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Graphene for integrated photonics

Cedric Huyghebaert, CTO

EPIC meeting on CMOS compatible Integrated Photonics
Leuven Belgium : 7-8 septmeber 2022

Black semiconductor

- Black Semiconductor is developing breakthrough technologies to traditional electronic systems with photonics.

- Black Semiconductor is a start-up issues out of RWTH & AMO in Aachen
- Founded in 2019
- Black semiconductor closed his seed round of 6,2m euros at the end of last year in support for the development of bringing optical circuits to any electronic chip.
- Operations started in Februari 2022

- Black Semiconductor is a European company developing this technology with the help of our great investors and growing tech team.

Advisors:

Andreas Umbach
Chairman of the Board
Retired CTO & VP at Finisar

Bill Leszinske
Advisor and member of the Board
Retired VP of storage at Intel

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The Problem

Multi-dimensional hard physical limits. Very large markets depend on performance boosts.

Current tech will reach his limits. Amount of data explodes.

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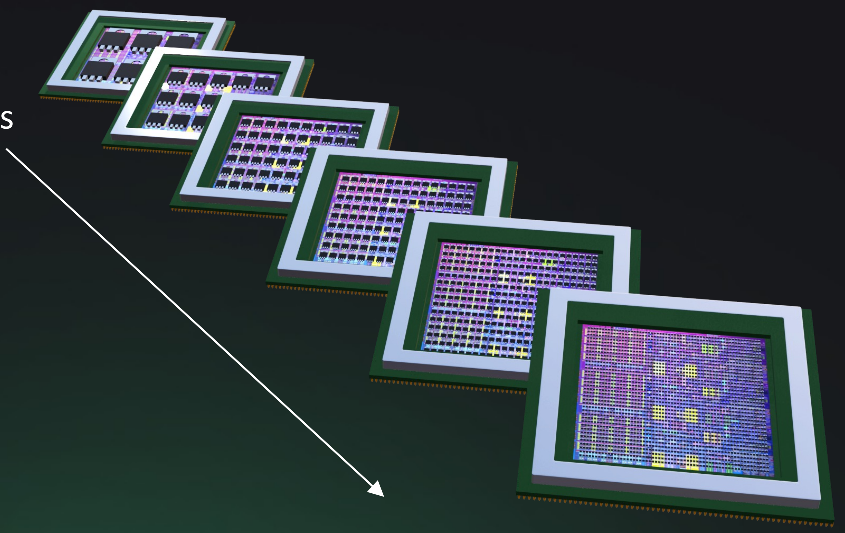
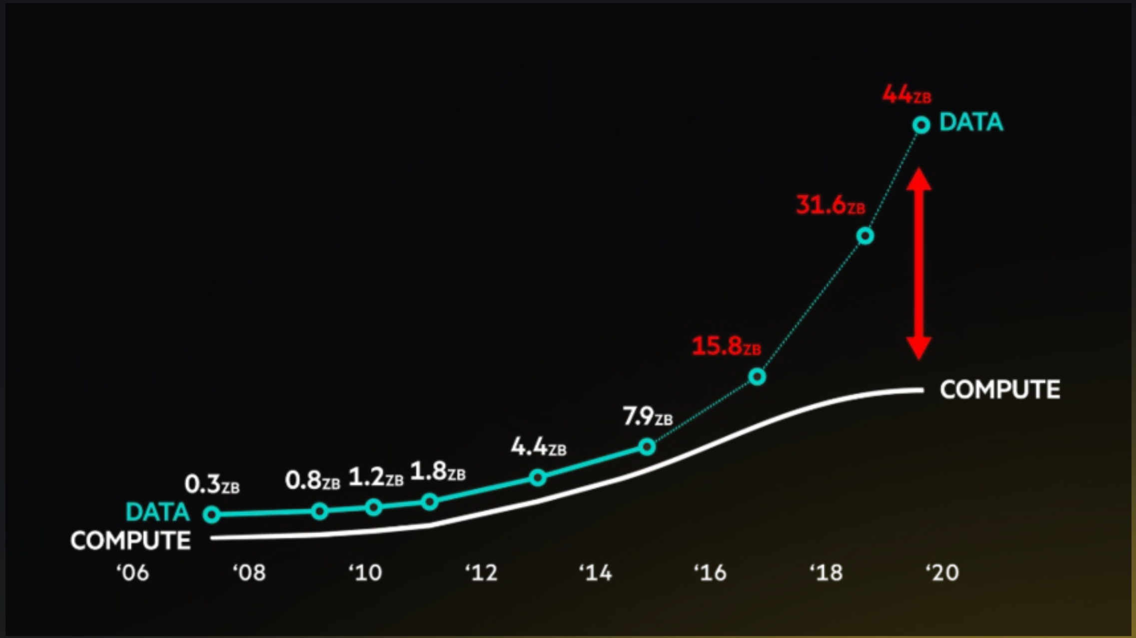


2023



DOWN scaling limits are visible!
How to continue increasing performance?

Data curve from IDC/EMC Digital Universe reports 2008-2017, Compute curve HPE analysis, Graphic: World Economic Forum https://www.weforum.org/agenda/2018/09/end-of-an-era-what-computing-will-look-like-after-moores-law/

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Photonic data interfaces are fastest

Highest possible data rates

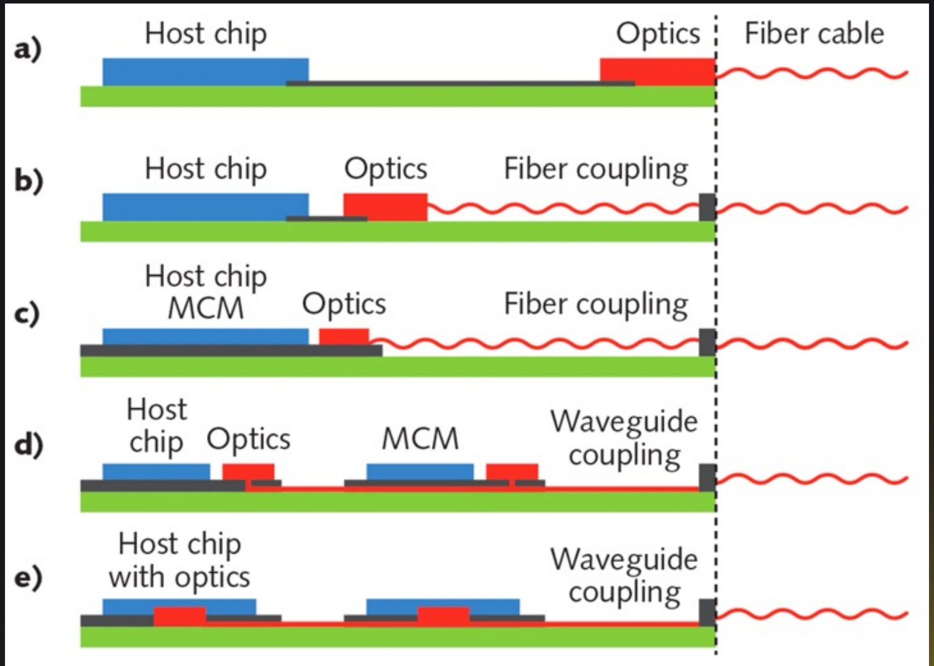
Electronic interconnects are too slow

photonic processing runs at maximum possible speed

No clock, novel architectures

Overcome existing limits

Tb/s chip to chip communication
ultimately unleash AI applications

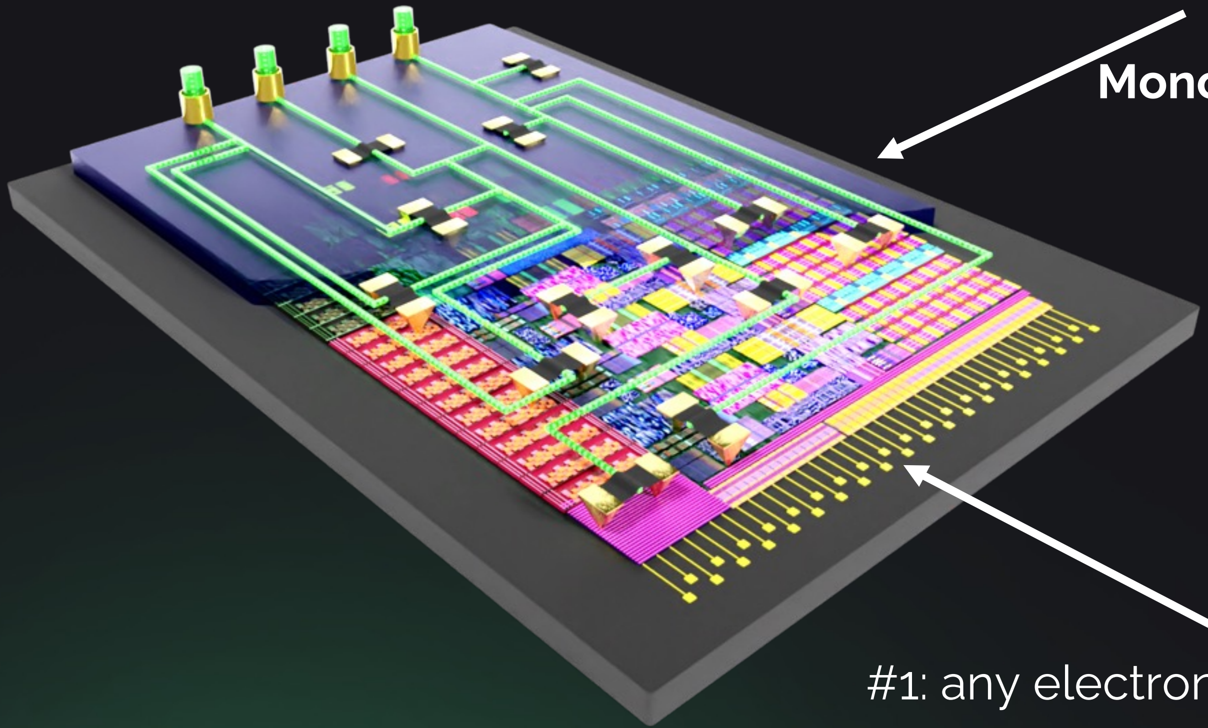


Laser Focus World Sep 13 2019

Solution: Photonic circuits on any electronics

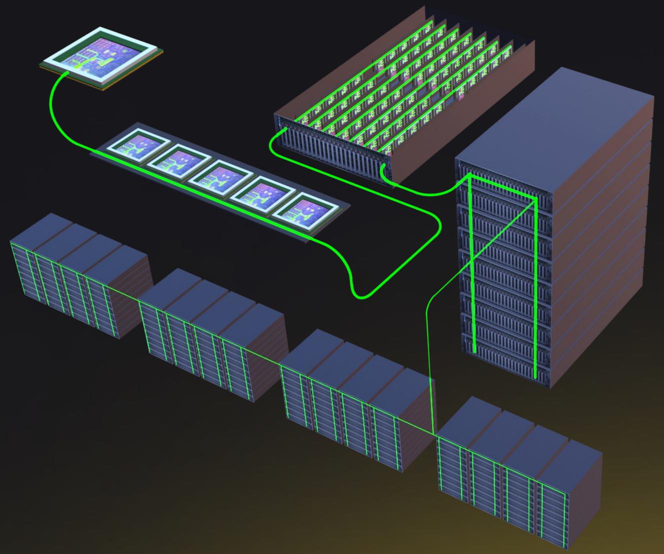
#2: photonic platform,

Monolithic Fabrication



#1: any electronic circuit,

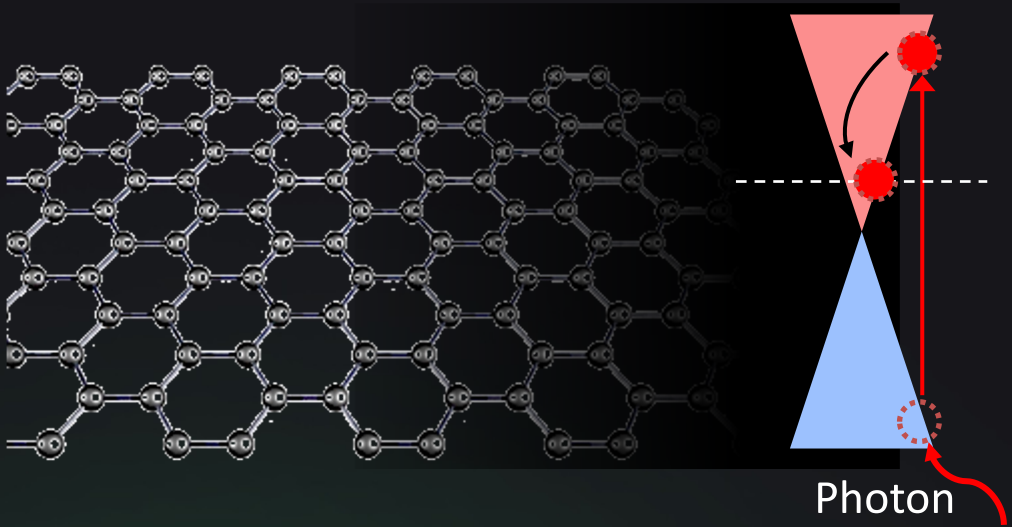
Free choice of technology



Boost # transistors
through Chip fabrics

How to make active photonics on top of CMOS?

Material



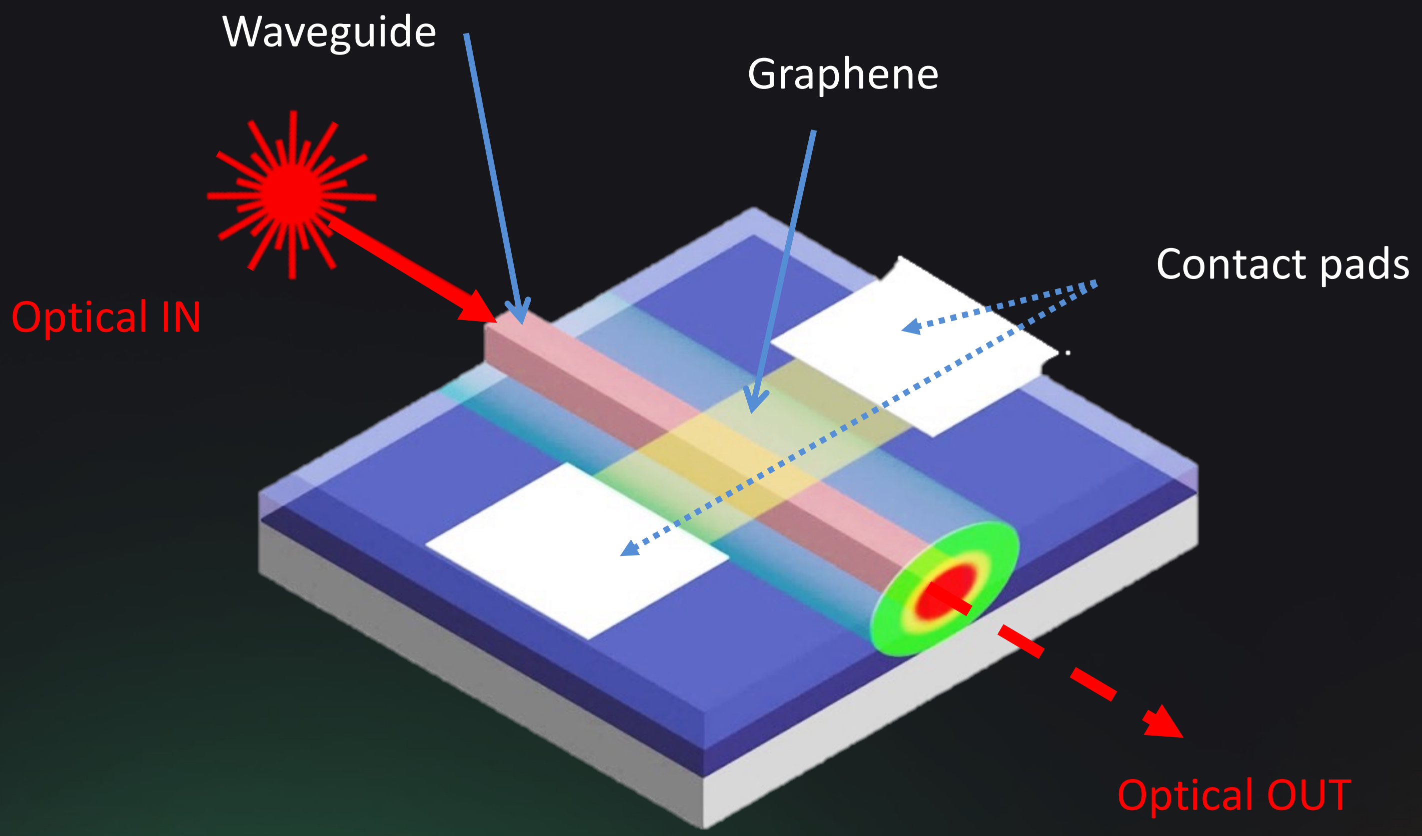
- Fast carrier dynamics: ultrafast devices
- Linear band structure: broadband devices
- Low density of states: efficient devices

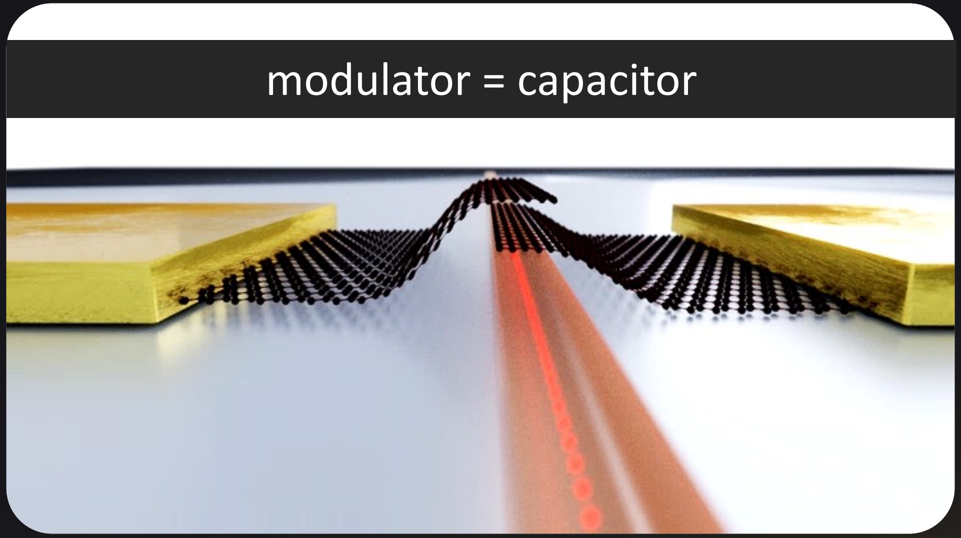
Fabrication and integration

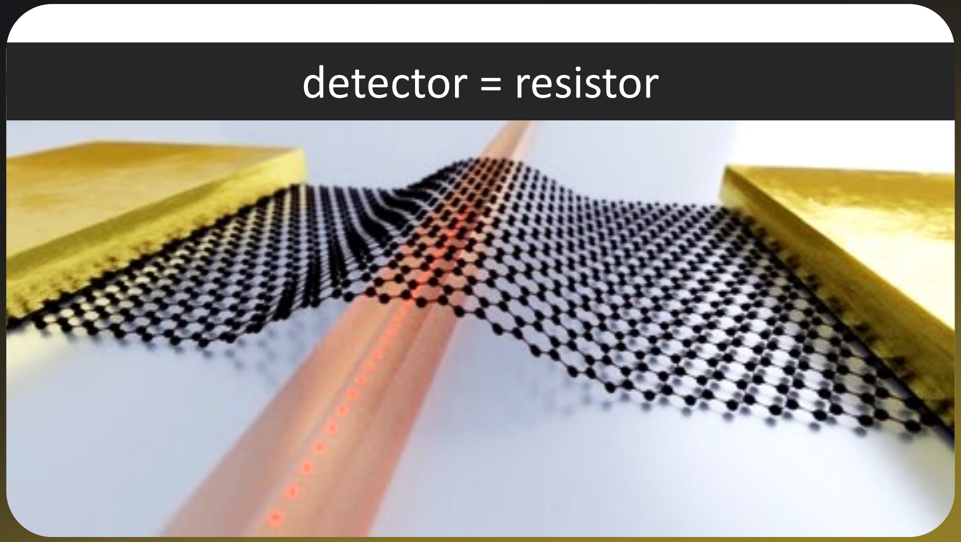
- Fabrication on large sacle
- BEOL integration

► Ultra fast, efficient and broadband photonic devices on wafer scale

Device schematic







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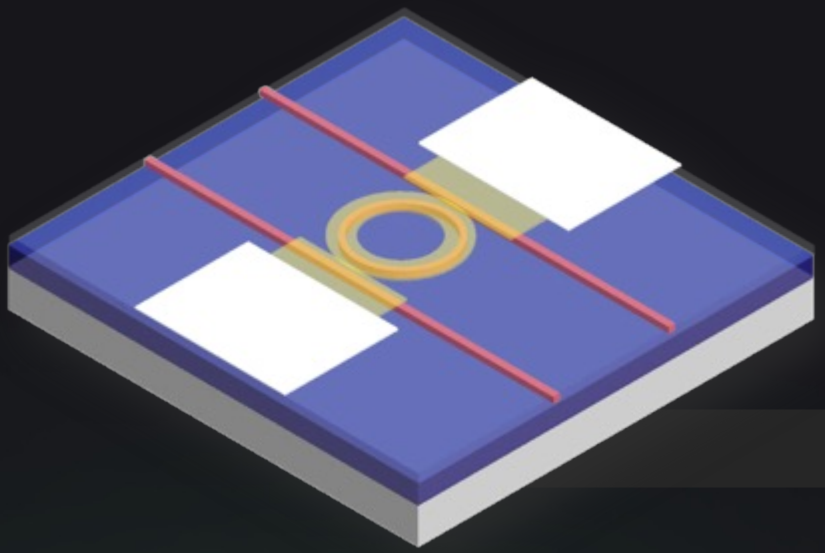
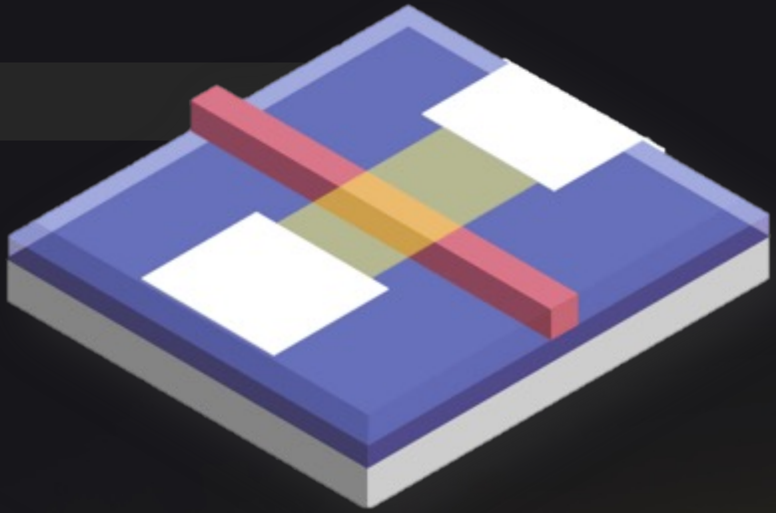
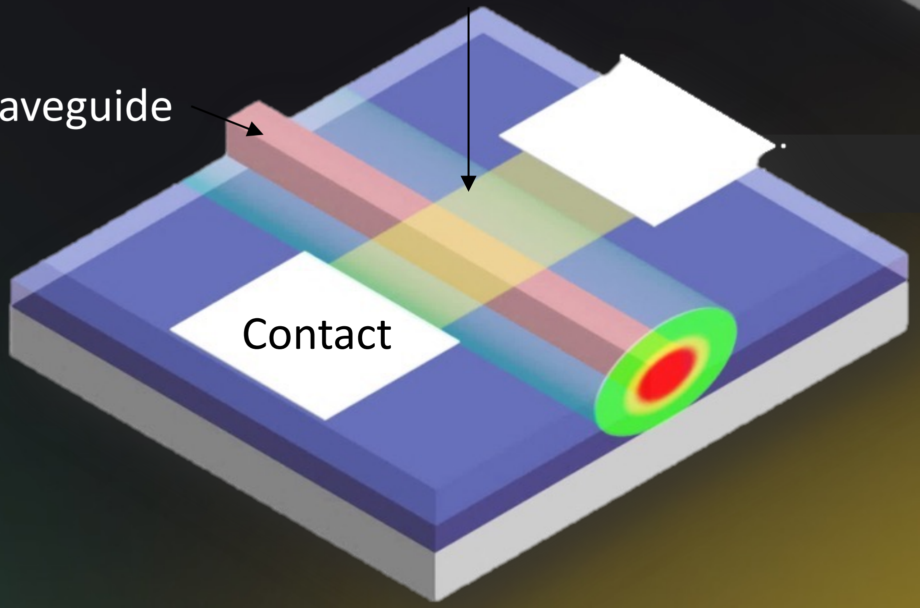
Graphene photonics platform



Efficient Modulators

Efficient Phase Shifters





Ultrafast Photodetectors

D. Schall et al., ACS Photonics 1 (9), 781-784 (2014).
D. Schall, et al., J. Phys. D: Appl. Phys., (2017).
S. Schuler et al., Nano Lett., 16 (11), 7107-7112 (2016).
D. Schall et al., Opt. Express 24, 7871-7878 (2016).
M. Mohsin et al., OSA paper IM4A.1 (2015).
M. Mohsin et al Scientific Reports 5, 10967 (2015).
M. Mohsin et al., Opt. Express 22, 15292-15297 (2014).
Mohsin, Schall et al. Opt. Express 25, 31660-31669 (2017)
D. Schall et al., OFC San Diego (2018).

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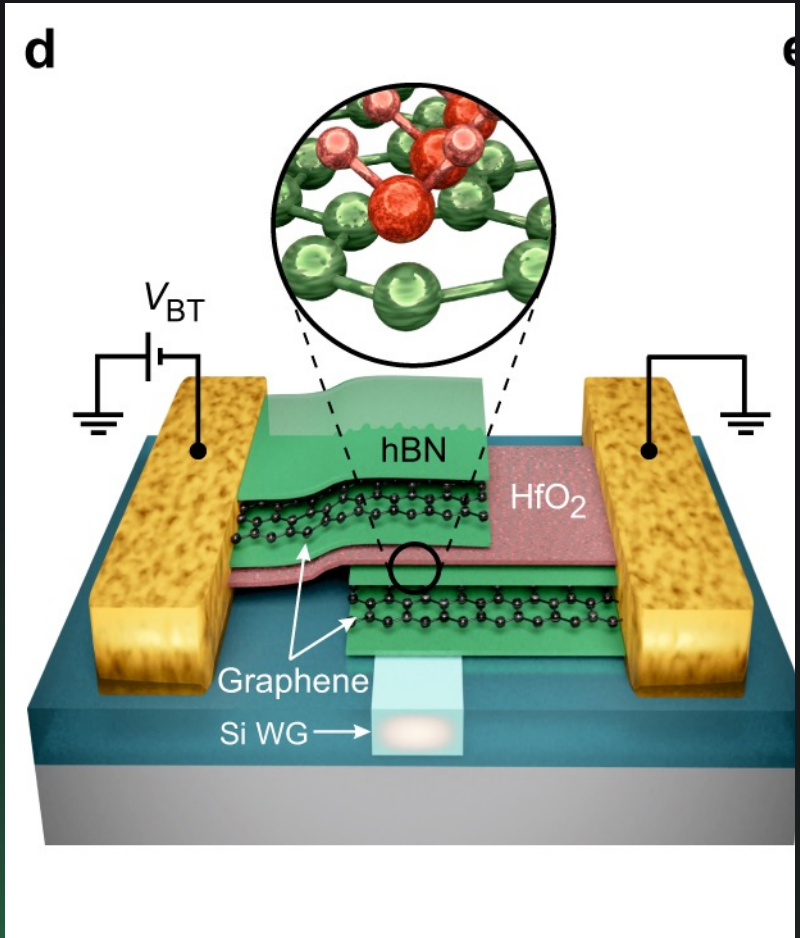
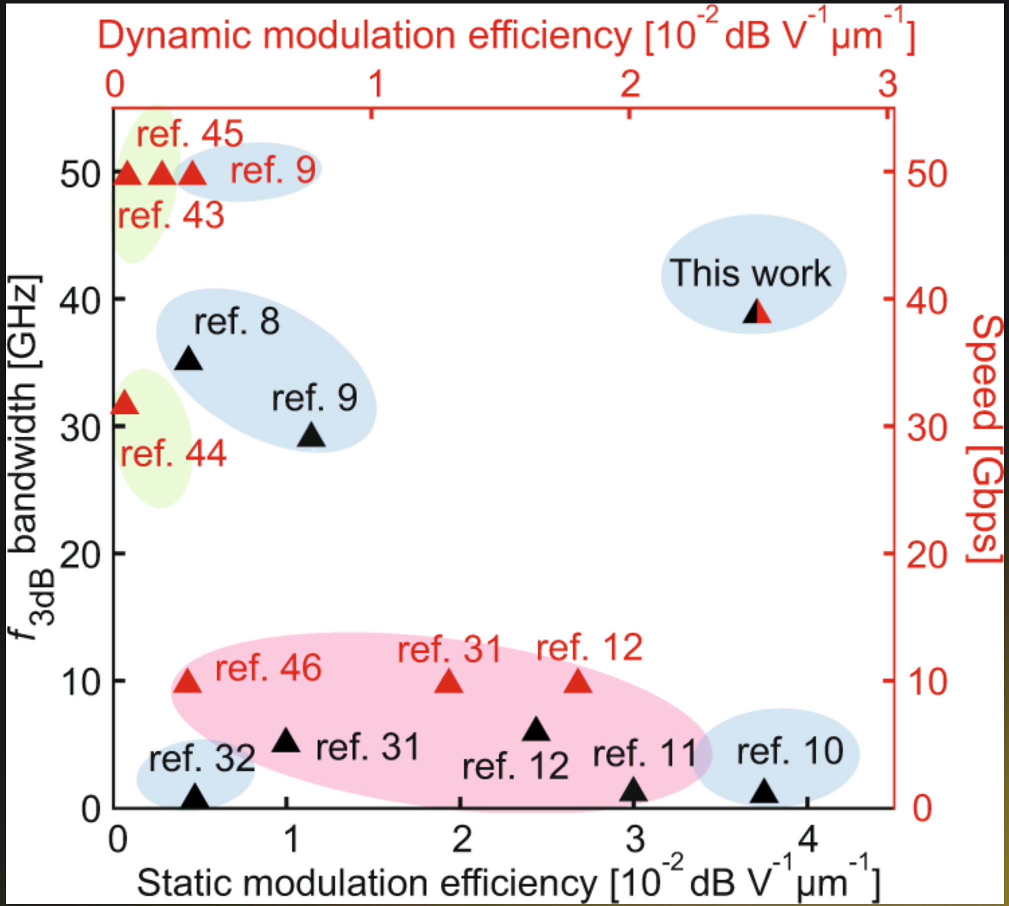
Graphene based modulator : fast and efficient





H.Agarwal et al. Nature Comms 1, 1070(2021)

Why graphene photonics?

- Graphene : new material –new standards :

  - low temp budget integration
  - Amorphous waveguide compatible
  - Modulator- and detector technology in graphene

  } Compatible with BEOL

  - Graphene grown on template : high temp budget needed but not on target wafer
  - Waferscale integration possible in principle
  - Flexible combination with any electronics
  - Low cost of integration possible

Roadmap for Black semiconductor integrated Photonics:

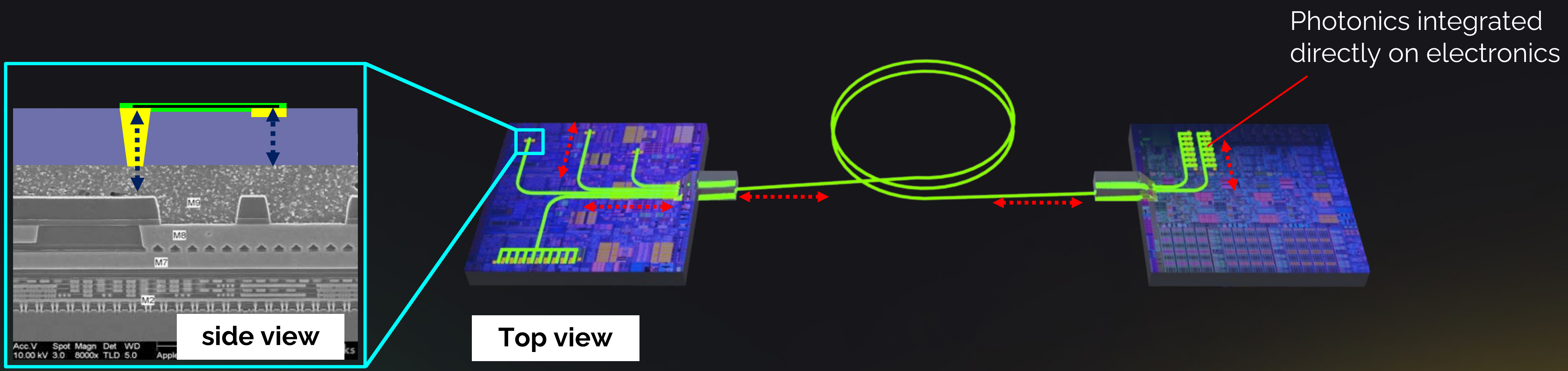
1. Build up passive photonics platform compatible with CMOS
   - Establish and platformize the key passive photonics components on top of CMOS
   - Solve and demonstrate packaging solutions

2. development of graphene photonics platform
   - graphene based photonics from Lab to industrial relevant production

3. photonics on any electronics (product phase)
   - full integration based on stage 1 and 2 technology
   - Unlock the full power of graphene based photonics integration on CMOS

Graphene photonic device integration on CMOS

Integration on Electronics, maximum performance



Integration on electronics: on-chip and chip to chip communication

- maximum performance

Challenges & opportunities

- Device performance strongly correlated with **graphene quality** and **dielectric environment of the graphene**

- High quality graphene not known to be able to grown directly on amorphous dielectrics => high quality requires **template** developments and **transfer developments** => non existing processes in today's semiconductor industry (developments are required)

- Trade-off between **speed** and **energy consumption** of graphene based devices

- **Reliability** of graphene based devices to be demonstrated

- Compatibility of **driver electronics** for Photonics with different CMOS nodes

- **Wafer level coupling solutions** for photonic links between chips : increase fiber densities

Thanks & Questions?

The Team

Dr. Cedric Huyghebaert

CTO

23 years of R&D and operational management at imec

Long time experience in 2D materials in lab as well as into 300 mm lines at imec

Management responsibility at imec

Dr.-Ing. Daniel Schall

CEO

10+ years of graphene photonics research at leading institute AMO

Inventor & manager of the group leading to Black Semiconductor

Created the first wafer-scale graphene photonic fabrication process

Sebastian Schall

CFO

5 years of busines process automation experience

finance background

former member of the board of a telecom start-up

Advisors:

Andreas Umbach

Chairman of the Board

Retired CTO & VP at Finisar

Bill Leszinske

Advisor and member of the Board

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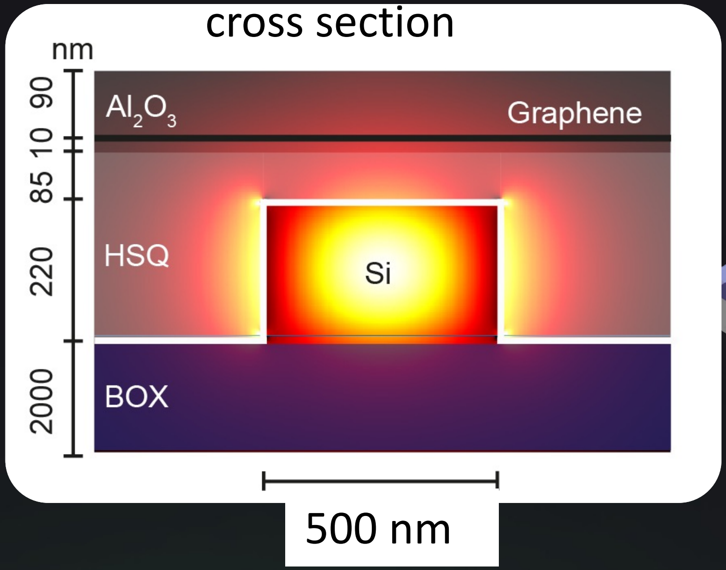
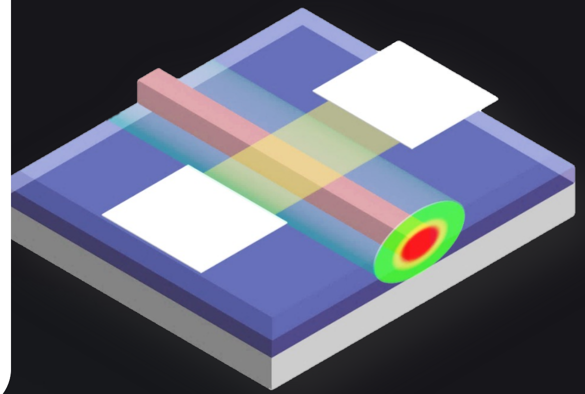
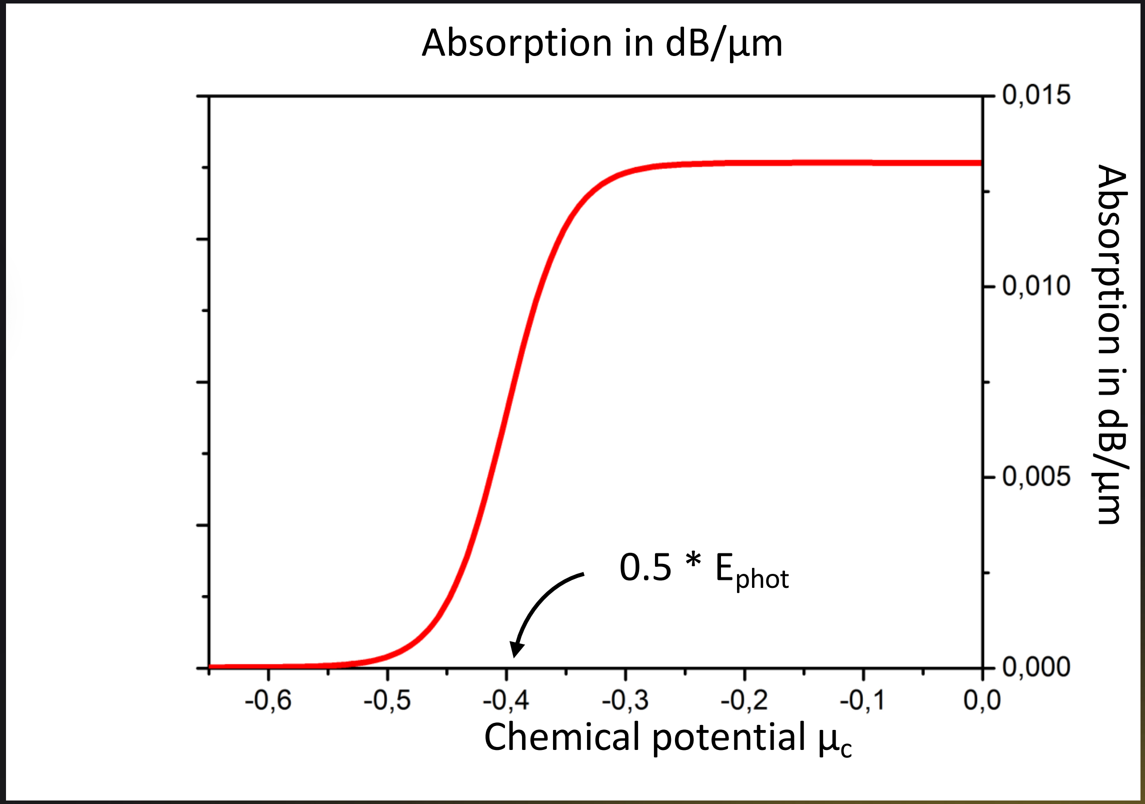
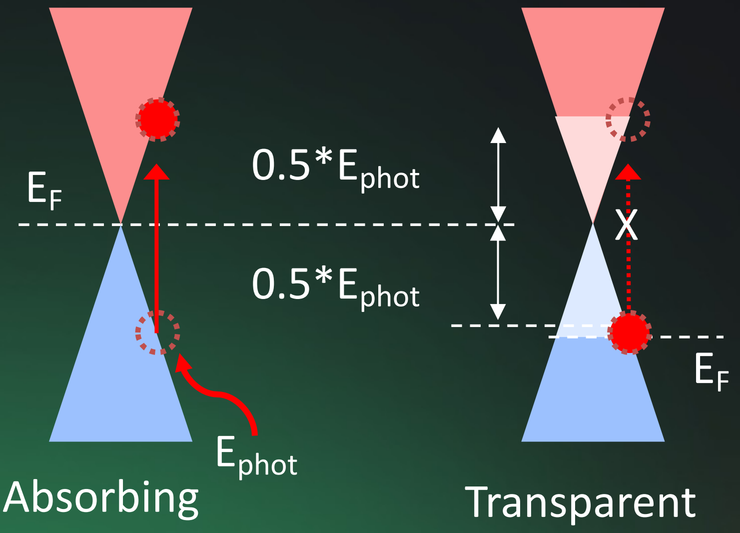
Graphene: tunable absorption



3D view







- λ = 1550 nm → E_{phot} = 0.8 eV
- For $|\mu_c| \geq 0.5 * E_{phot}$ states are blocked → graphene is transparent

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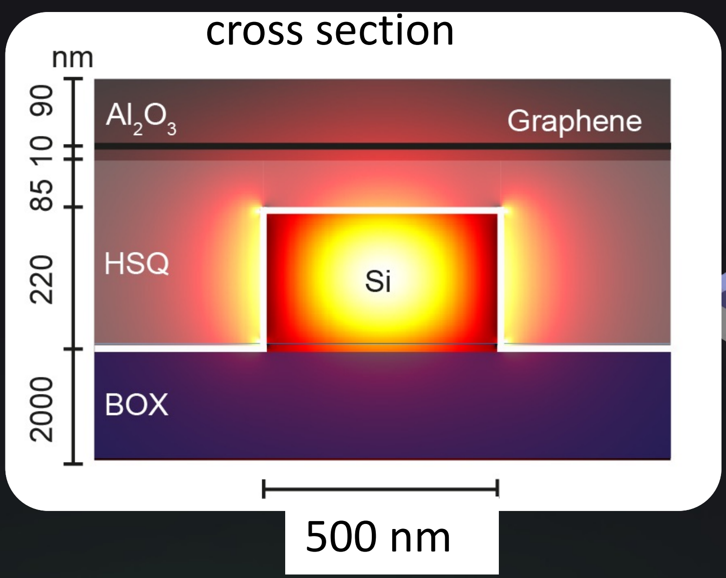
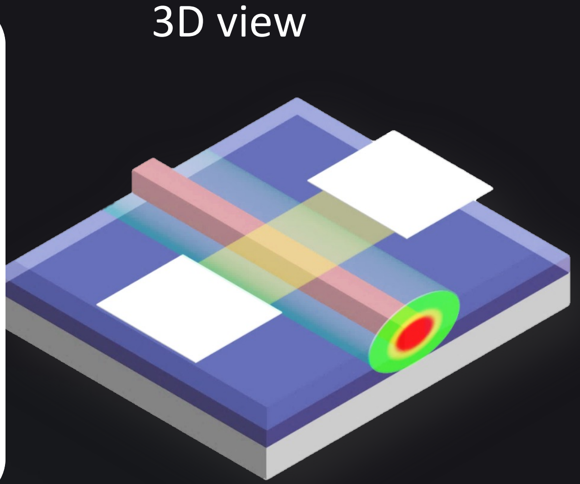
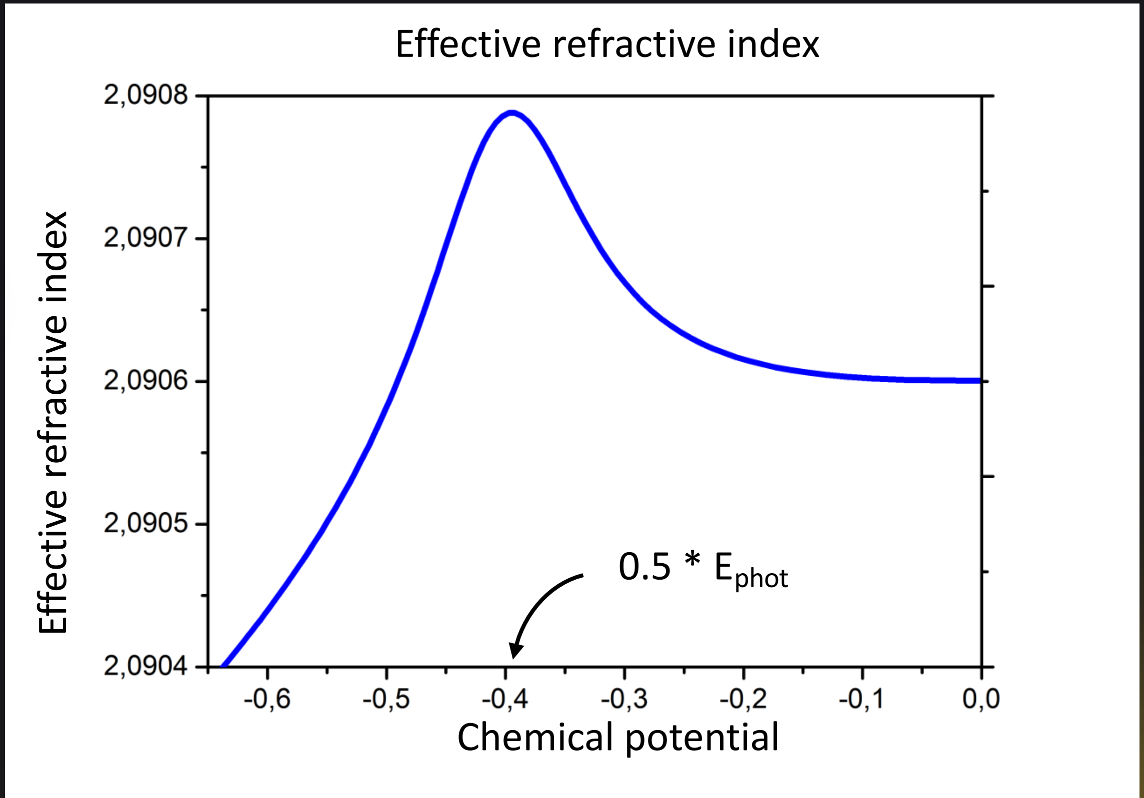
M. Mohsin et al. Scientific Reports 5,10967 (2015)

Graphene: tunable refractive index







- λ = 1550 nm → E_{phot} = 0.8 eV
- Kramers-Kronig relates the absorption to the refractive index
  → refractive index is a function of the electro chemical potential

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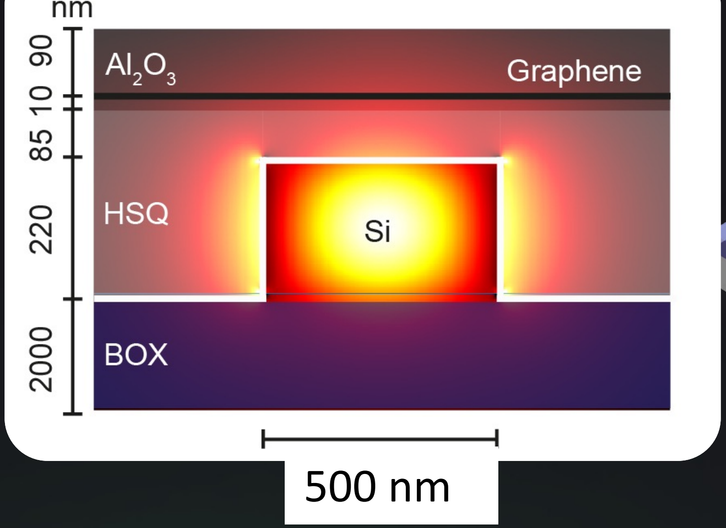
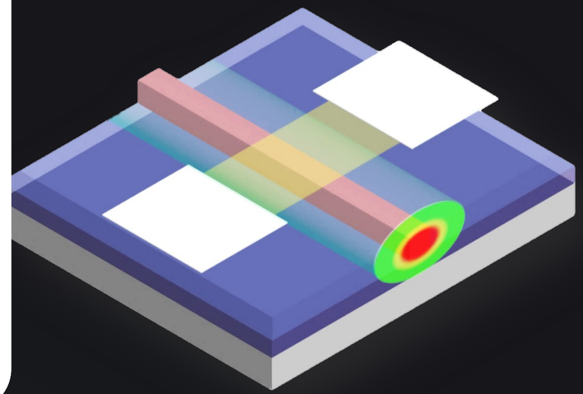
M. Mohsin et al. Scientific Reports 5,10967 (2015)

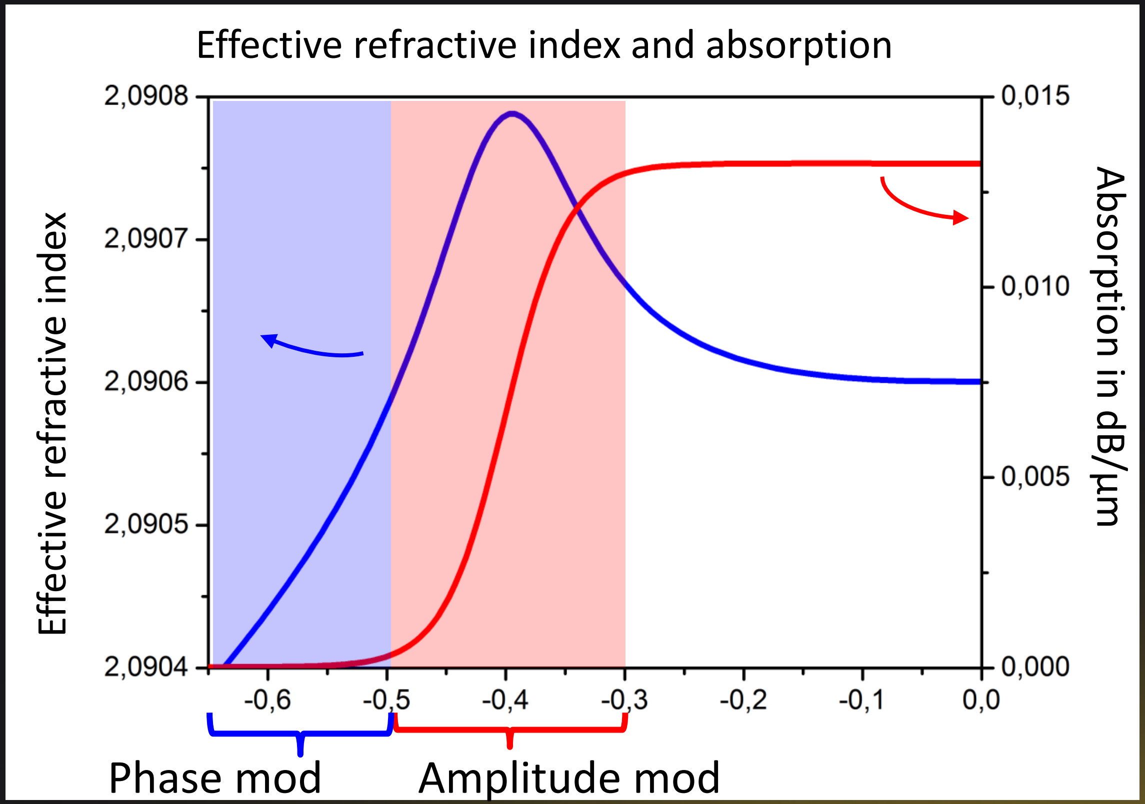
Absorption and phase modulator

cross section



3D view



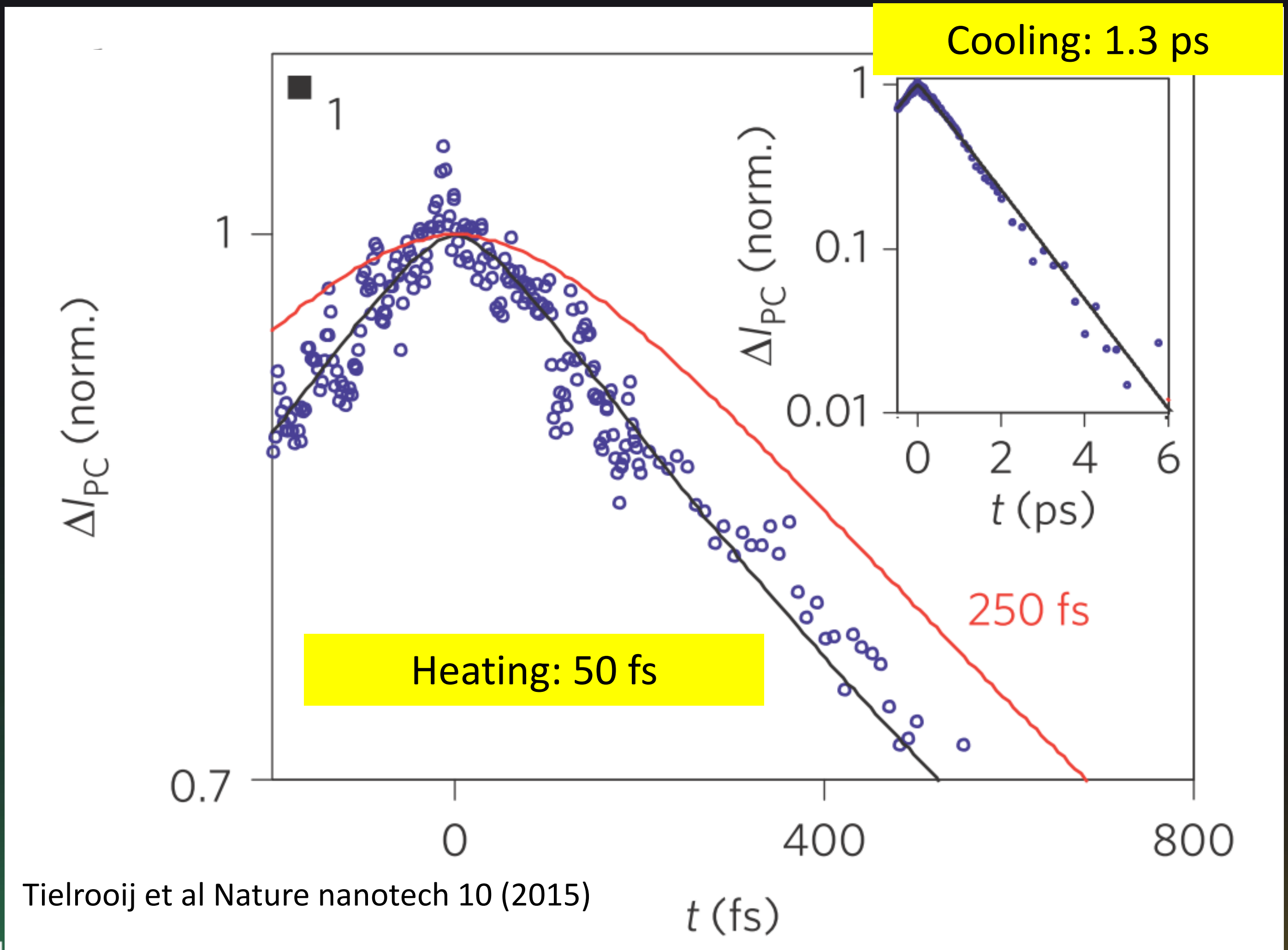


- Refractive index and absorption depend on the chemical potential
- high mobility gives low absorption for $\mu < -0.4$ eV
  preferred for phase modulators.

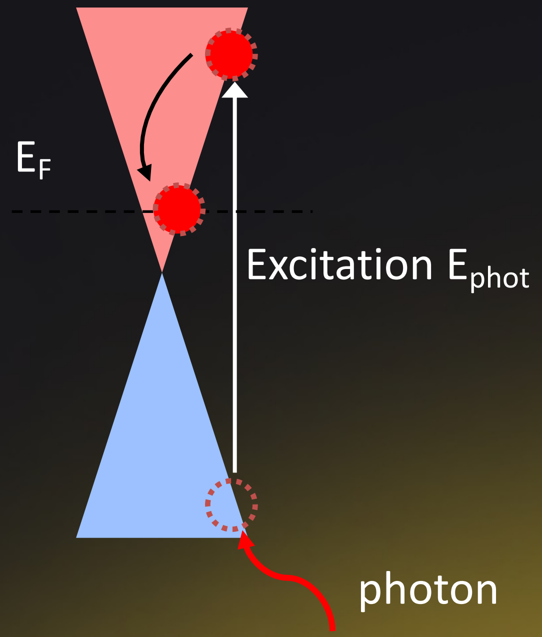
Phase and absorption modulator realizable

M. Mohsin et al. Scientific Reports 5,10967 (2015)

Ultrafast carrier dynamics in graphene



Tielrooij et al Nature nanotech 10 (2015)



Graphene photodetector

Type	Responsivity (A/W)	Bandwidth (GHz)	Data rate Gbps	Wavelength nm
Graphene	DC 0.2 [1] DC 0.55	>130 [1]	56	1480 to 1620 and 1980
Graphene/plasmonic [2]	0.5	>110	100	
Graphene [3]	0.36	>110	40	
Ge on Si [4]	0.8 – 0.9	120	56	
Si Ring [5]	>0.23	45	112	1310 (o-band)

1) Schall et al. OFC (2018)
2) Ma et al. ACS Photonics 6, 154 (2019)
3) Ding et al. arXiv:1808.04815v3 (2018)
4) Vivien et al. Optics Express 20, 1096 (2012)
5) Sakib et al. OFC Th4A.2 (2020)

Graphene absorption modulator

Type	Modulation (dB)	Attenuation (dB)	Modulation/ Attenuation	Length (µm)	Bandwidth (GHz)	Data rate Gb/s
Graphene [1]	16	3	5	300	0.7 (DC device)	-
BEOL currently being developed	3-5	1-2	2-5	120-200	5-50*	5-56*
Graphene [2]	1.3	20	0.07	120	29	50
Graphene Simulation	16	<1	>15	<15	>50	-
Ge on Si [3]	4.6	4.1	1.1	40	>50	28

1) M. Mohsin et al. Optics Express 22, 15292 (2014)
2) Giambra et al., Optics Express 27, 20146 (2019)
3) S. Gupta et al. OFC (2015)

*) bandwidth depends on the device design. Theoretical bandwidth based on thechnology paramters is 400 – 500 GHz
Datarate targets: 4 Gbps, 25 Gbps, 56 Gbps 112 Gbps; all NRZ.