2572-11

Winter College on Optics: Fundamentals of Photonics - Theory, Devices and Applications

10 - 21 February 2014

Silicon photonics: Waveguide modulators and detectors

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http://silicon-photonics.ief.u-psud.fr/

Silicon photonics:
Waveguide modulators and detectors

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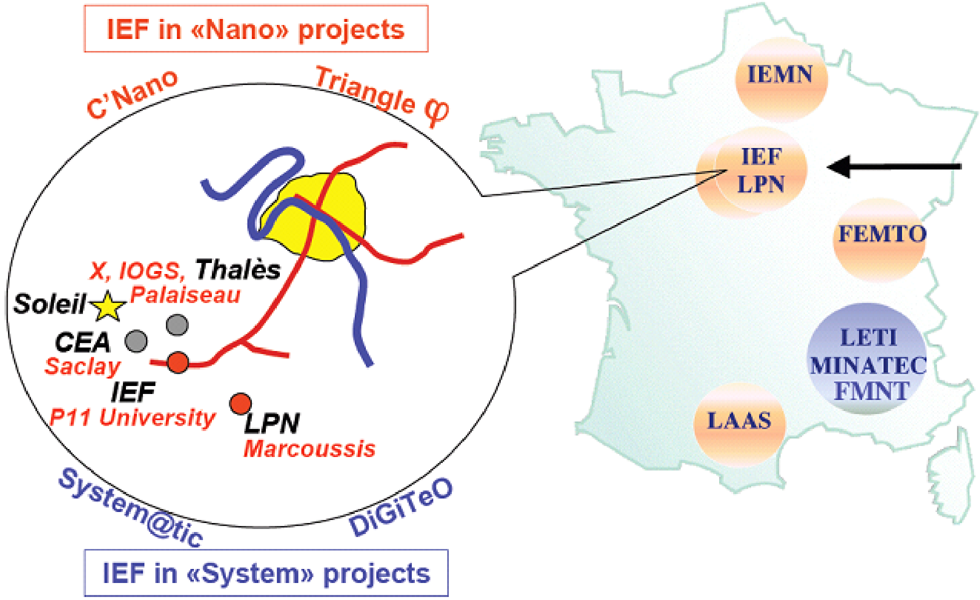


IEF is a joint research unit between CNRS and University of Paris Sud

135	CNRS researchers, professors and lecturers, technical staff
+100	PhD students, Post-Doc and visitors
~ 400	students undergoing training within IEF's ground

Spintronics and Si-based Nano-electronics

Micro-Nano systems and systems

Photonics

University Technology Center (CTU) MINERVE

University Technology Center

IEF-MINERVE member of The French Network on "Basic Technological Research" (RTB)

University Technology Centre (1000 m²):

Photolithography:

- 2-sided UV lithography with wafer bonding
- Deep UV lithography (248 nm)
- 2 e-beams (Raith150 and 100keV nanobeam)
- Laser

Etching:

- Wet etching (KOH, TMAH, …)
- Dry etching :
  - fluoride gases RIE (2 systems)
  - ICP Si deep etching
  - IBE
  - 0_2 plasma etching
  - Chloride gases RIE

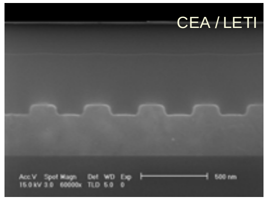
…

Silicon photonics group

- 4 permanent Researchers
- 2 engineers, technicians
- 16 PhD students
- 2 post-doc
- 2-4 master students / year

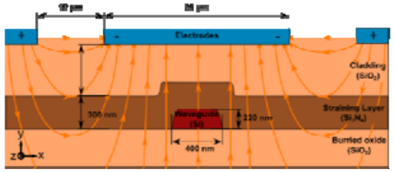
Passive devices

Grating couplers
- ➢Waveguides
- ➢Splitters
- ➢Optical Distribution
- ➢Multi-wavelength circuits



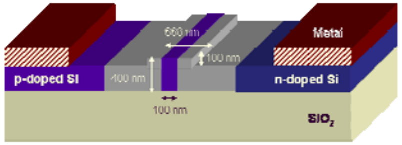
Strained Si photonics

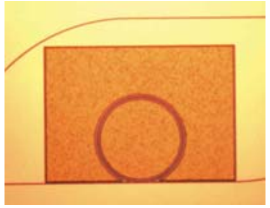
- ➢ Pockels effect



Optical modulators

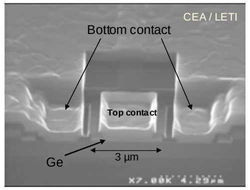
- ➢All silicon
- ➢NL materials
- ➢Plasmon

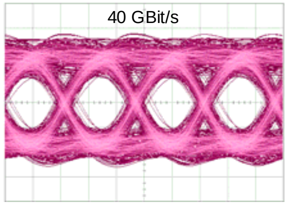




Ge detectors

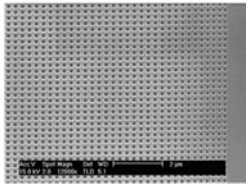
- ➢Surface illuminated
- ➢Integrated
- ➢APD

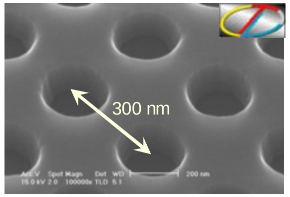




Photonic crystals

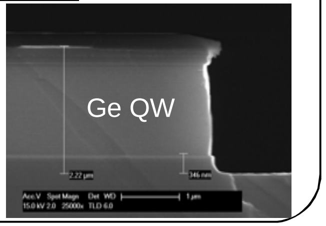
- ➢Slow light
- ➢Superprism
- ➢NL enhancement



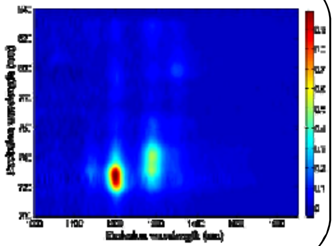


Ge-SiGe QW photonics

- ➢ Source
- ➢ Modulator
- ➢ detector



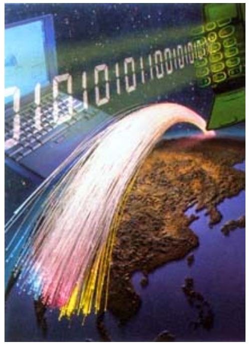
Carbon nanotubes for photonics



Outline

- Motivation (Pavel's and Lorenzo's talks)
- Photodetectors on silicon
  - √ Main characteristics
  - √ Results
- Optical modulators
  - √ Figures of Merit
  - √ Modulation in silicon
  - √ Results
- Conclusion

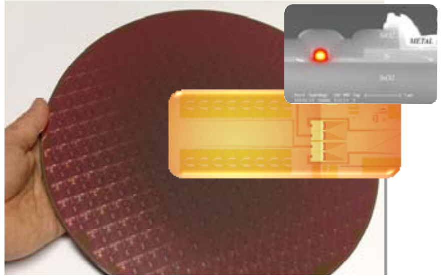
FTTH



Optical telecommunications

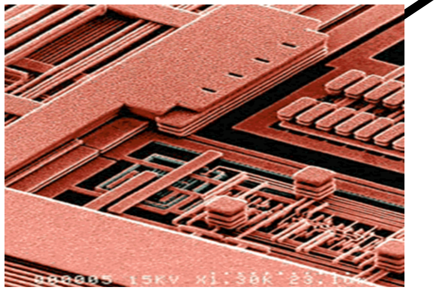
Environment

Data centers

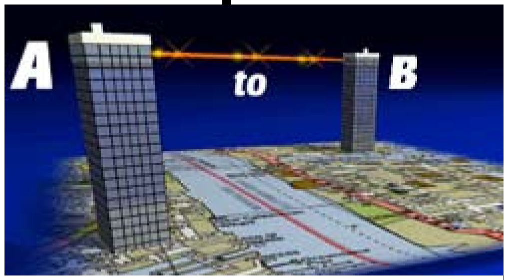


Silicon photonics

Chemical/Biological sensors



Interconnects

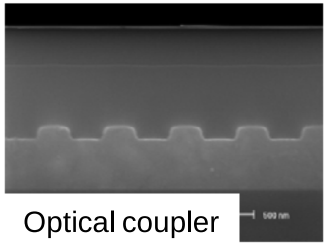


Free space communications

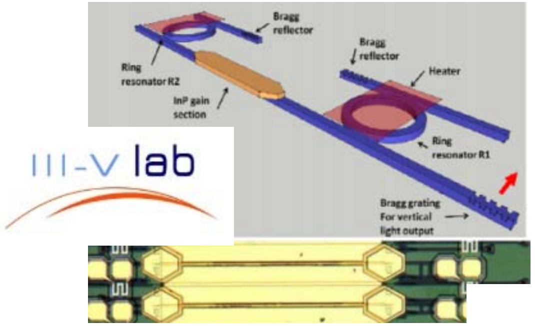
Military

Silicon photonic building blocks

Off-chip III-V laser

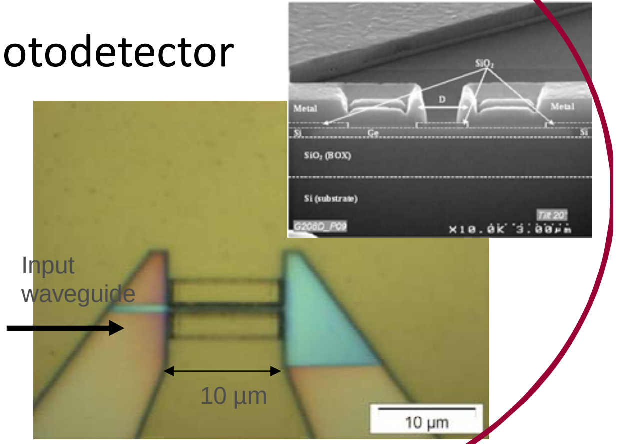

Optical coupler

On-chip III-V laser on Si



Germanium-based laser

photodetector



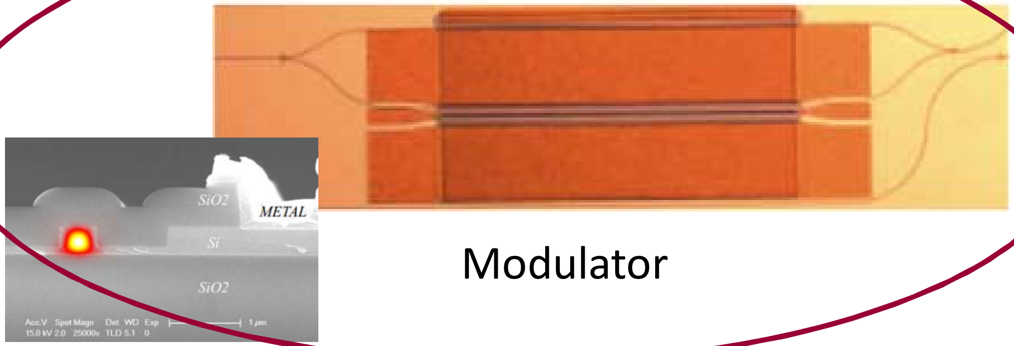
Emitter

Laser

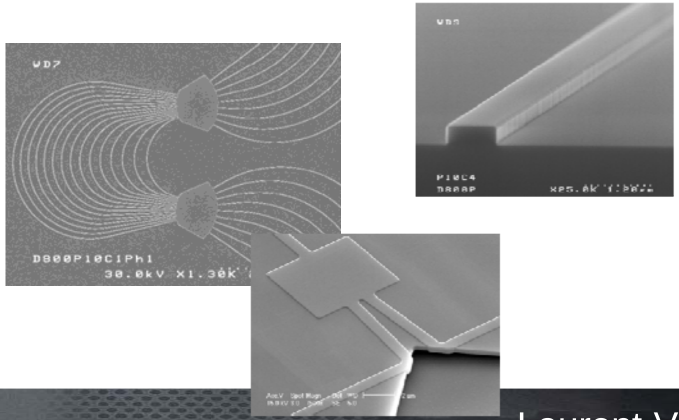
Modulator

Receiver

Detector

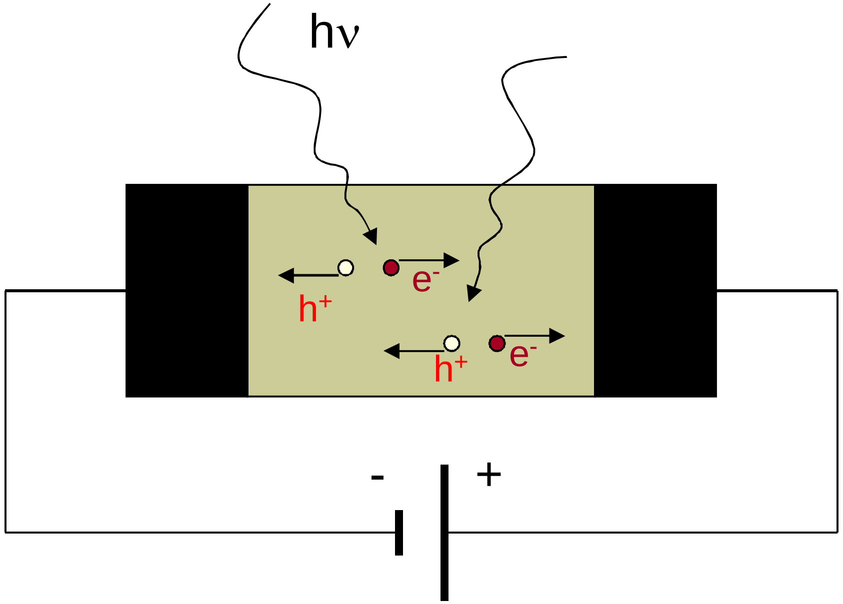


Modulator



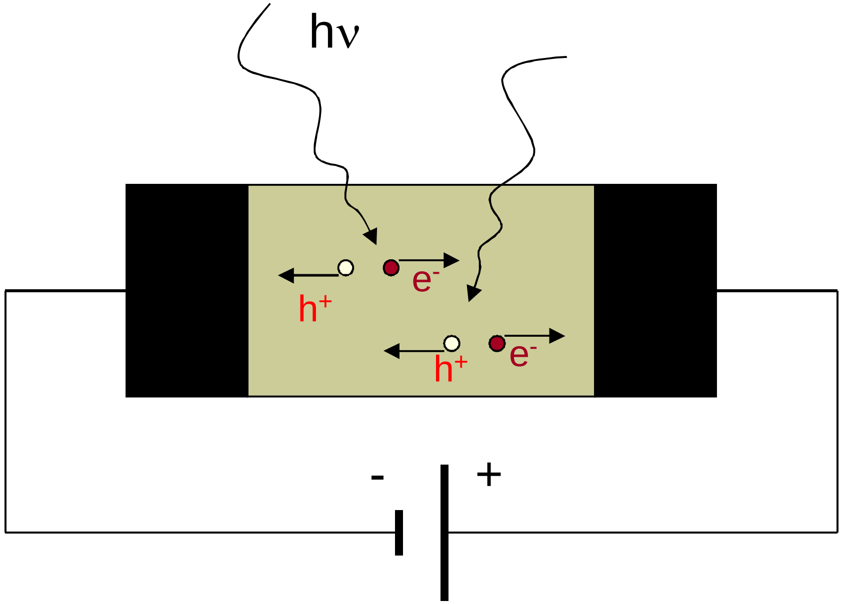
Photodetection

Main characteristic of the material?



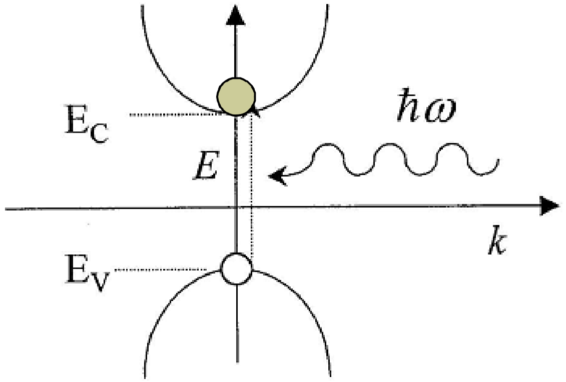
Basic principle

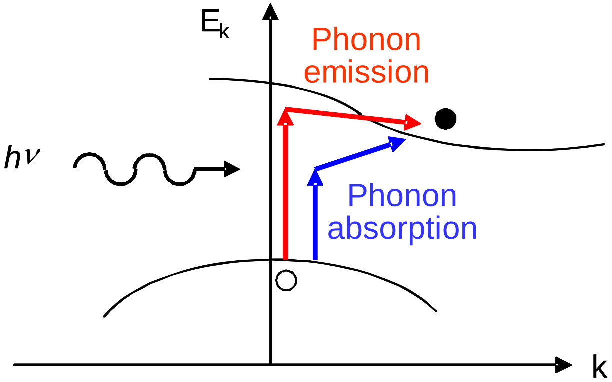
- The aborption of photons generates electron-hole pairs
- Photogenerated carriers are then collected thanks to an external field
  - √ Photocurrent



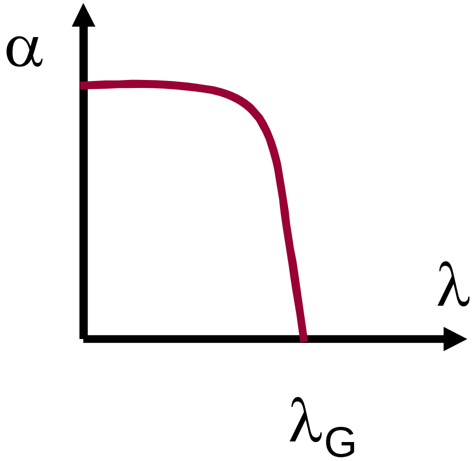
Absorption mechanisms (II)

- Direct gap SC (III-V SC)
- Indirect gap SC (IV-IV SC)

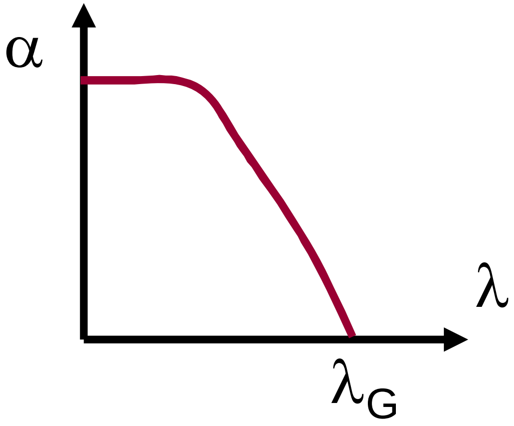




✓ absorbed photons ***generate*** free electron-hole pairs

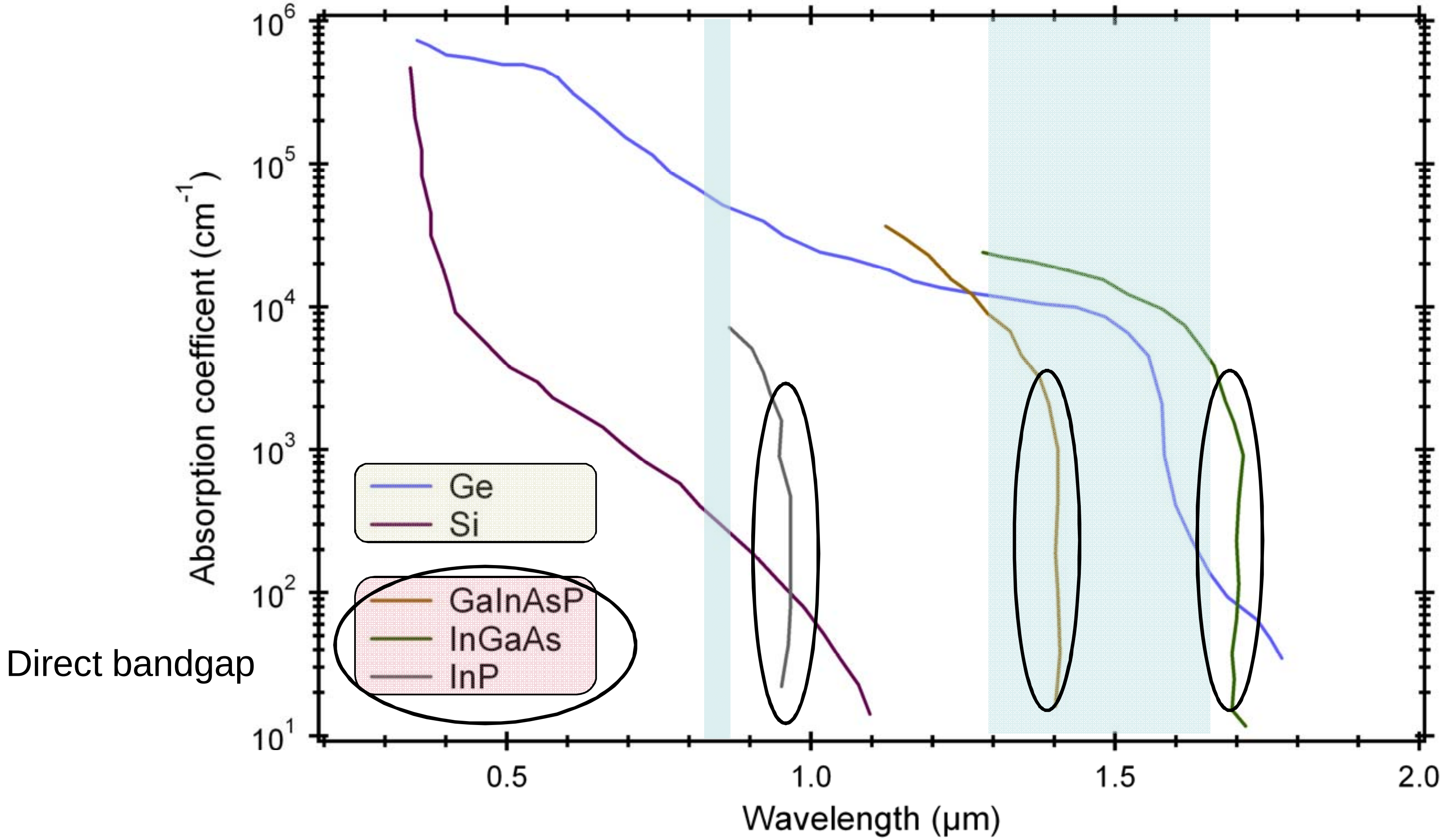


$$E_G=hc/\lambda_G$$



Material choice

- Wavelength ranges:
  - √ 1.3 µm – 1.6 µm
  - √ 0.85 µm



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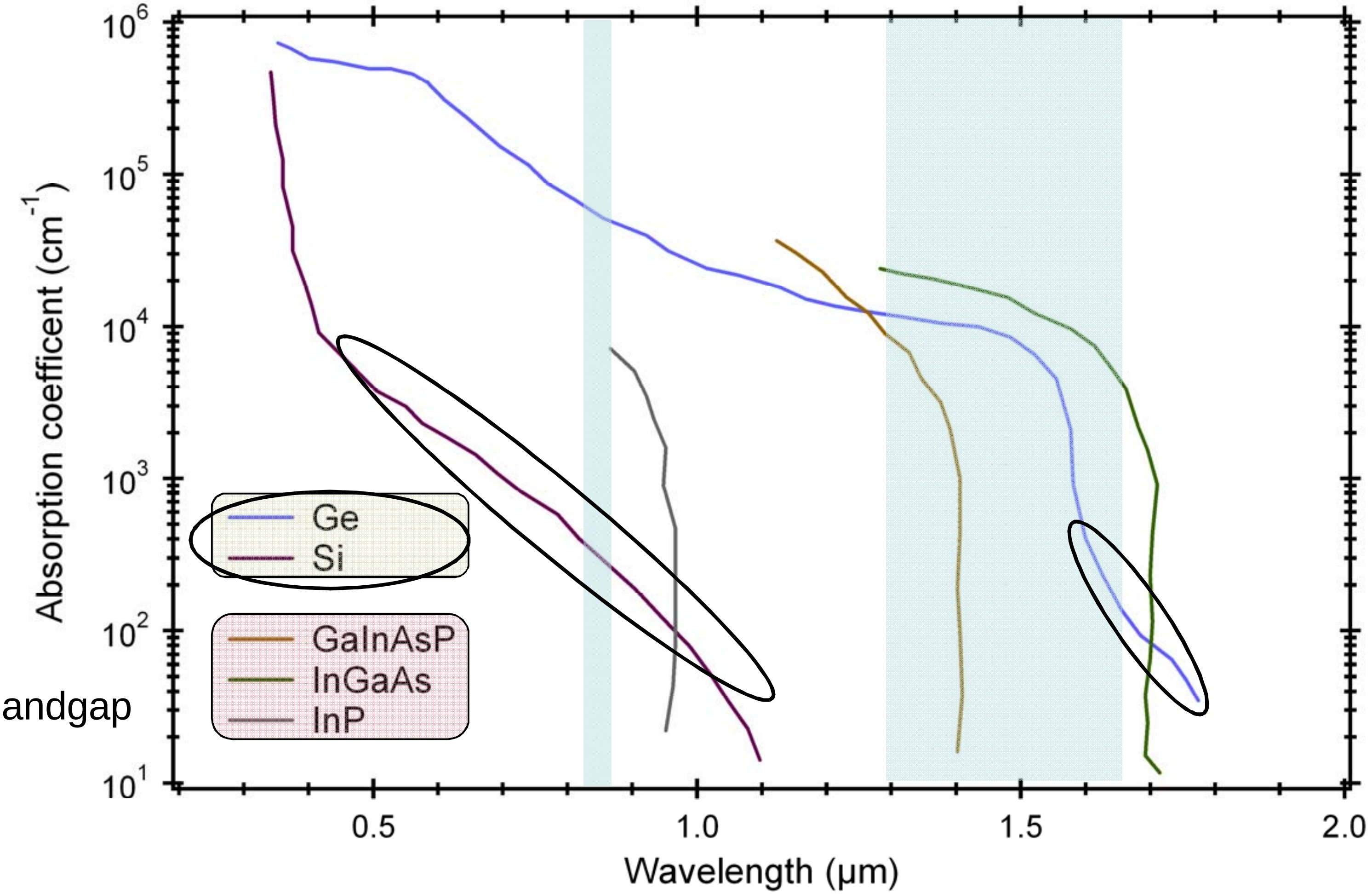
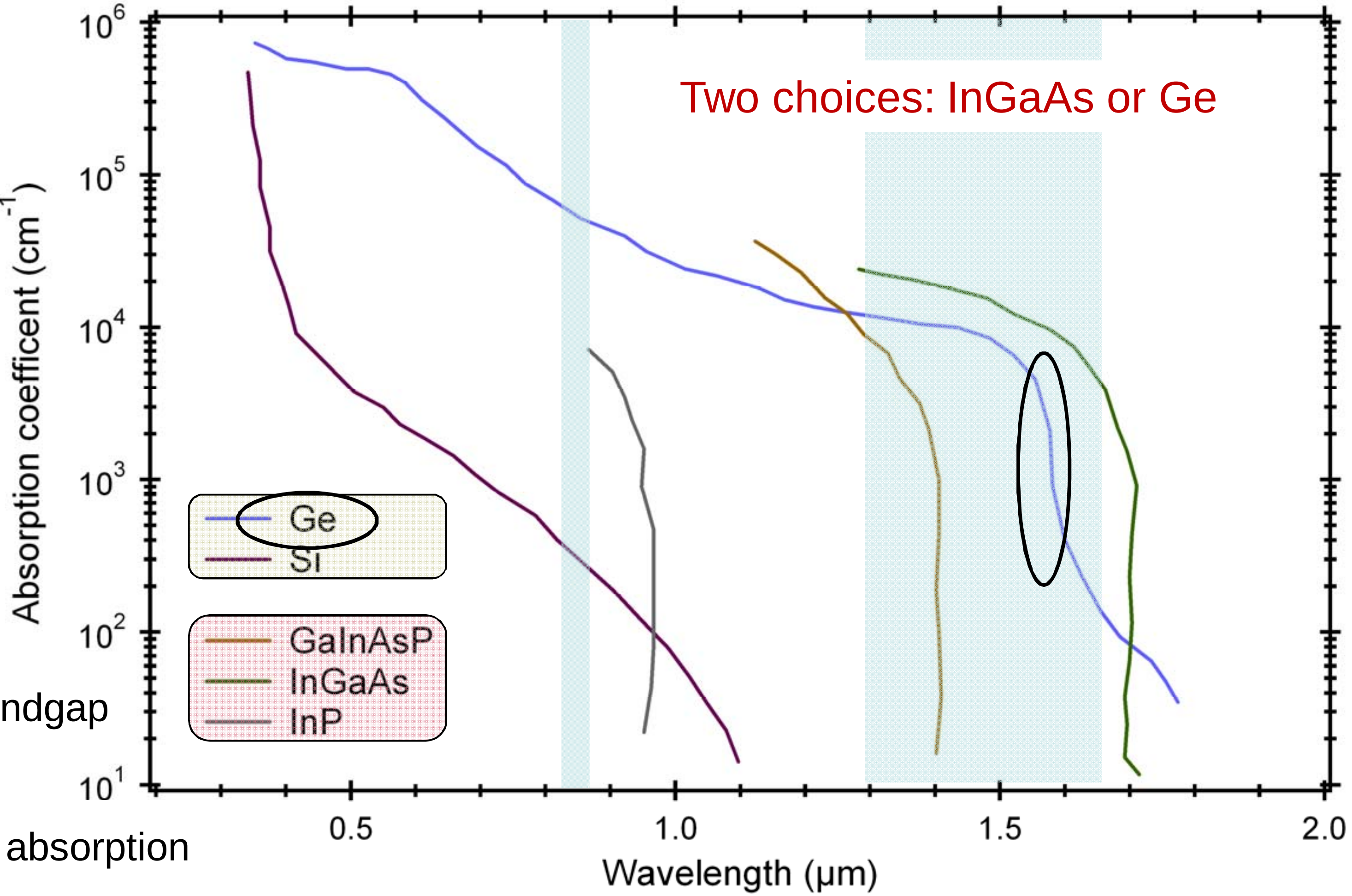


Indirect bandgap

Material choice

- Wavelength ranges:
  - √ 1.3 µm – 1.6 µm
  - √ 0.85 µm



Indirect bandgap

↓

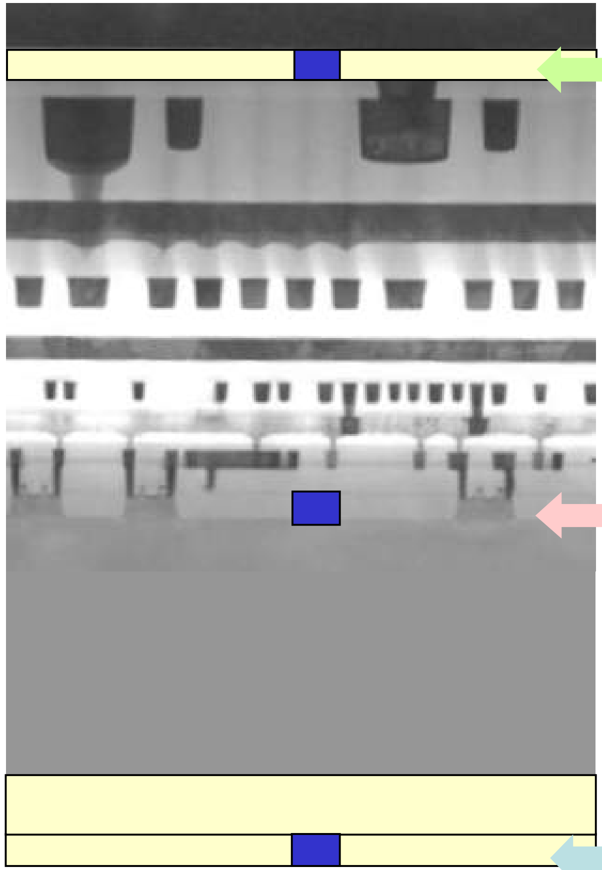
Direct gap absorption

Material choice

- InGaAs versus Germanium

What is the best material for light detection in near-IR wavelength range ?

Material choice versus electronic photonic integration scheme



BE: Back end FE:Front end

Photonic layer at the last levels of metallizations with back-end fabrication

1) Wafer bonding of PIC (high T°C)

2) BE fab(<400°C)

- Use of standard FE CMOS technologies
- High integration density (AboveIC)
- Multilevel process capability

Combined front-end fabrication

- Specific FE CMOS technology and library
- Flip-Chip hybridization of InP components
- Moderate integration density
- Efficient connections of EIC and PIC

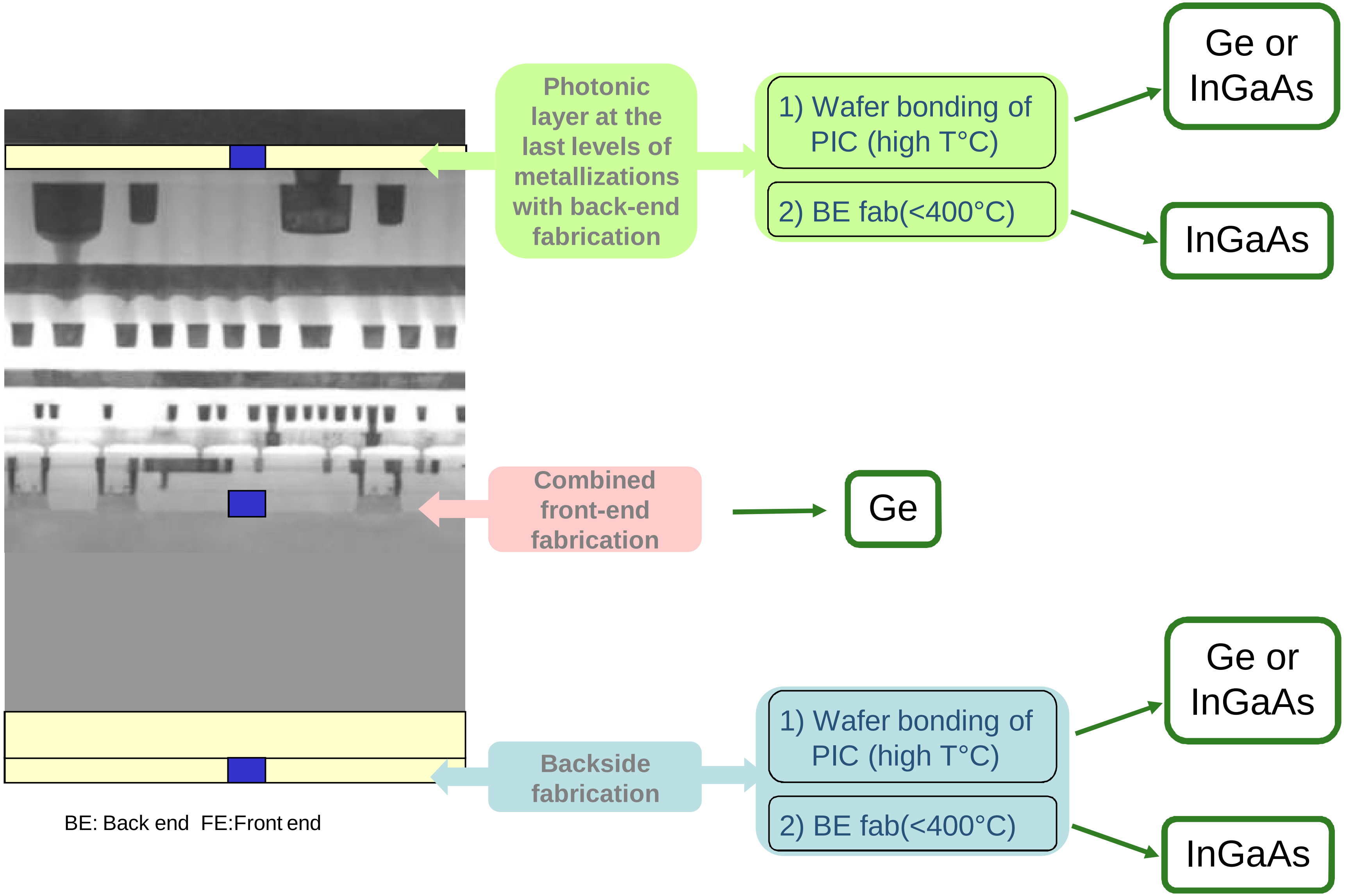
Backside fabrication

1) Wafer bonding of PIC (high T°C)

2) BE fab(<400°C)

- Through substrate connections
- High integration density

Material choice versus integration scheme



Photonic layer at the last levels of metallizations with back-end fabrication

1) Wafer bonding of PIC (high T°C)

2) BE fab(<400°C)

Ge or InGaAs

InGaAs

Combined front-end fabrication

Ge

Backside fabrication

1) Wafer bonding of PIC (high T°C)

2) BE fab(<400°C)

Ge or InGaAs

InGaAs

BE: Back end FE:Front end

Are III-V materials integrated in silicon platform?

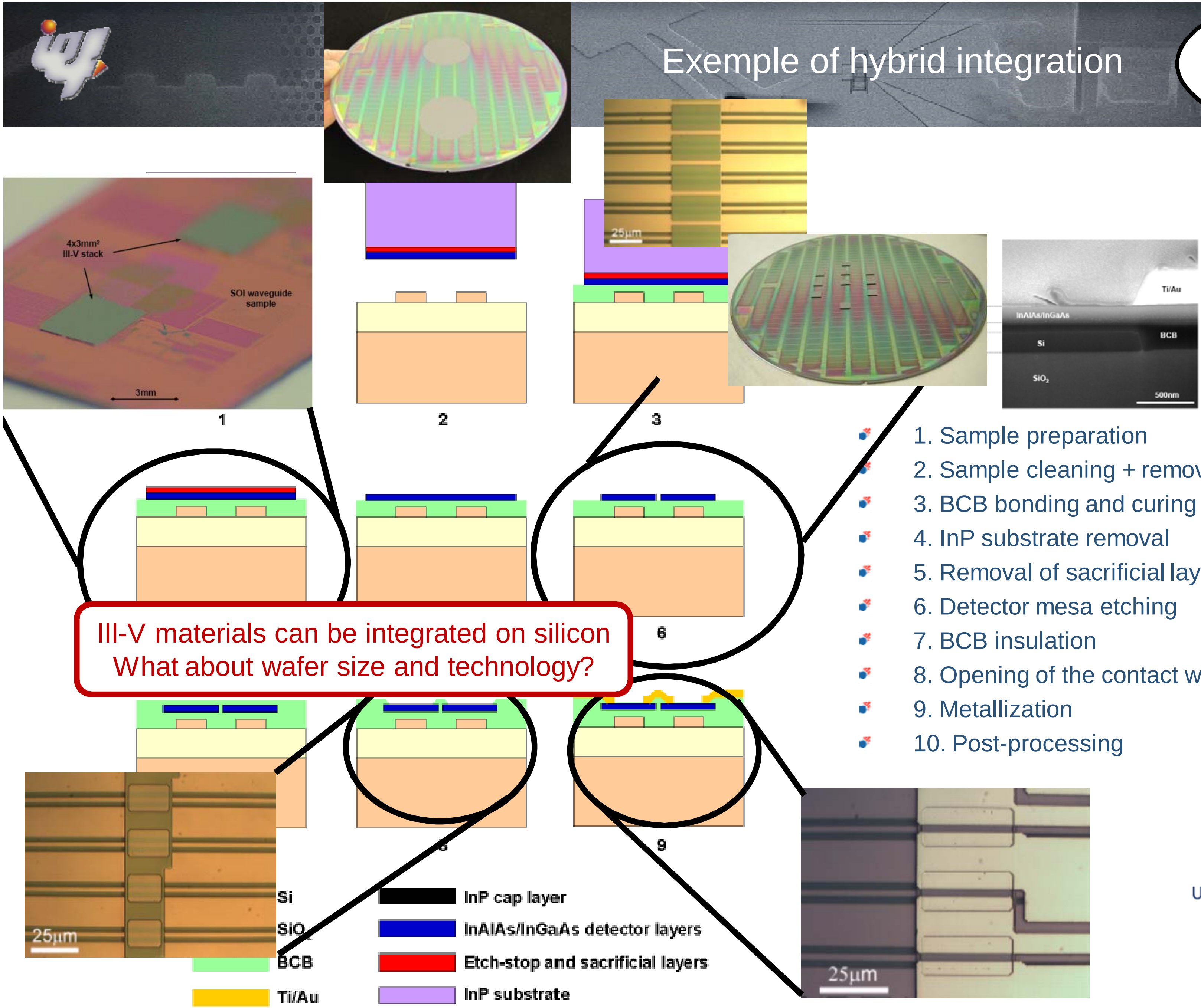
✓ Monolithic integration via epitaxial growth

No viable solutions yet

✓ Hybrid integration

BCB or molecular bonding

Exemple of hybrid integration



III-V materials can be integrated on silicon
What about wafer size and technology?

1. Sample preparation
2. Sample cleaning + removal of cap layer
3. BCB bonding and curing
4. InP substrate removal
5. Removal of sacrificial layers
6. Detector mesa etching
7. BCB insulation
8. Opening of the contact windows
9. Metallization
10. Post-processing

Germanium on silicon:
Pros and Cons

☺

- Absorption coefficient of pure Ge:
  - $\alpha \approx 9000\ \mathrm{cm}^{-1}$ at $\lambda = 1.3\,\mu\mathrm{m}$
    $\Rightarrow L_{ABS}^{95\%} \approx 3.3\,\mu\mathrm{m}$ (!)
    $\Rightarrow$ Low capacitance devices
    $\Rightarrow$ High frequency operation

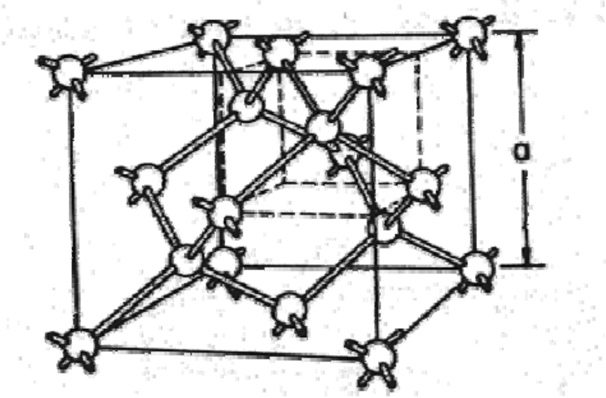
- High carrier mobility

Crystal lattice structure of Silicon and Germanium

- Si and Ge have a diamond lattice structure (two interdigitated FCC lattices)

Properties	Silicon	Germanium
Lattice parameter: a (Å)	5.431	5.658
Atomic density (cm^{-3})	$5,0.10^{22}$	$4,42.10^{22}$
Atom radius (Å)	0.117	0,122
Lattice structure	Diamond	Diamond

Lattice parameter mismatch: ~4.2 %



Germanium on silicon: Pros and Cons

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    $\Rightarrow L_{ABS}^{95\%} \approx 3.3\mu\text{m}$ (!)
    $\Rightarrow$ Low capacitance devices
    $\Rightarrow$ High frequency operation

- High carrier mobility

☹

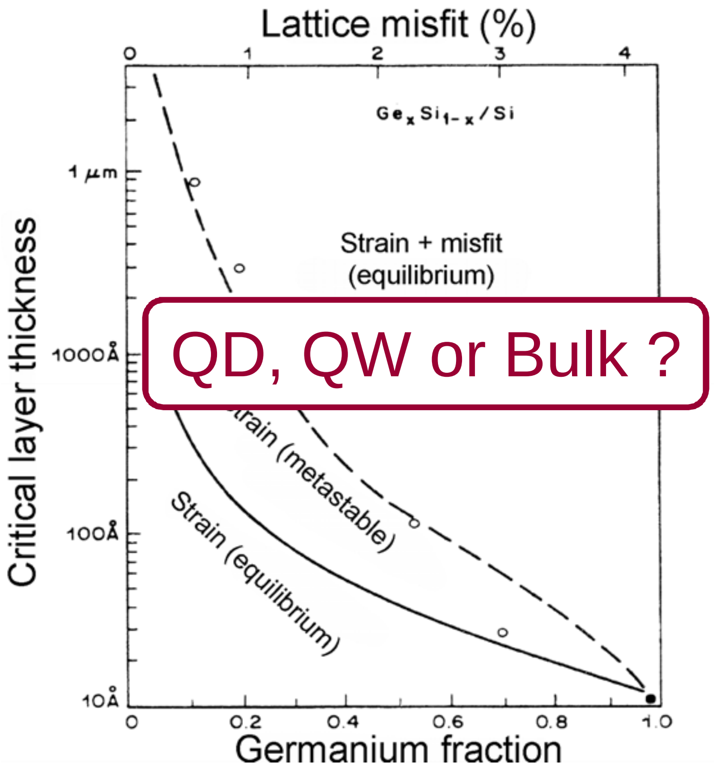
- Lattice misfit with Si of about 4.2%
  $\Rightarrow$ specific growth strategies required (wafer-scale and localized)

- Low indirect bandgap: $E_G = 0.66\text{eV}$
  $\Rightarrow$ high dark current for MSM devices

Can we directly growth Ge on silicon?

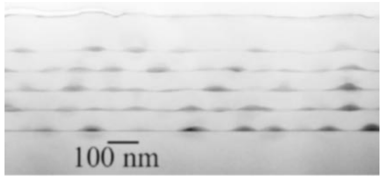
The lattice mismatch

- 4.2% of lattice mismatch between germanium and silicon

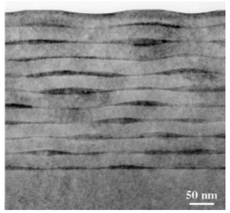


QD, QW or Bulk ?

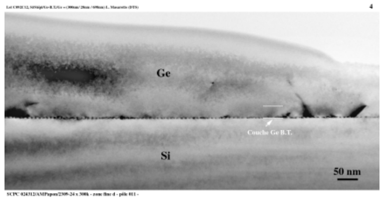
SiGe on Si



Ge quantum dots



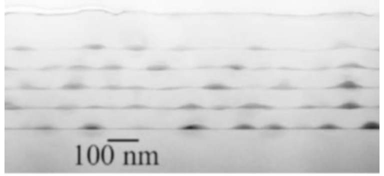
$Si_{1-x}Ge_x/Si$ quantum wells



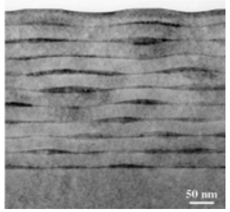
Pure Ge on Si

Ge-based structures

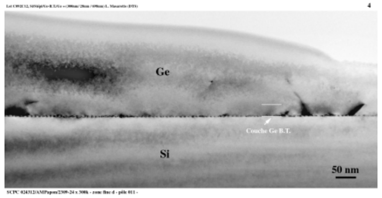
- Ge quantum dots
  - $\alpha \sim 20\,\mathrm{cm}^{-1}$ (90% absorption length ~ 1.1mm)



- $Si_{1-x}Ge_x/Si$ quantum wells
  - $\alpha \sim 100\text{-}200\,\mathrm{cm}^{-1}$ (90% absorption length ~ 230-110µm)

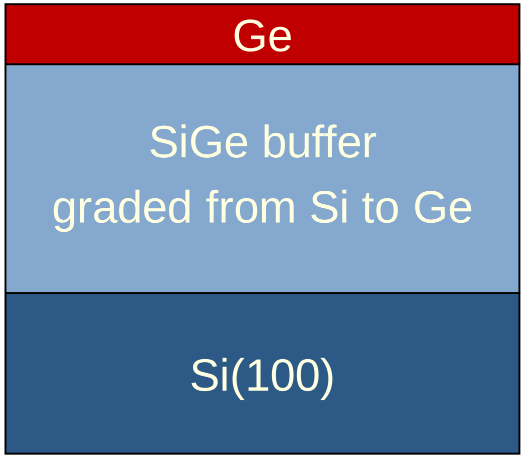


- Pure Ge on Si
  - $\alpha \sim 7500\,\mathrm{cm}^{-1}$ (90% absorption length ~ 3µm)



Ge growth strategies

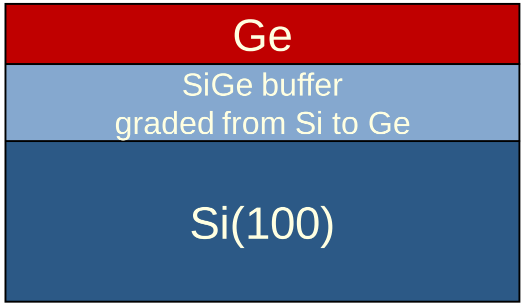
- Thick virtual SiGe substrates (10µm)
  - √ Need for a new integration scheme – difficult to integrate with SOI waveguides.



Ge growth strategies

- Thick virtual SiGe substrates (10µm)
  - √ Need for a new integration scheme – difficult to integrate with SOI waveguides.

- Growth on thin SiGe buffers
  - √ The thickness of the thin SiGe buffer is around 1µm
    - ➢ Always too thick for integration with SOI



Ge growth strategies

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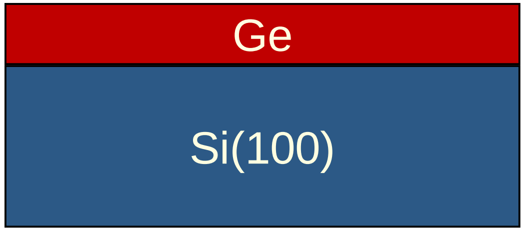
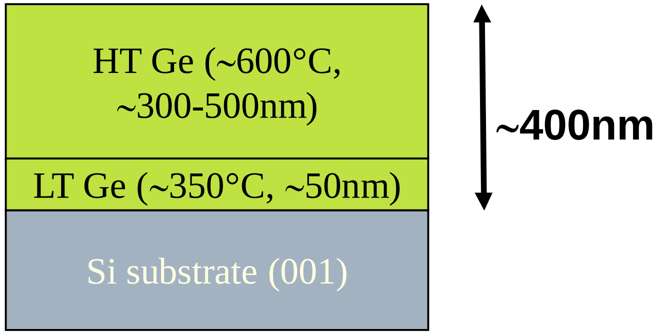
- Growth on thin SiGe buffers
  - √ The thickness of the thin SiGe buffer is around 1µm
    - ➢ Always too thick for integration with SOI
- Direct Ge growth on Si



Germanium growth

- Two-step growth process:
  - √ Direct growth of Ge on Si using a low temperature (~350°) CVD process
    ⇒ thin (a few 10nm) highly-dislocated Ge layer
  - √ Growth of a thick Ge layer (a few 100nm) at a higher temperature (~600°)
    ⇒ high quality Ge absorbing layer

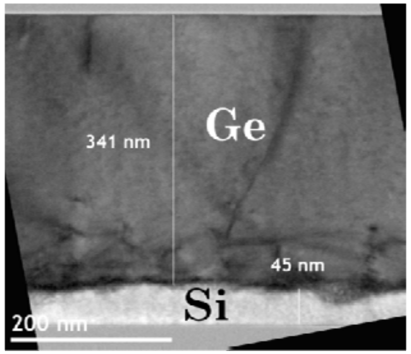
- Thermal annealing to reduce the dislocation density


HT Ge (~600°C, ~300-500nm)

LT Ge (~350°C, ~50nm)

Si substrate (001)

~400nm



Epitaxial growth techniques

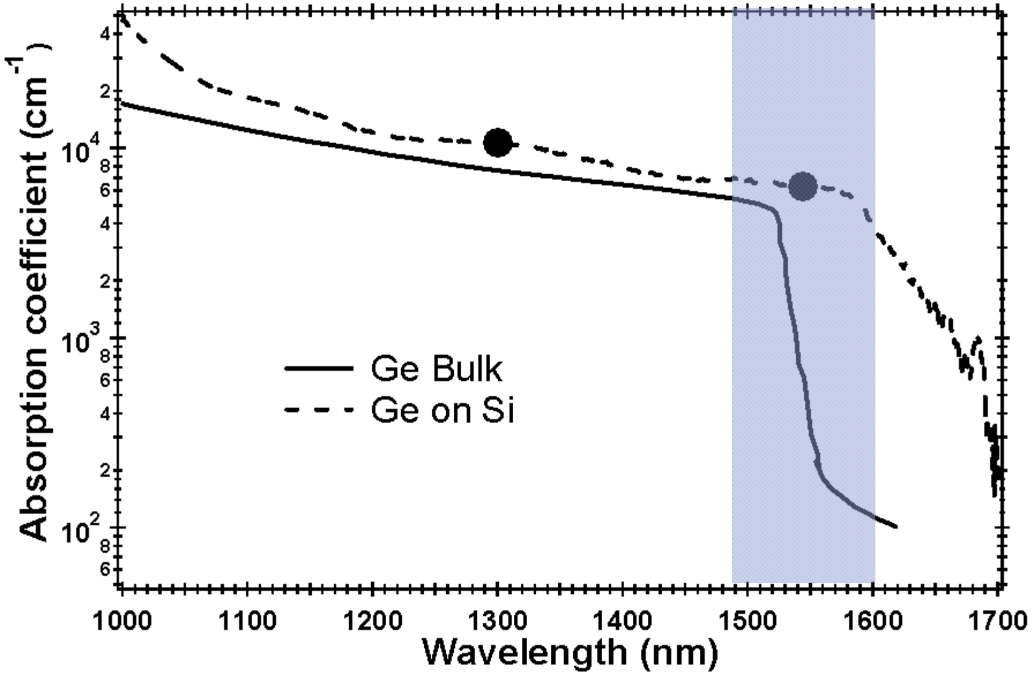
❑ Molecular beam epitaxy (MBE)

- Solid sources evaporated ⇒ gas sputtering on the wafer
- Ultra-high vacuum required ($P \sim 10^{-10}$ Torr)
- Low thermal budgets ($T < \sim 550°C$)
- High-control of layer and multi-layer thicknesses (<nm)
- Low growth rates (<1 nm/min)

❑ Chemical Vapor Deposition (CVD):

- High-control of layer and multi-layer thicknesses (<nm)
- Proper for large wafer-scale fabrication
- A large variety of CVD techniques have been developed, depending on the pressure and heating systems:
  - Ultra-High Vacuum CVD (**UHV-CVD**)
  - Reduced-pressure CVD (**RP-CVD**)
  - Low-energy plasma-enhanced CVD (**LEPE-CVD**)

Absorption of Ge-on-Si



- The red-shift of the absorption edge is due to the tensile strain-induced bandgap narrowing within the Ge layer, resulting from the difference in the thermal expansion coefficients of Ge and Si

Strong absorption up to 1.6µm

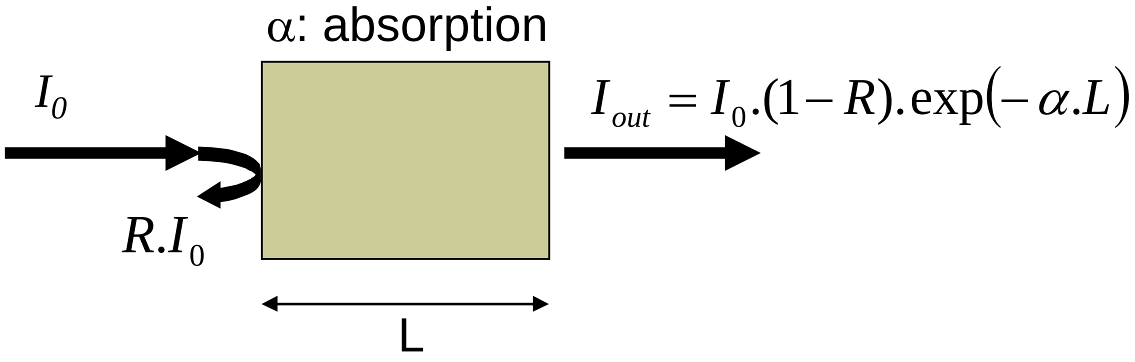
Photodetector characteristics

Photodetector characterisitics: Quantum efficiency (I)

- Quantum efficiency (η):
  - √ Probability of detecting an incident photon by generating an electron/hole pair that contributes to the photocurrent
  - √ Ratio of the generated carriers to incident flux of photons (i.e.: ratio of the photocurrent to the incident light power)
  - √ The spectral response is governed by the spectral character of the quantum efficiency

Photodetector characterisitics: Quantum efficiency (II)

- Quantum efficiency (η) depends on:
  - √ Reflectance on the surface
  - √ Absorption



$$I_{out} = I_0.(1-R).\exp(-\alpha.L)$$

The amount of flux that is absorbed in the material

$$I_{abs} = 1 - I_{out} = I_0.(1-R).[1-\exp(-\alpha.L)]$$

$$\boxed{\eta = (1-R).[1-\exp(-\alpha.L)]}$$

Photodetector characterisitics: Responsivity

- Responsivity (ℜ) is often more useful to characterize the response of photodetectors

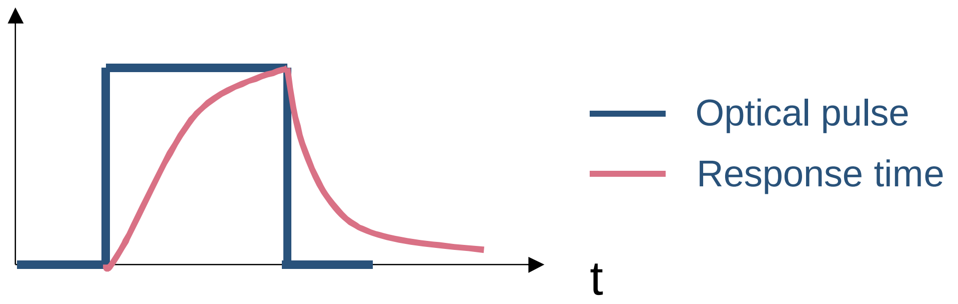
$$\Re = \frac{q.\eta}{h.\upsilon} = \frac{\eta.\lambda(\mu m)}{1.24}$$

- Responsivity is typically linear with wavelength but real photodetectors exhibit a deviation from the ideal behaviour due to photogenerated carrier trapping

Photodetector characterisitics: Response time (I)

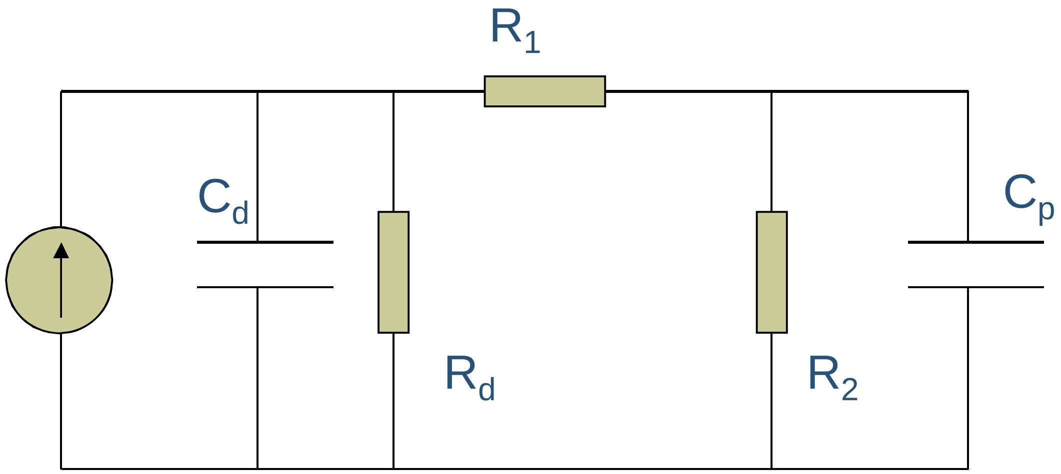
- Response time of the photodetectors:
  - √ Internal response time
  - √ External response time

- Internal response time
  - √ Transit time of carriers: depends on the velocity of carriers in SC (varies with the doping level and the material)
  - √ Diffusion time of carriers: diffusion of carrier to be collected. Mainly depends on the structure



Photodetector characterisitics: Response time (II)

- External response time



typical schematic electrical circuit of the photodiode

C_d: Diode capacitance

C_p: Parasitic capacitance

R_d: Diode resistance

R_1: contact and substrate resistances

R_2: charge resistance

R_1 and $R_d << R_2$

$$\text{Response time} = R_2\,(C_P + C_d)$$

Photodetector specifications (I)

- “Compatibility” with silicon technology
  - Silicon-based materials will be better
  - Large wafer scale technology
  - Permit electronic integration (Transimpedance amplifier – TIA)
  - Low cost integration schemes
- Broadband detection (1.3 -1.6 µm)
  - High absorption coefficient
- Low dark current
  - Electrical configuration of photodetectors,
  - Quality of the absorbing layer.

Photodetector specifications (II)

- ☐ High bandwidth (frequency operation > 10 GHz)
  - ✓ Low carrier transit time,
  - ✓ Low RC constant – depend on the considered electrical structure (pin diode, MSM detector).
- ☐ High responsivity
  - ✓ Optimize the light interaction with absorbing layer.
- ☐ Compactness
  - ✓ Strong absorption coefficient

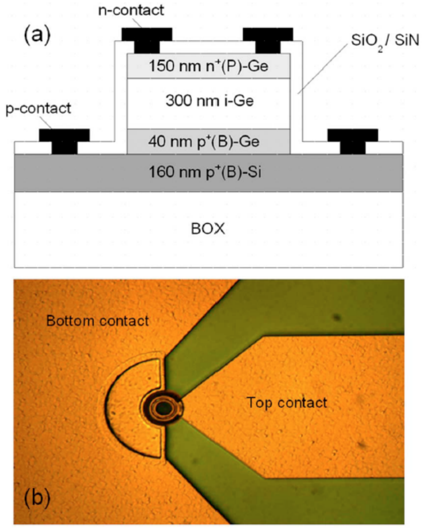
Photodetector integration

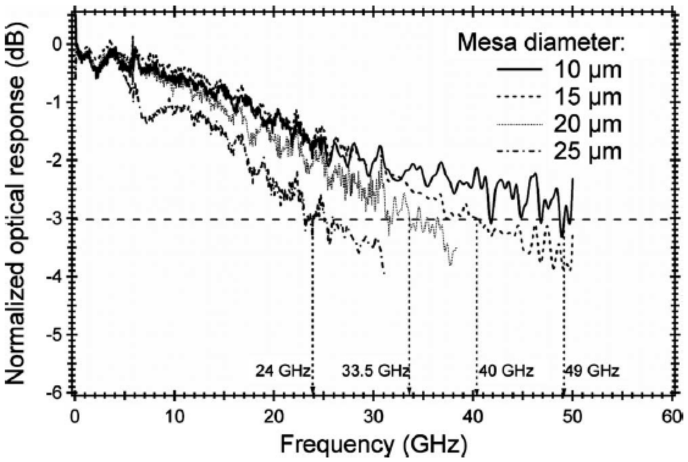
Two approaches

Surface illuminated photodetectors

☺ High bandwidth
“Simple” process

☹ “Low” responsivity





Responsivity ~0.1 A/W

Photodetector integration

Two approaches

Surface illuminated photodetectors

☺ High bandwidth
“Simple” process

☹ “Low” responsivity

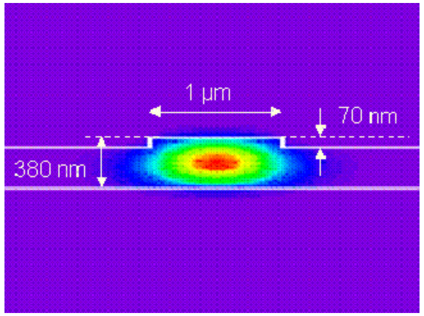
photodetectors integrated in waveguide

☺ High bandwidth
High responsivity

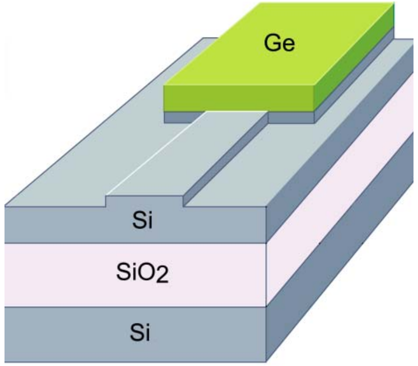
☹ Optical coupling

Integrated photodetectors: optical coupling

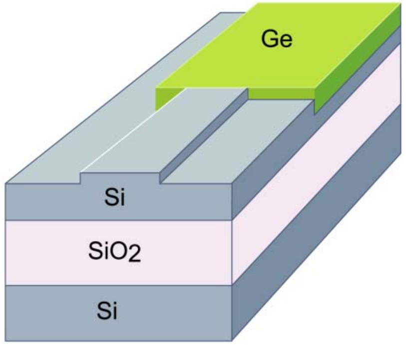
SOI waveguides



Single mode (TE)

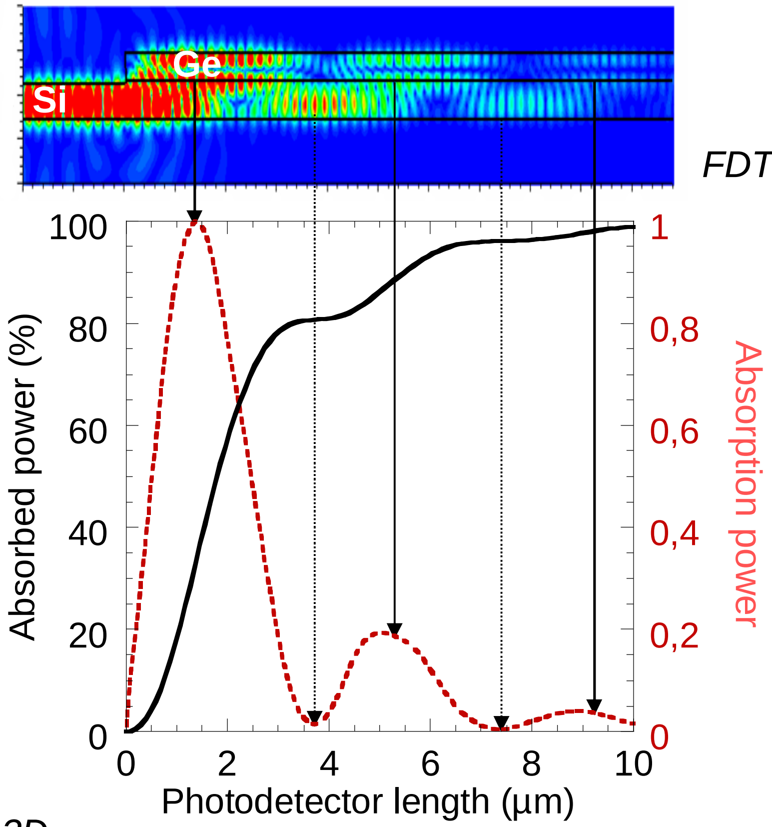


Vertical coupling



Butt coupling

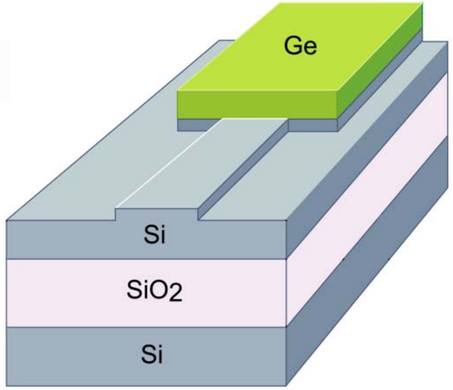
Vertical coupling

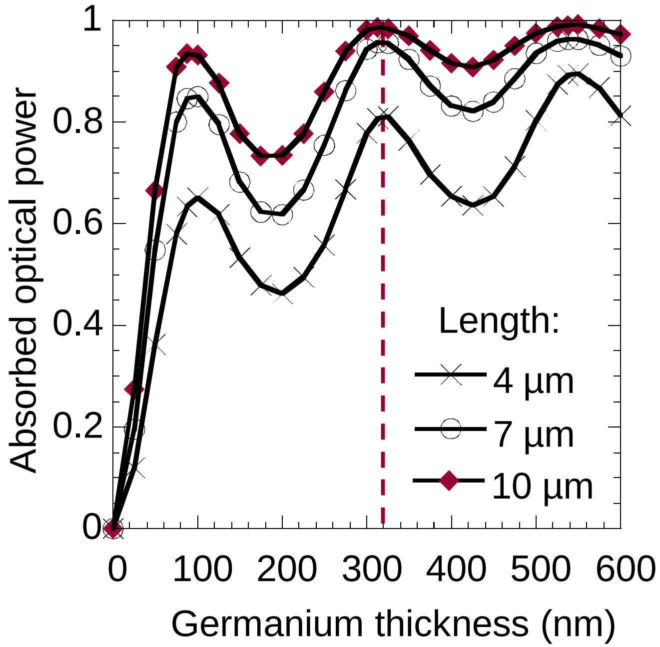


FDTD 3D

BEP 3D

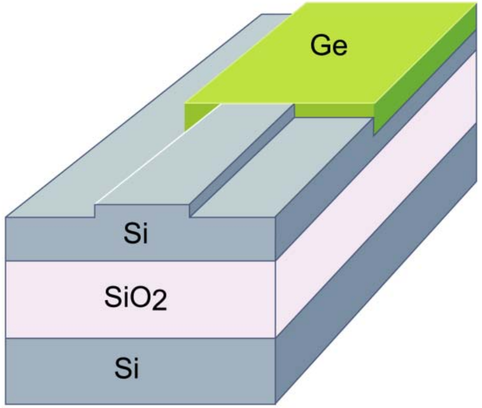
M. ROUVIÈRE, et al., Optical Engineering, 44 (2005) 183-187

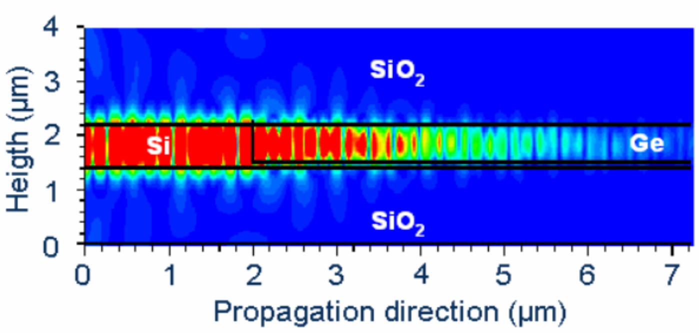




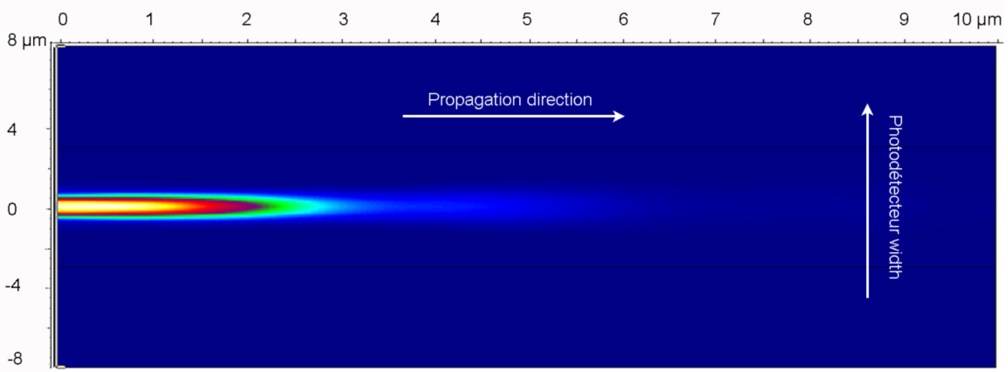
95 % absorption length < 10 µm with 310nm germanium thickness

Butt coupling



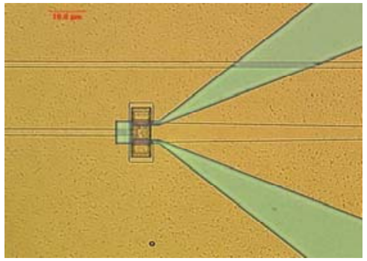


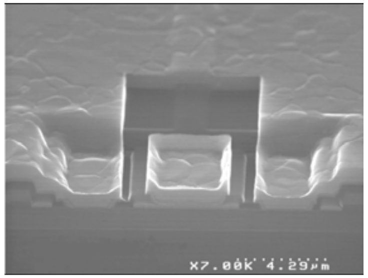
95% absorption length < 4µm

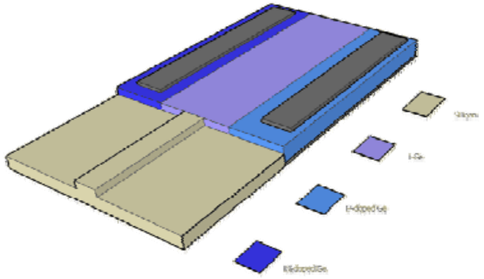


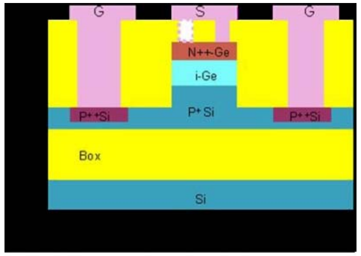
Negligible lateral divergence

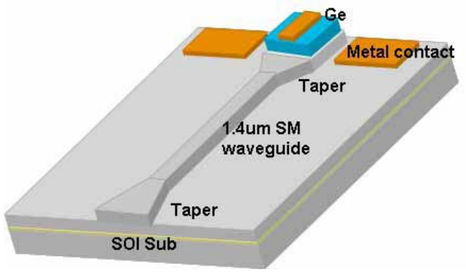
Ge Photodetectors

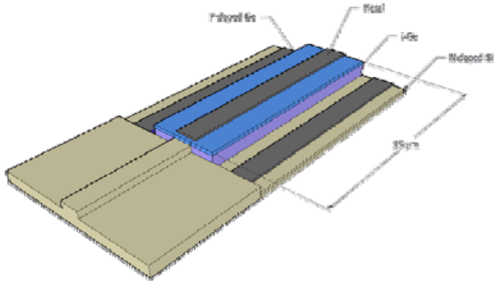


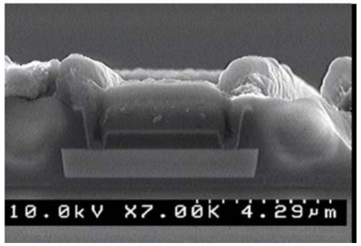


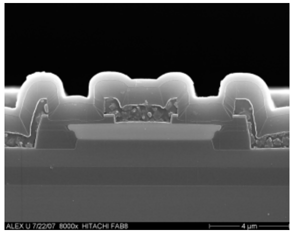










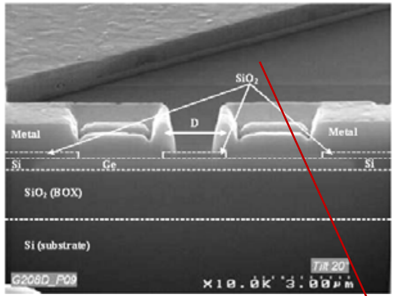


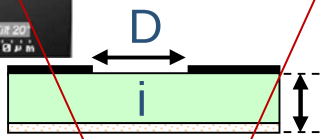
Europe: PSUD-IEF, CEA-Léti, Stuttgart Univ., Roma Univ. …

Asia: Tokyo Univ., A*Star, Petra, AIST, Chinese Academy of Sciences, …

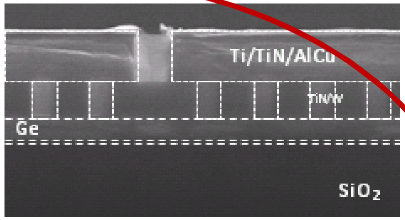
North America: Intel, MIT, IBM, Cornell, Luxtera, Ligthwire, Kortura, Oracle …

Photodetector: electrical structures

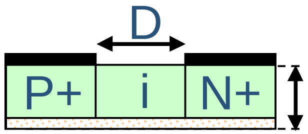




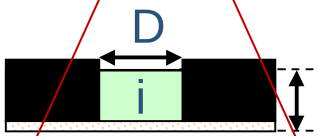
Surface contact MSM



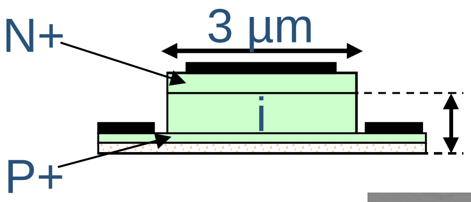
PIN



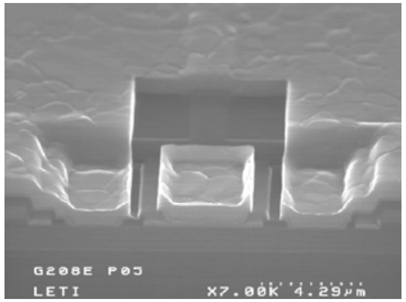
Lateral PIN



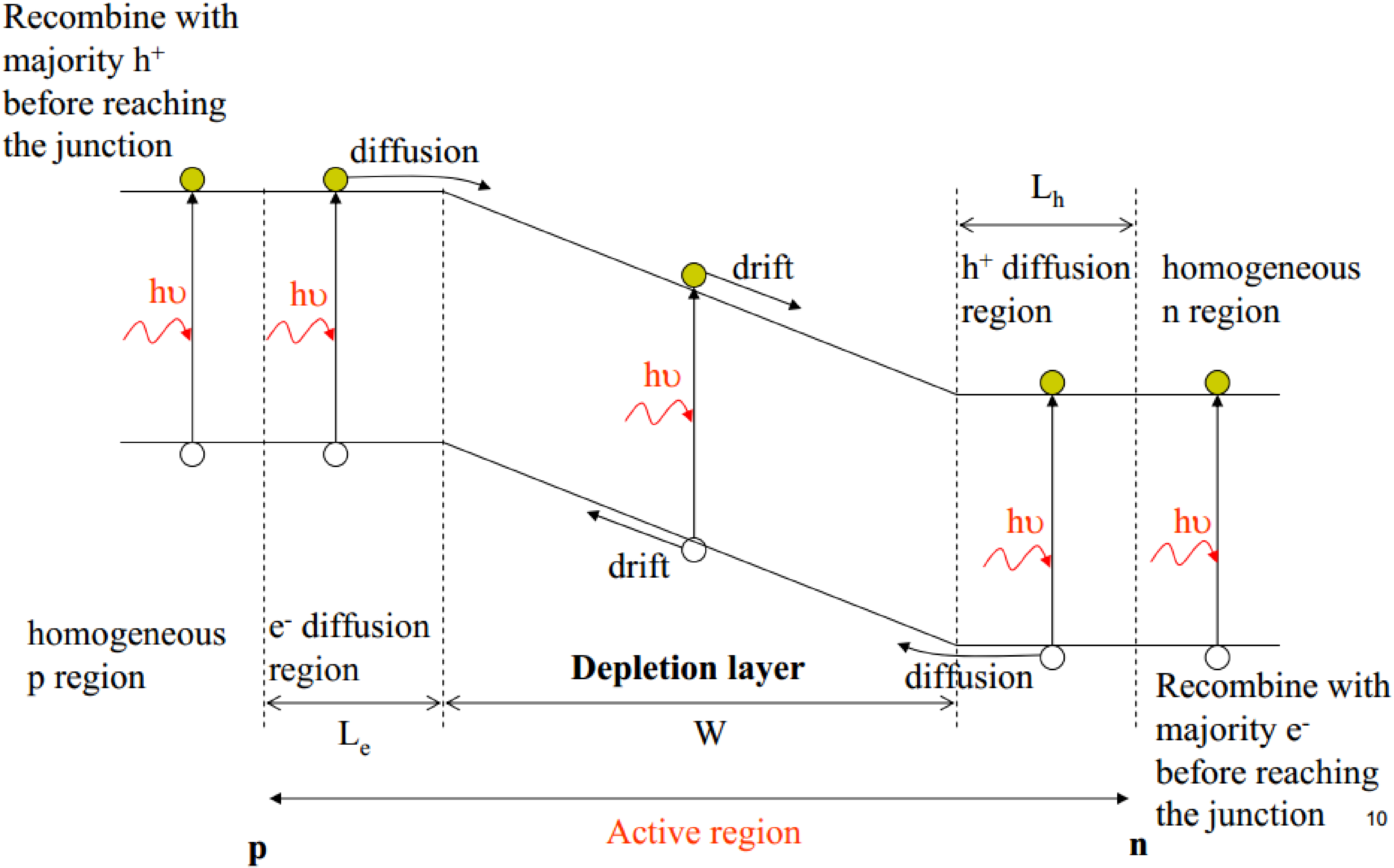
Lateral contact MSM



Vertical PIN



Diode band structure



Recombine with majority h$^+$ before reaching the junction

homogeneous p region

e$^-$ diffusion region

Depletion layer

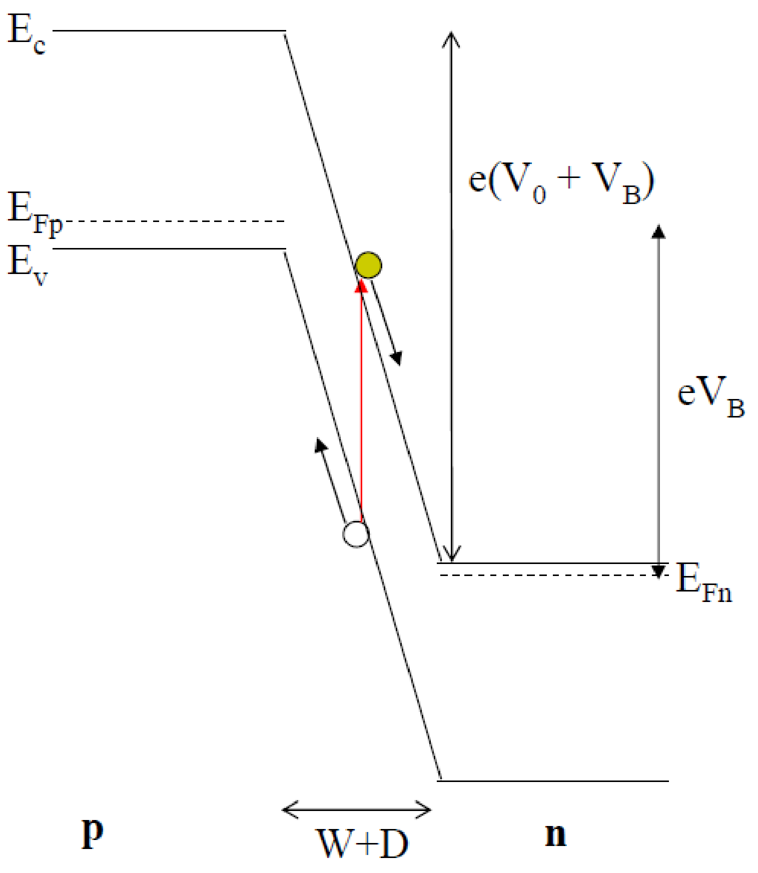
h$^+$ diffusion region

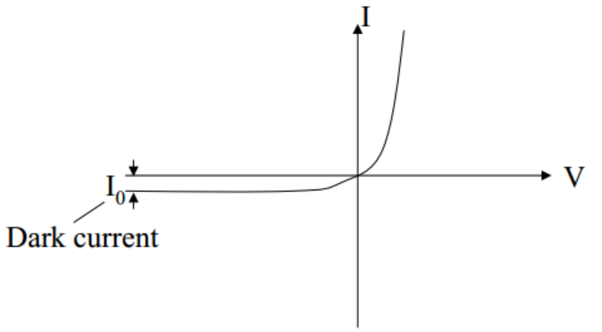
homogeneous n region

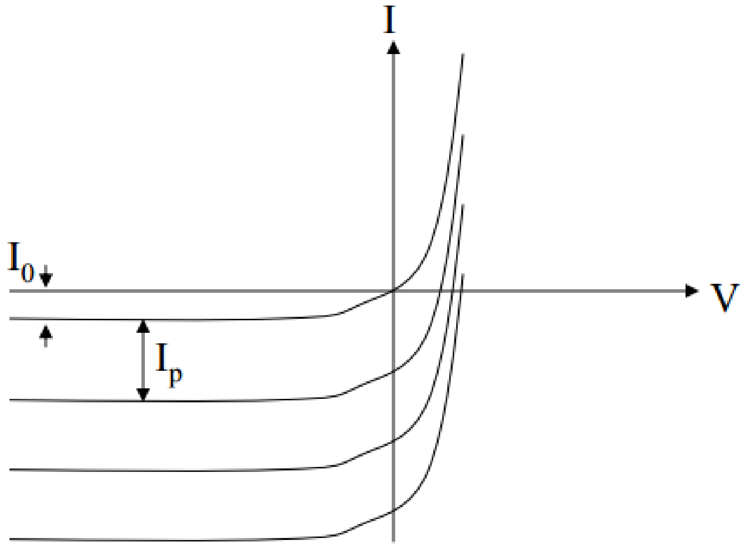
Recombine with majority e$^-$ before reaching the junction

Active region

Diode band structure



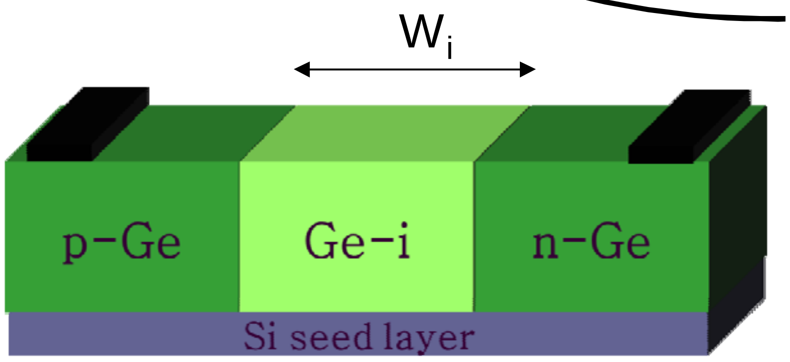


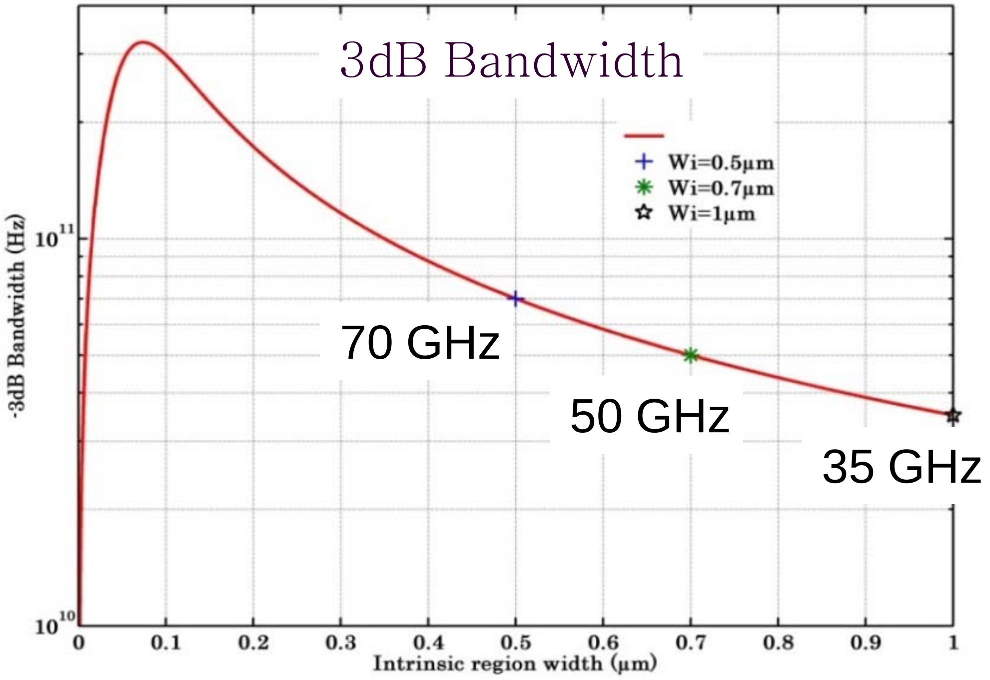


Forward or reverse bias ?

PIN Photodiodes : Design considerations

- Junction disposition
  - √ Lateral PIN
    - ➢ Contact on Ge: only one etching step
    - ➢ Definition of intrinsic region by ion implantation

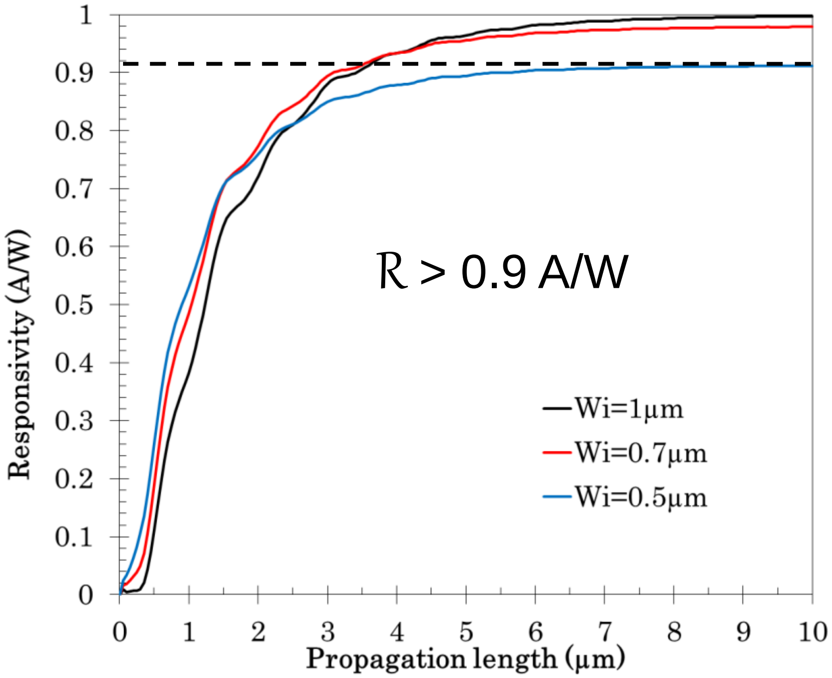




70 GHz

50 GHz

35 GHz

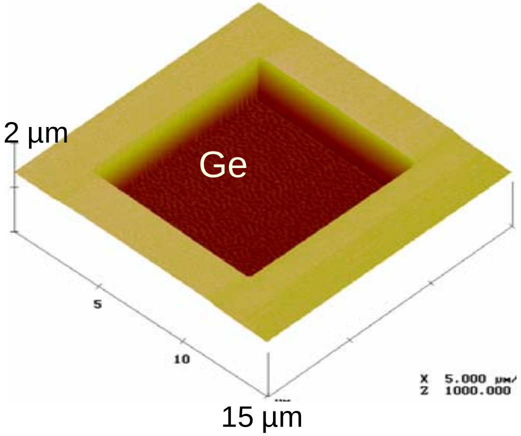


R > 0.9 A/W

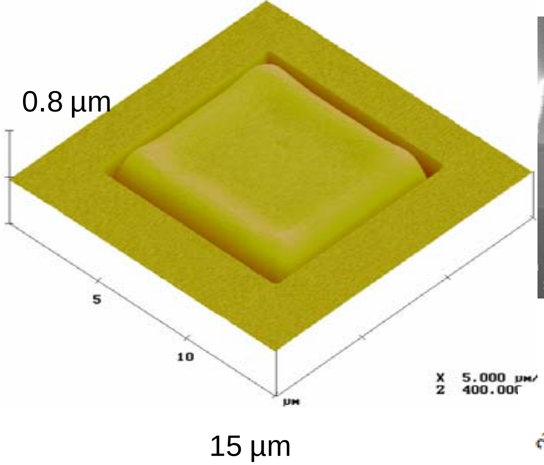
Device Fabrication: Ge Growth

- Two RPCVD steps to overcome lattice mismatch issue

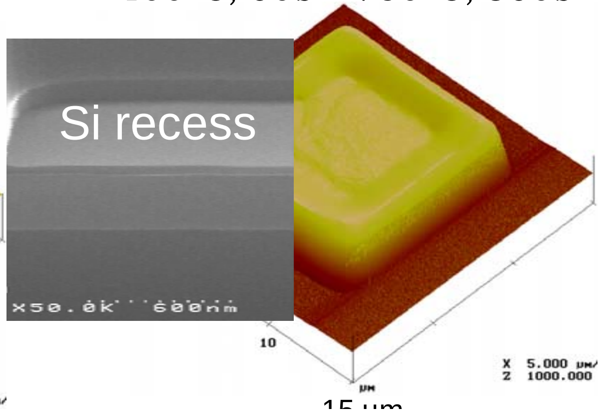
Ge « Seed » layer
400°C, 60s



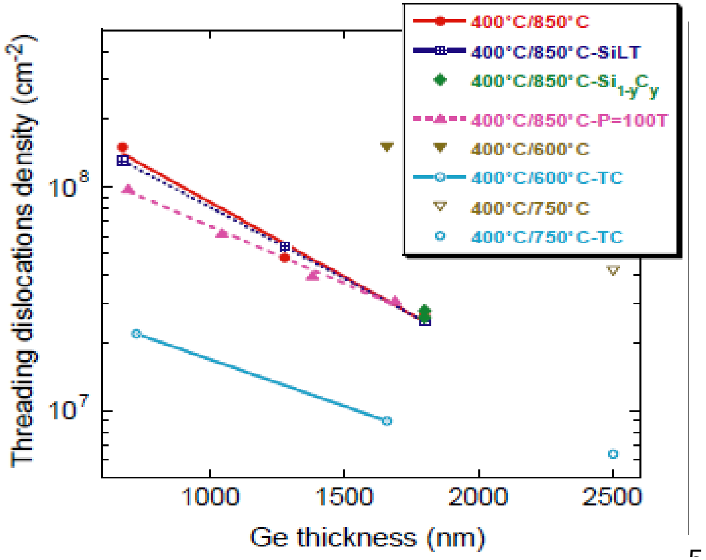
400°C, 60s + 750°C, 180s



400°C, 60s + 750°C, 360s



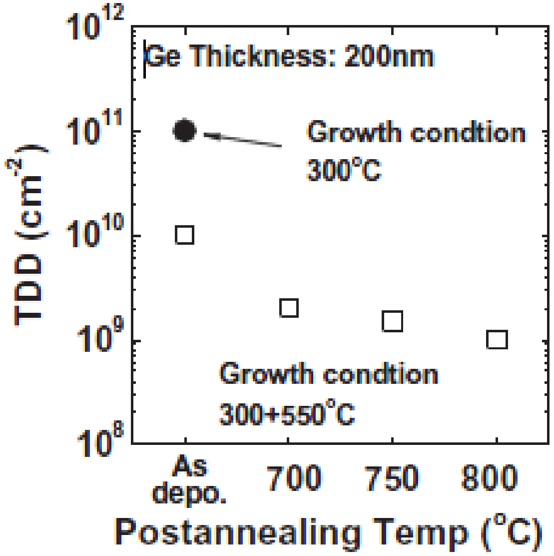
- Overgrowth of Ge
  - To avoid faceting inside the cavity
  - To reduce Threading Dislocation Density (TDD)



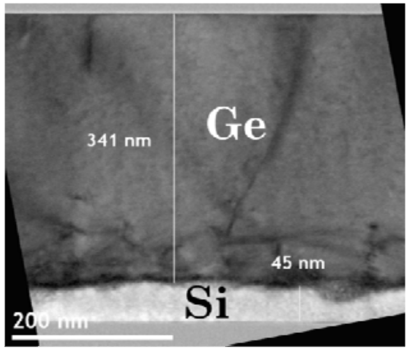
J.M. Hartmann et al., *J. Crystal Growth*, **274**, 90-99 (2005)

Device Fabrication: Ge Growth

- Post epitaxial thermal cycling to further reduce TDD in the Ge layer
- CMP step to remove protruded Ge
- SiO_2 encapsulation
- Ion implantation of Ge
  - √ N-type : Phosphorus
  - √ P-type : Boron
- Rapid Thermal Anneal



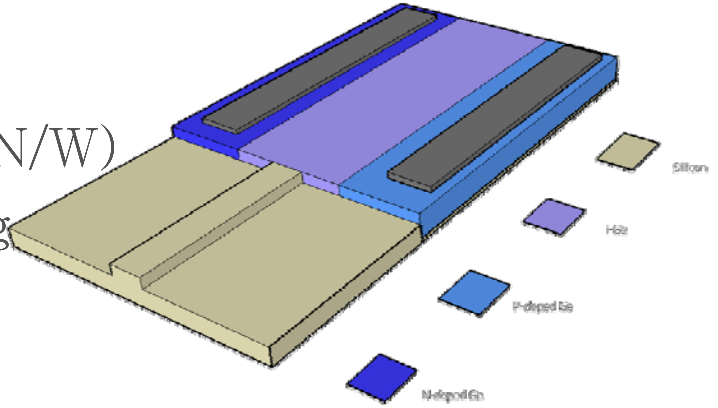
Y. Yamamoto et al., *Solid-State Electronics*, **60-1**, 2–6, (2011).

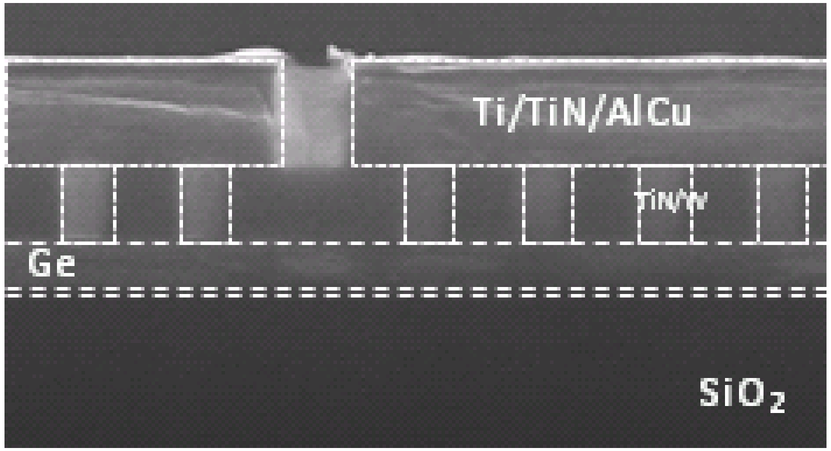


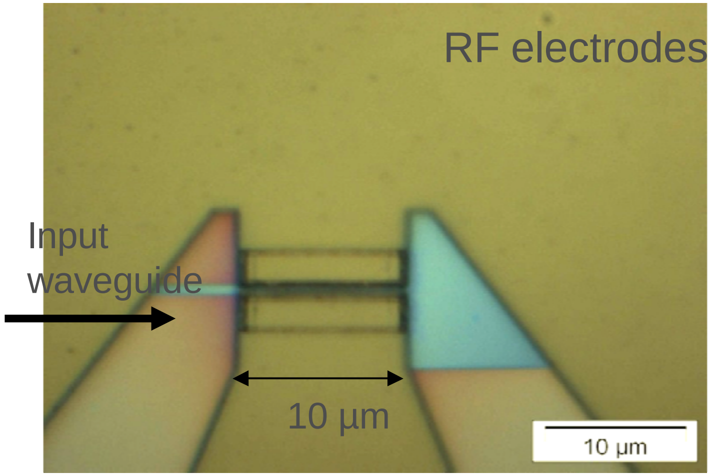
Device Fabrication: Contact and Metal

- Oxide encapsulation
- Planarization
- Contact definition
  - 0.4x0.4µm vias for metal filling (TiN/W)
  - Ti/TiN/AlCu pad defined by etching

Lateral





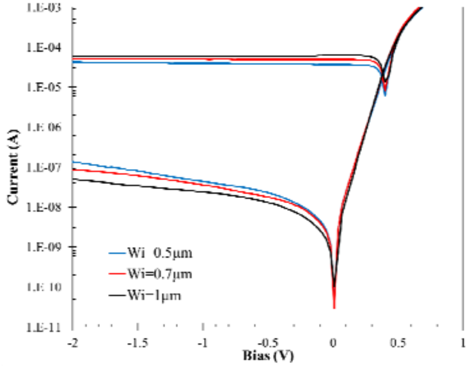


Results : Dark current and responsivity

Dark current median, mean and best values (373 dies per wafer)

Photodiodes		Wi=0.5µm			Wi=0.7µm			Wi=1µm		
Wafer		1	2	3	1	2	3	1	2	3
@-1V	Median (nA)	85	74	112	66	62	80	68	61	71
	Mean (nA)	433	105	1707	350	83	576	347	110	963
	Best (nA)	32	25	27	18	9.5	9	19	17	6
Yield		99.2%	99.7%	97.8%	100%	100%	99.7%	100%	100%	99.7%

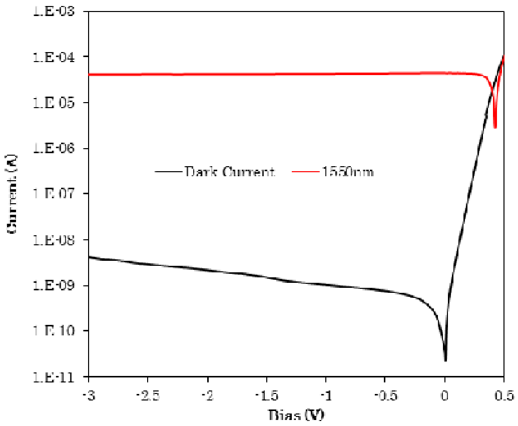
New run: dark current ~1nA @ -1V for $W_i = 0.5\mu m$

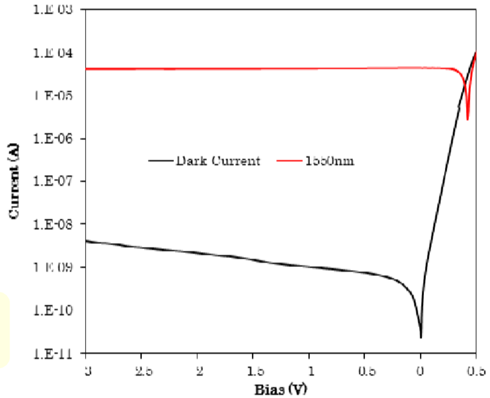


Responsivity @ 1550nm under Zero bias

Wi=0.5µm	0.5A/W
Wi=0.7µm	0.6A/W
Wi=1µm	0.8A/W

Efficient carrier collection at zero bias due to strong built-in electric field

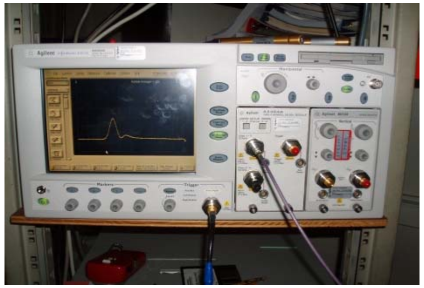


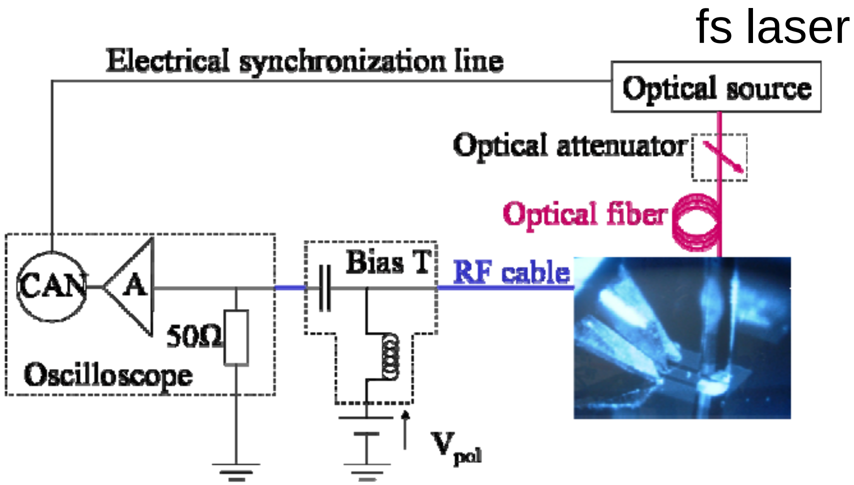


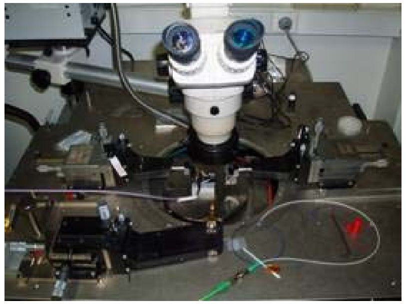
Measured responsivity lower than theoretical values

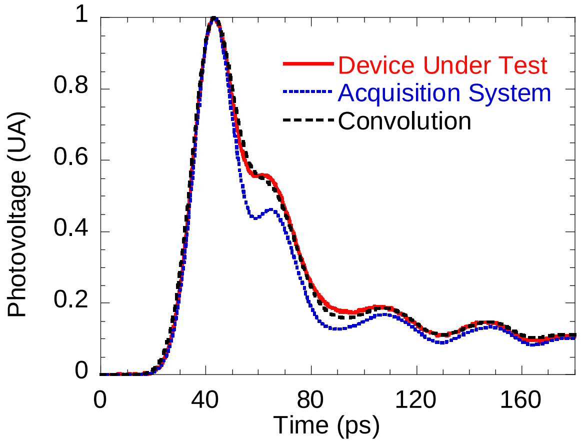
Characterization methods: Bandwidth (I)

❑ Femtosecond pulse experiments





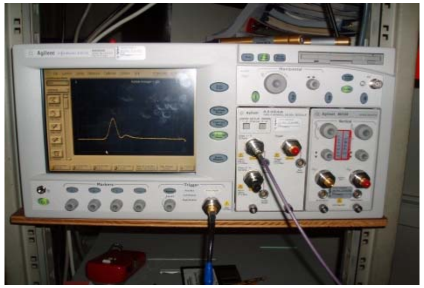


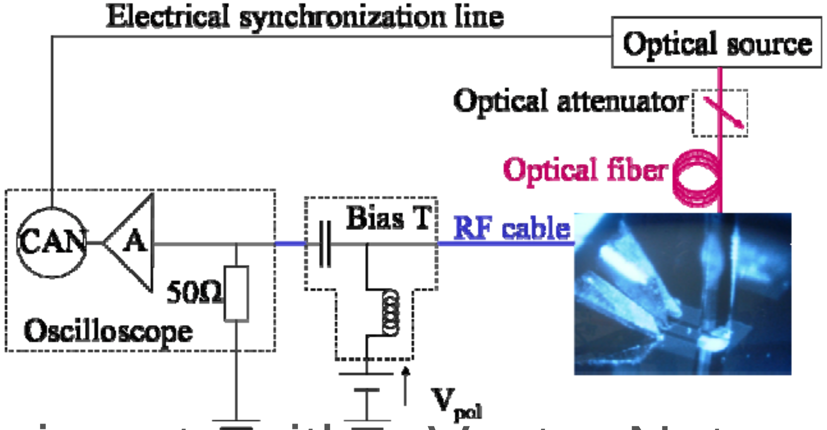


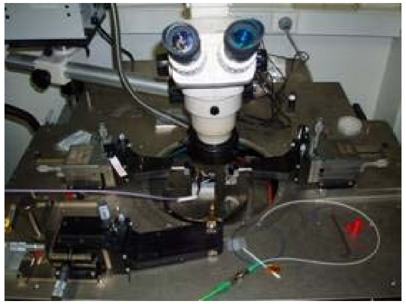
→ Response time (ps)

Characterization methods: Bandwidth (I)

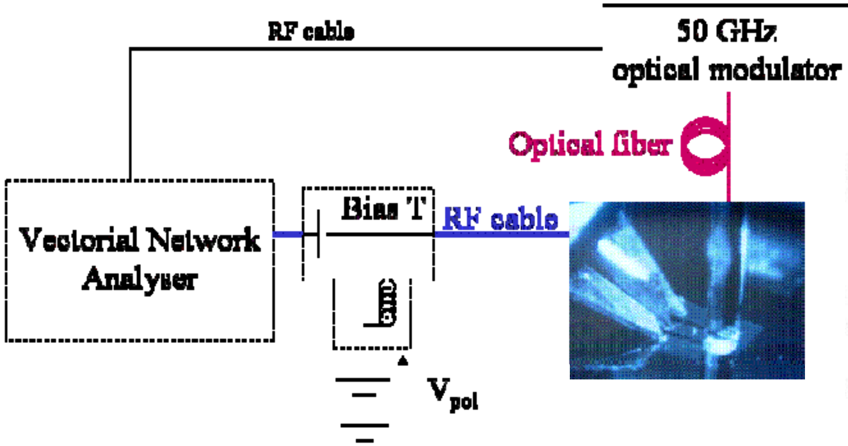
- Femtosecond pulse experiments

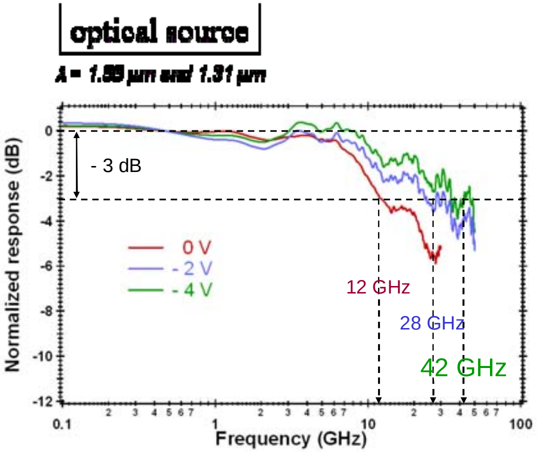






- Opto-RF experiments with a Vector Network Analyzer

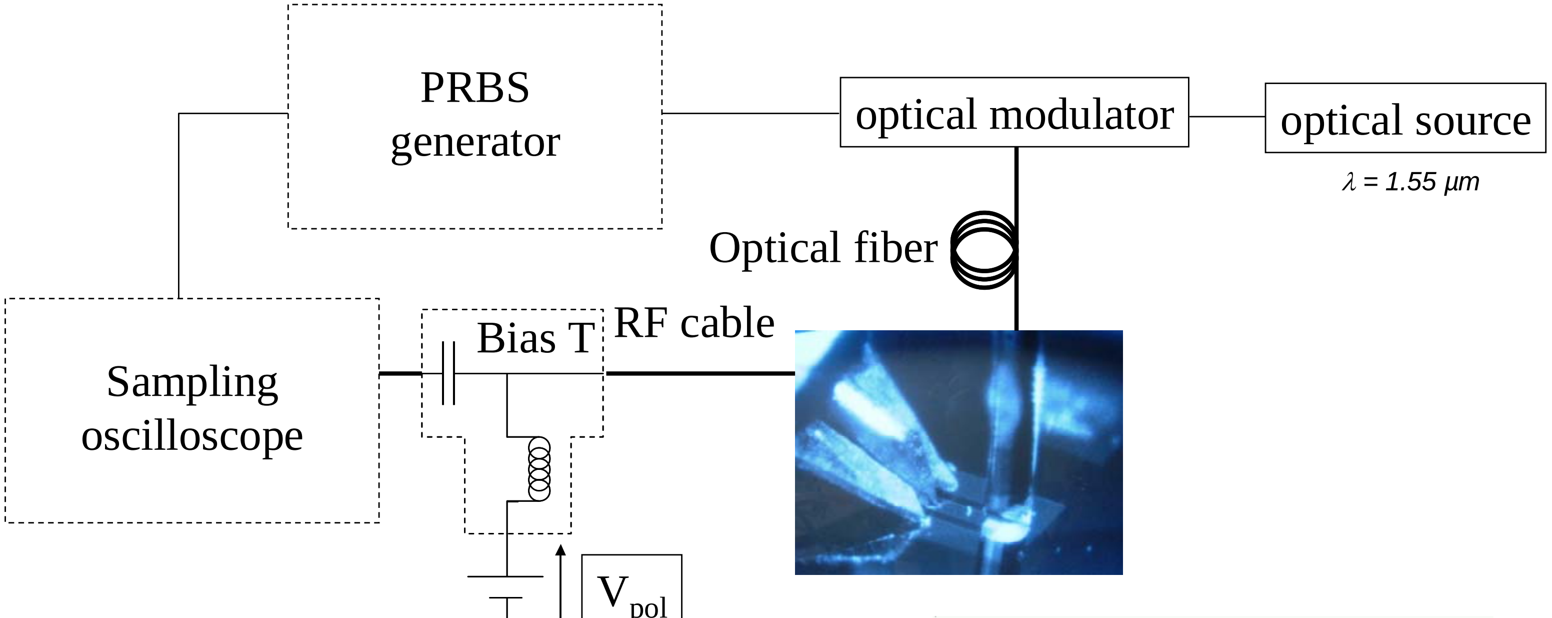




Characterization methods: Bandwidth (II)

- Data transmission measurements

Pseudo Random Binary Sequence



PRBS generator

optical modulator

optical source

$\lambda = 1.55\ \mu m$

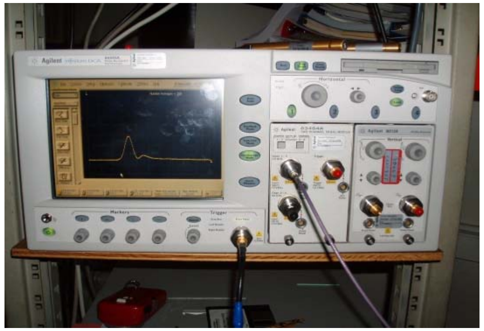
Optical fiber

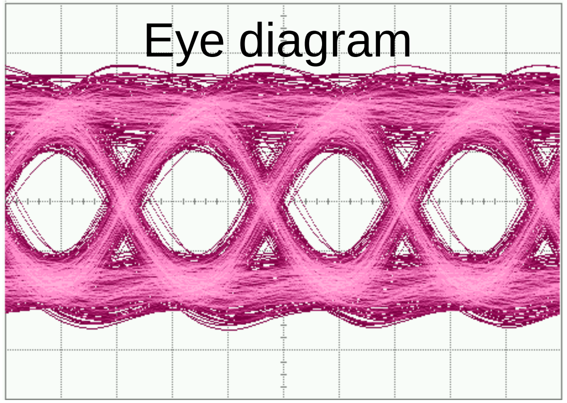
Sampling oscilloscope

Bias T

RF cable

V_{pol}

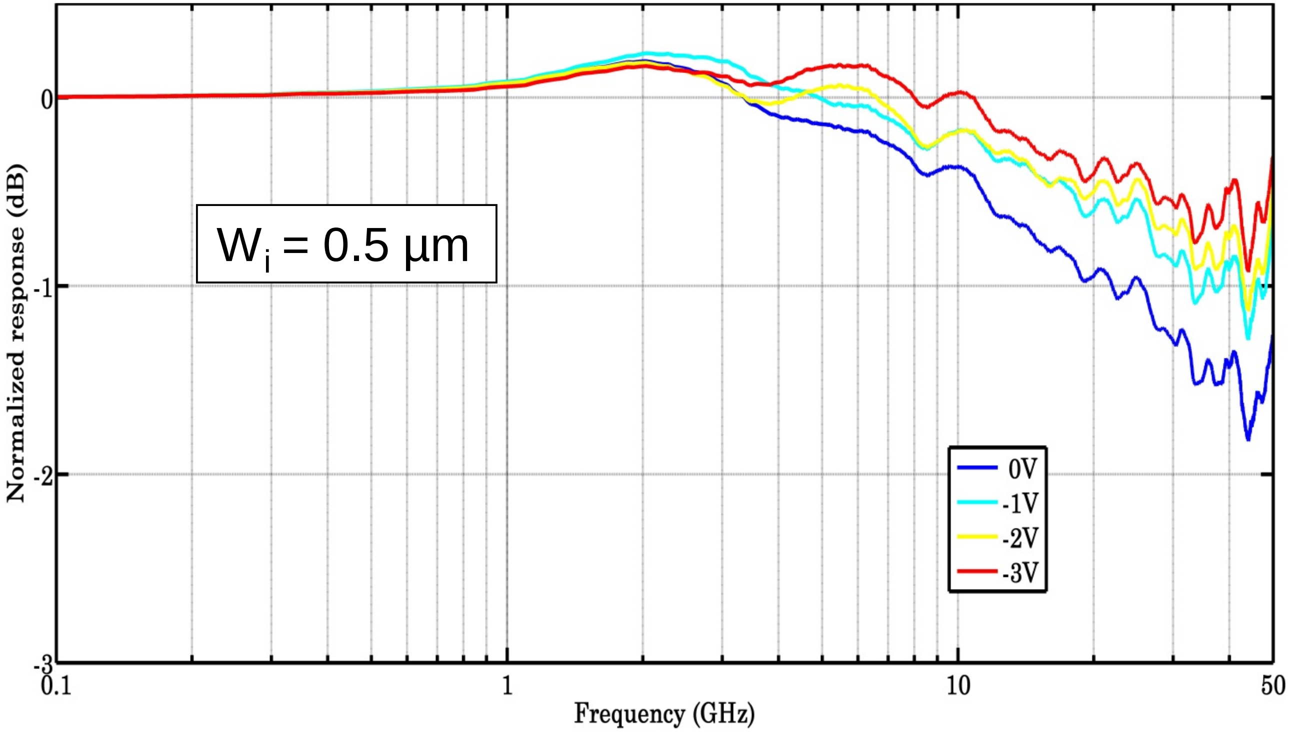




Eye diagram

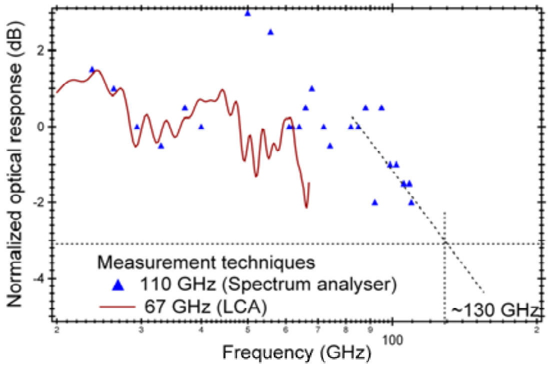
Results : Bandwidth measurement

- Opto-electric frequency response measurement using 50GHz Lightwave Component Analyzer (@1550nm)



-3dB Optical Bandwidth

Over 50GHz @ 0V



Bandwidth higher than theoretical values

Discussions

Lower responsivity

	Exp (A/W)	Theo (A/W)
W_i=0.5µm	0.5	0.91
W_i=0.7µm	0.6	0.96
W_i=1µm	0.8	0.99

=> Loss of photo-generated carriers

Higher bandwidth

Measured BW: >130GHz

Theoretical BW: 70GHz

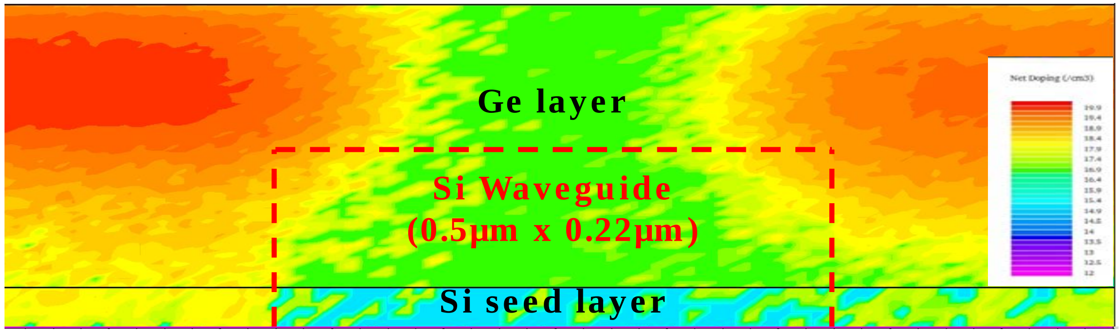
=> Faster carrier collection

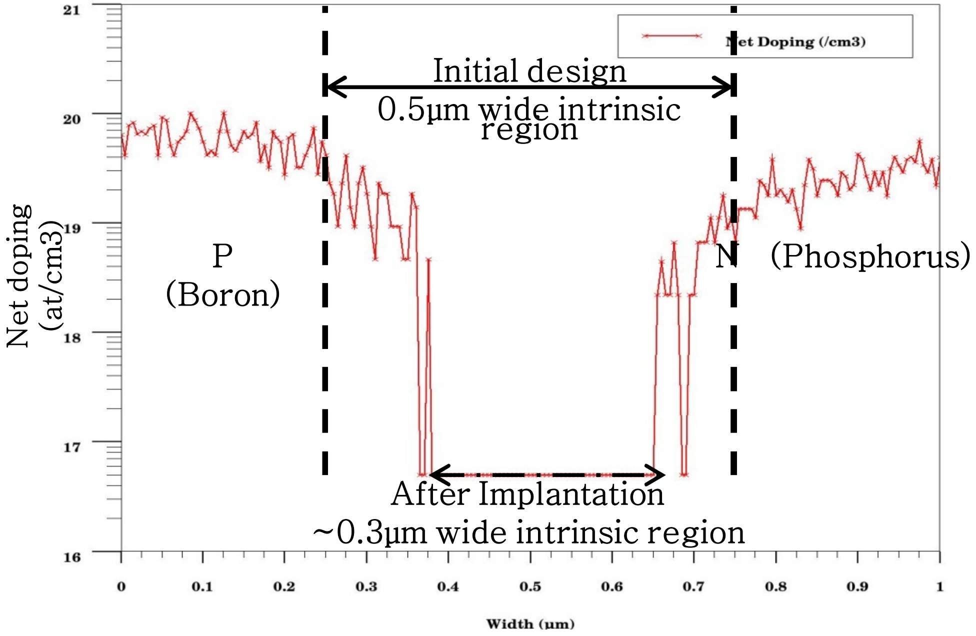
Why are the responsivity lower
and the BW higher than theoritical values?

Reduction of the absorption region width

Discussion: Ion implantation

- Ion implantation
  - √ Monte Carlo simulation of ion implantation process





<u>Narrowing of the intrinsic region</u>

→Absorption inside the doped region

√ Max responsivity ~0.6A/W

→Increase of the electric field strengt

√ Max BW ~ 120 GHz

Data transmission

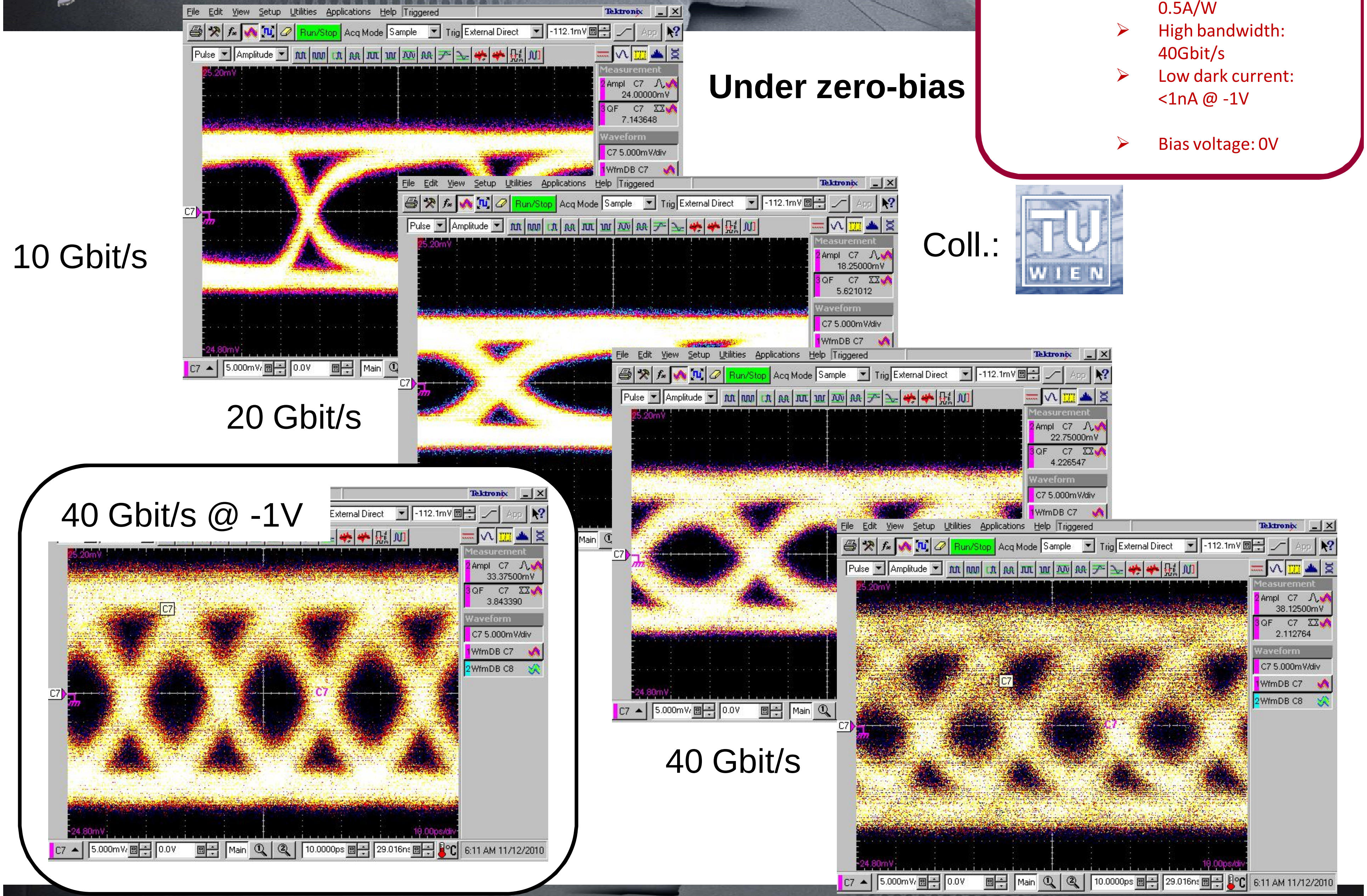
Results beyond specifications

- High responsivity: > 0.5A/W
- High bandwidth: 40Gbit/s
- Low dark current: <1nA @ -1V

- Bias voltage: 0V

Under zero-bias

Coll.: TU WIEN


10 Gbit/s

Ampl C7 24.00000mV
QF C7 7.143648
C7 5.000mV/div

20 Gbit/s

Ampl C7 18.25000mV
QF C7 5.621012
C7 5.000mV/div

40 Gbit/s

Ampl C7 22.75000mV
QF C7 4.226547
C7 5.000mV/div

40 Gbit/s @ -1V

Ampl C7 33.37500mV
QF C7 3.843390
C7 5.000mV/div

Ampl C7 38.12500mV
QF C7 2.112764
C7 5.000mV/div

How can we increase the receiver bandwidth?

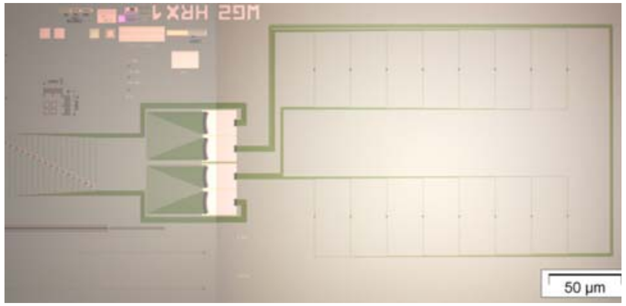
….Towards Tbit/s….

To improve bandwidth of receiver

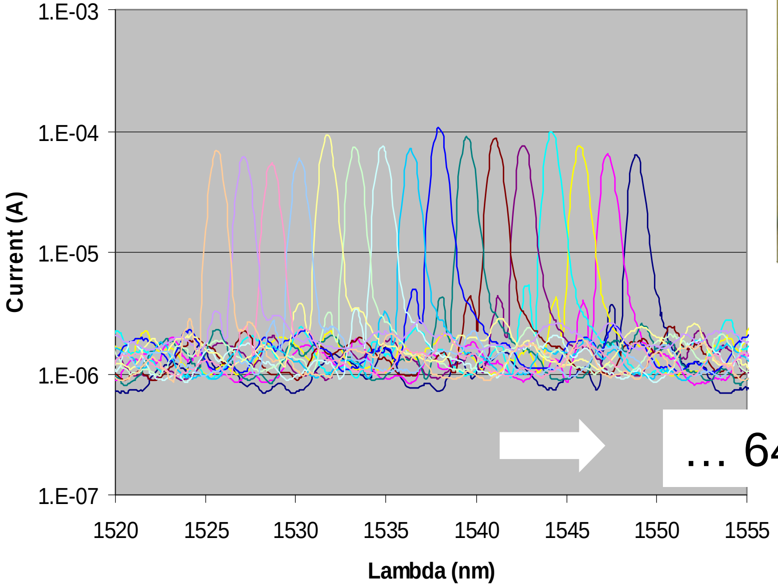
Bandwidth = Parallelism x Frequency

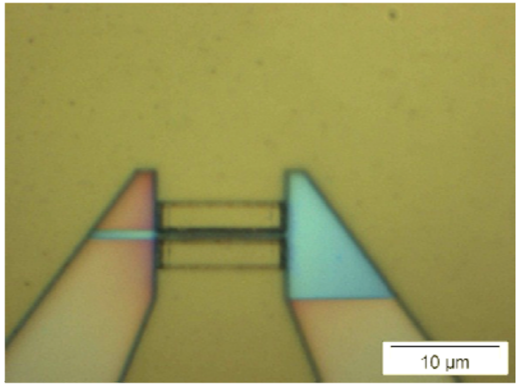
- Need more wavelengths

- 40Gbit/s detector



2 x 16 channels 200GHz
centered at about 1550nm





… 640 Gbit/s and more…

Conclusion

- Germanium photodetectors are more and more considered as a mature silicon photonics devices.

- The PD characteristics are close to the one of III-V PD.
  - √ Incredible at the beginning.

- The trends
  - √ Development of complex circuits for Tbit/s operation
  - √ Integration with CMOS circuits (TIA)
  - √ Avalanche PD …
    - ➢new route to reduce the power consumption of the emitter
    - ➢Photon counting – Quantum optics