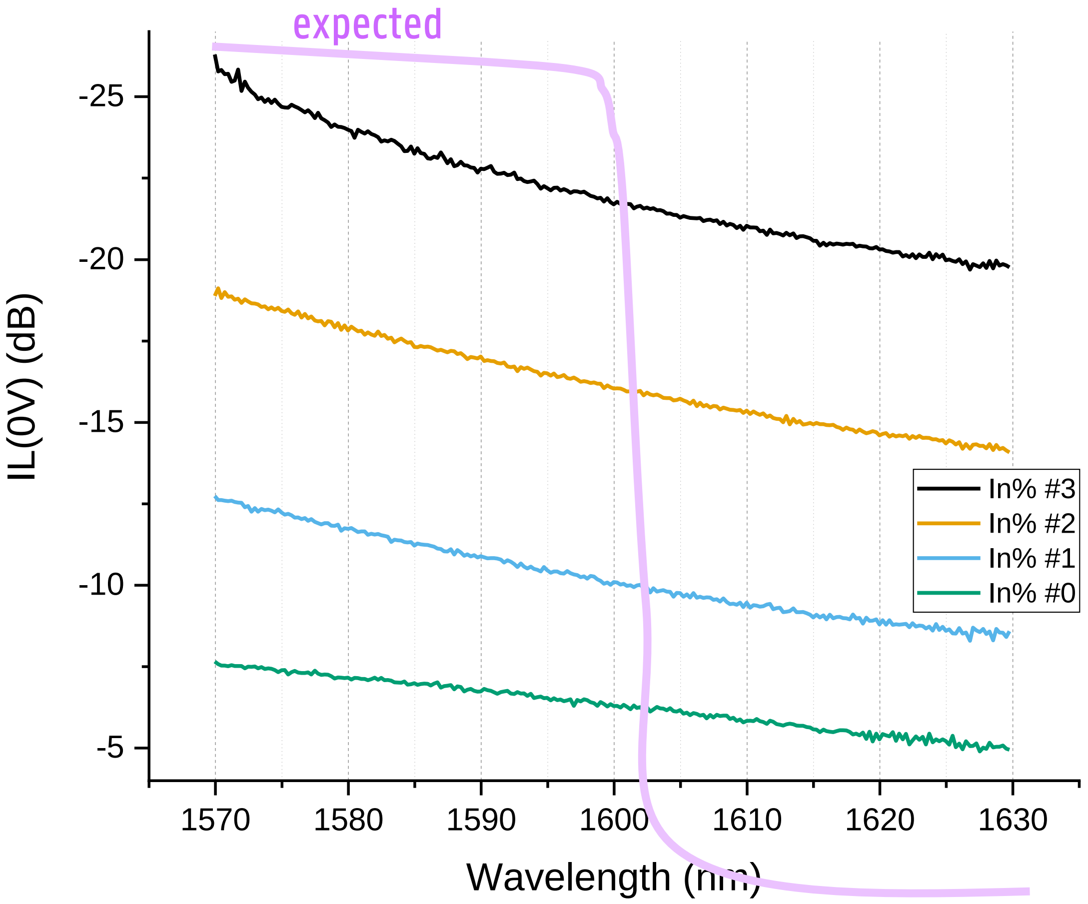
- On an existing SiPh platform with new III-V window + doping maskset
- Devices with waveguide width 0.7um
  - With 4 different III-V lengths of devices
  - 4 different In% targets of InGaAs grown on different wafers

Design Parameter	**Values**
In % (XRD reading)	46% (**#0**), 50% (**#1**), 55% (**#2**), 60% (**#3**)
Si Doping	1×10^{19} cm^{-3}
Waveguide Width (WW)	0.7 μm
III-V Width (35W)	250 nm
Intrinsic Width (IW)	$\sim$ 0 nm
Lengths	9, 19, 41, 79 μm

Insertion loss at 0 V

Loss spectra show no indication of **sharp band edge** of InGaAs in this spectral window for any In% case

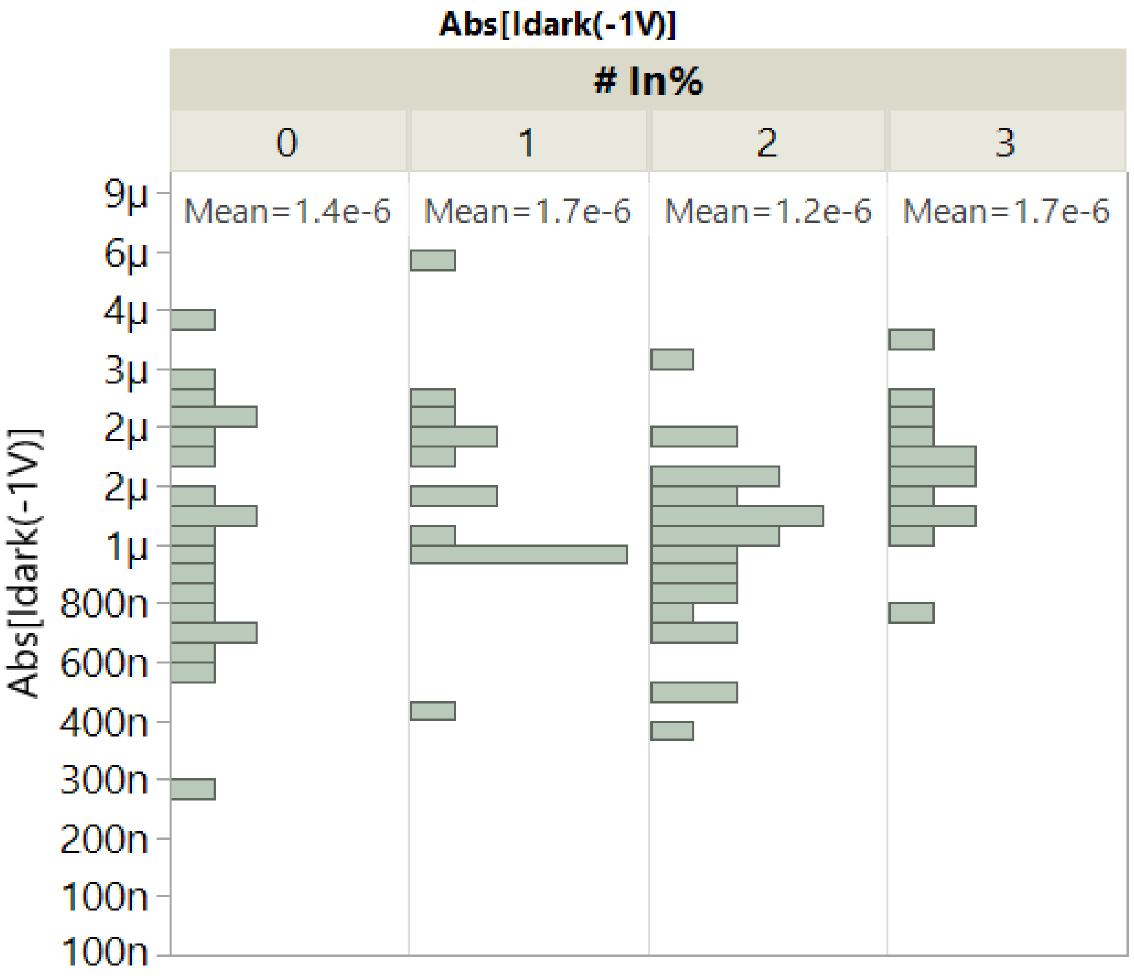
- In composition nonuniformity
- Brings difficulty to distinguish losses due to defectivities or InGaAs absorption



Dark currents at -1 V

Dark currents at -1 V bias are at around 2 μA levels

No In% dependence observed



Bias effects on Insertion Loss

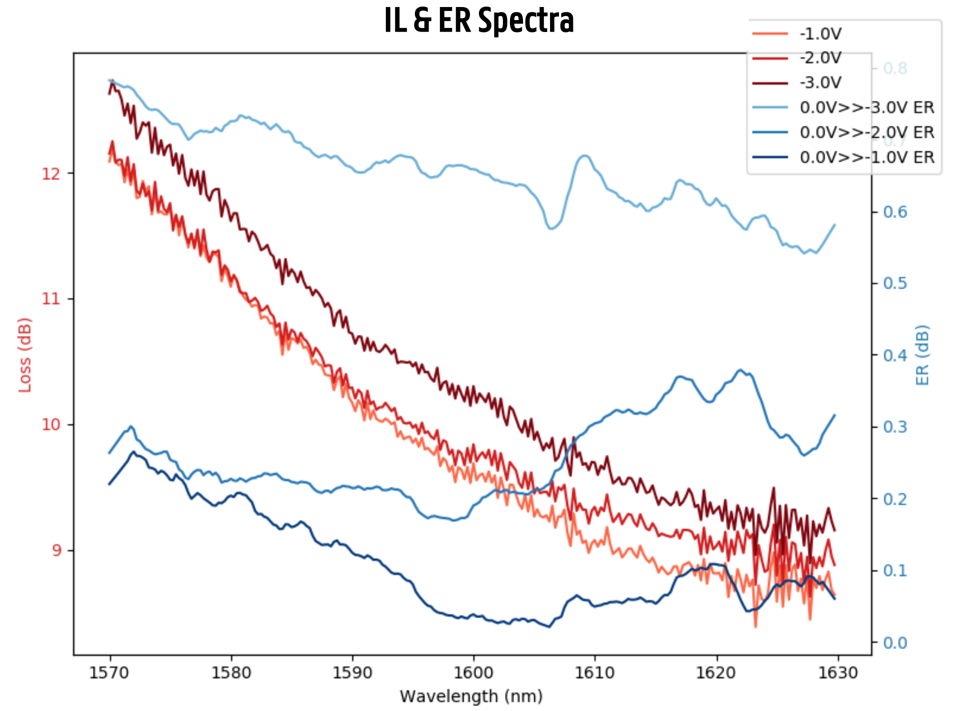
For modulation

Extinction ratios (ER) between different bias points are calculated as:

$$ER(dB)[xV] = IL_{xV}(dB) \; - IL_{0V}(dB)$$

Best ER are observed for narrow waveguides of 0.7um

- Typically <1dB
- Mostly governed by the high reverse currents – carrier effects

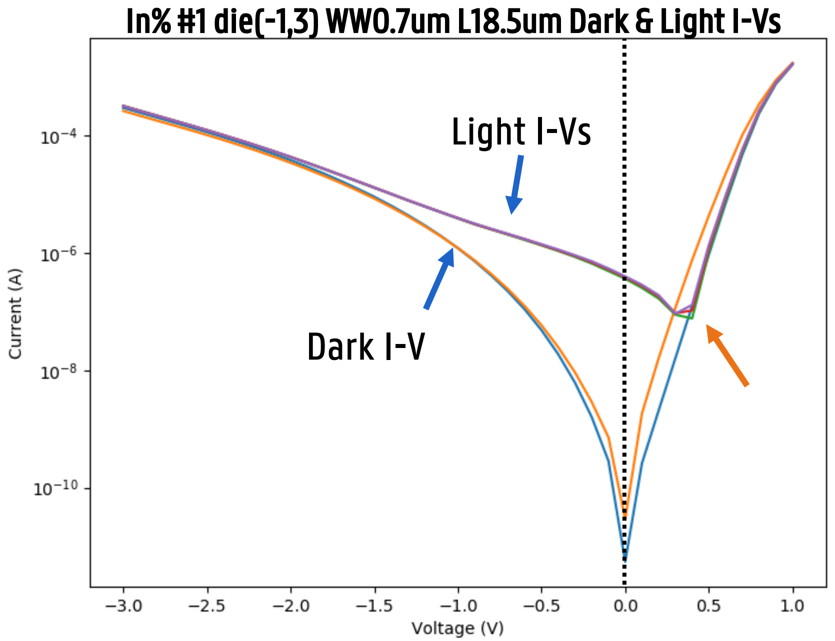


Photocurrent Generation

For photodetection

Devices of narrow waveguide width of 0.7um exhibit some photocurrent generation

- Responsivities below <0.1 A/W for -1 V bias
- High dark current limited



Conclusions on wide-field grown InGaAs devices on Si

1. First iteration of InGaAs on Si with wide-field approach
2. Material composition inhomogeneities and defects were major limiting factors
   - Band-edge distribution across the spectra
   - High dark currents and insertion losses
3. Limited device performances observed

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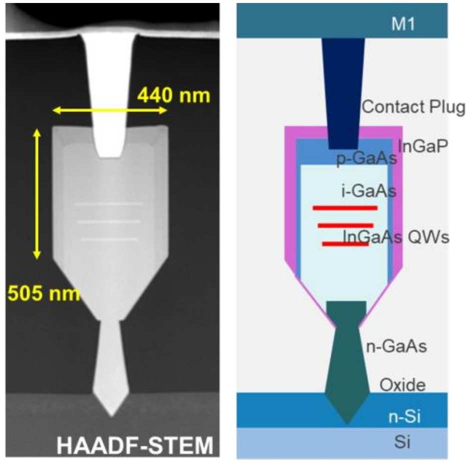

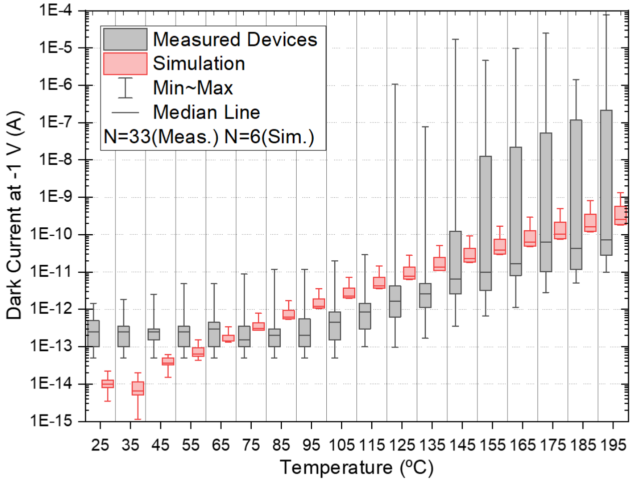

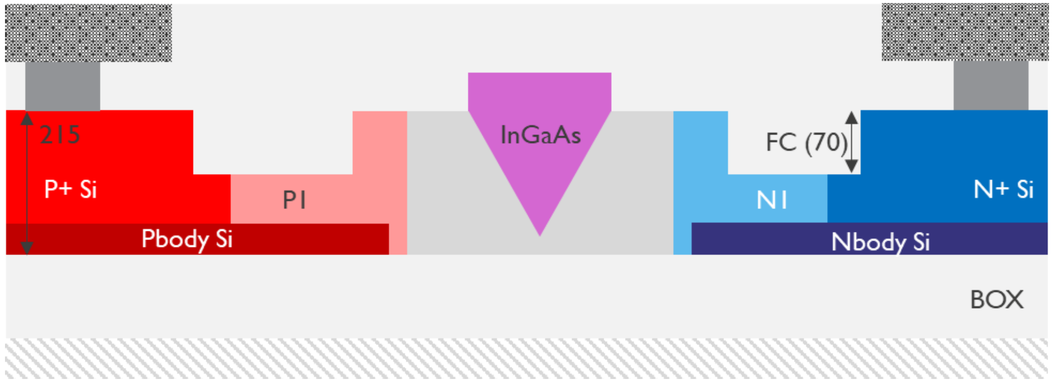

Conclusions

1. Successfully demonstrated InGaAs/GaAs MQW NRWPDs operating at 1020 nm
   1. Achieved very high responsivity of **0.65 A/W** at -1 V with extremely low **1.98×10^{-8} A/cm^2** dark current density
   2. Measured RC bandwidth of **1.9 GHz** (1.1 GHz for sparsely contacted devices)
2. Analyzed leakage mechanisms through high-temperature measurements
   1. Developed a comprehensive device model
   2. Bulk SRH type leakage mechanisms were found to be major leakage contributors
   3. Surface leakage plays an effect in the forward subthreshold bias regime
3. Explored selective-area growth of wide-field grown InGaAs on Si for EAM and PDs:
   1. Devices were found ineffective due to defects and composition inhomogeneity, requiring further efforts

Future

For Nano-Ridge Photodetectors (NRPDs):

- Extend the operation wavelength to telecom bands (O-band or C-band)
- Enhance overall optoelectronic (OE) bandwidth
- Achieve efficient coupling between nano-ridges and Si waveguides
- Co-integrate with other active nano-ridge devices (e.g., lasers, modulators)
- Improve design and material quality to enhance field performance and reliability
- Explore different application fields such as sensing

For Wide-Field Grown InGaAs on Si:

- Improve epitaxial growth uniformity and effectively reduce defects
- Explore new defect-reducing techniques including seed layer optimizations
- Maintain compatibility with existing silicon photonics platforms for quick integration

Take Home Messages

1. It is very hard to bring III-V devices with silicon photonics platforms, but we made it for photodetectors!
2. High material quality matters a lot for the best device performance.

Thank you!

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GHENT UNIVERSITY

imec

Cenk Ibrahim Özdemir

CenkIbrahim.Ozdemir@ugent.be