PHOTONICS RESEARCH GROUP

Graphene-Silicon Photonic Integrated Devices for Optical Interconnects

Chiara Alessandri

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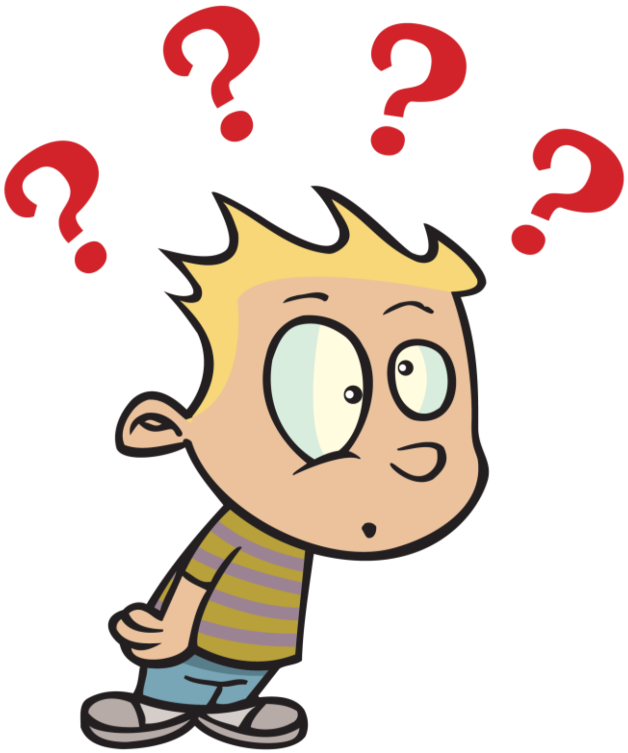
embracing a better life

So… What is this about?



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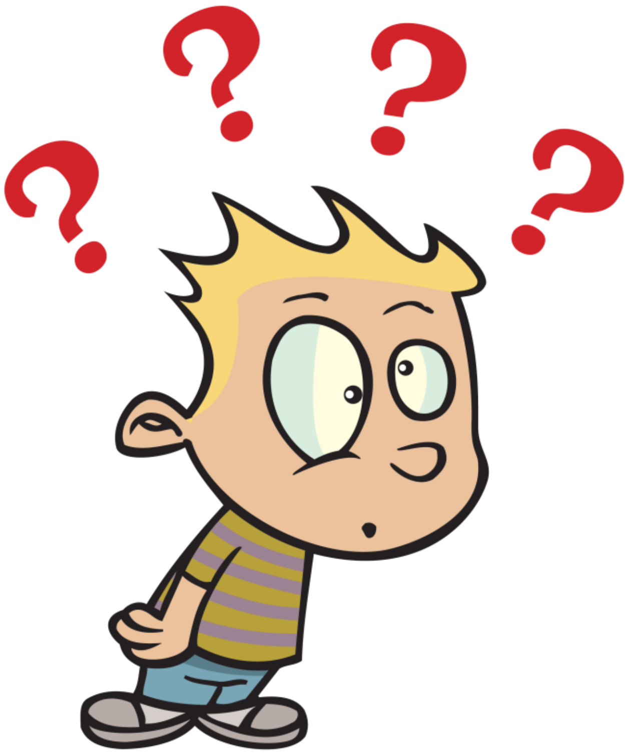
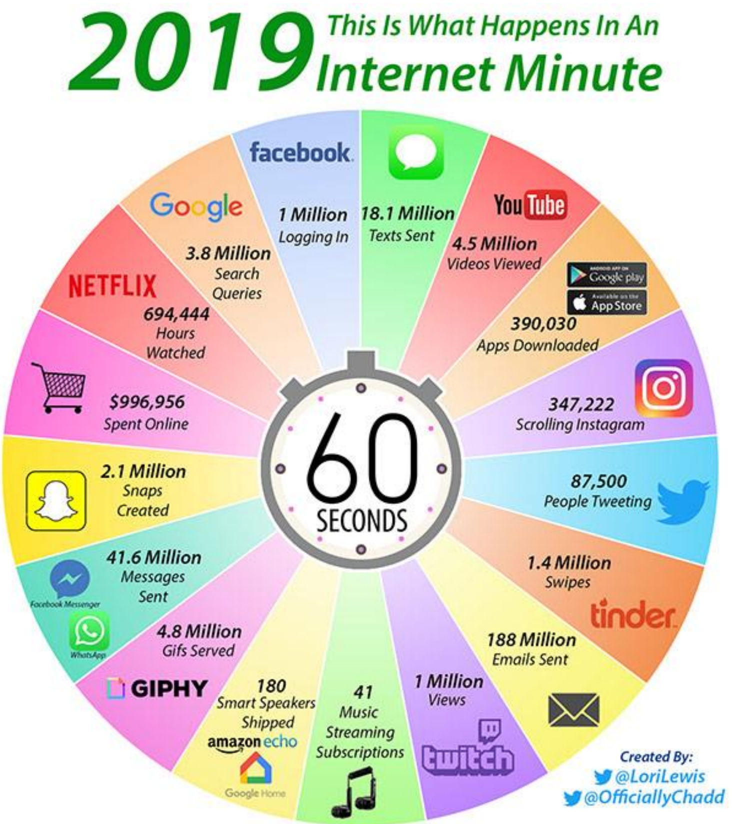
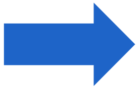
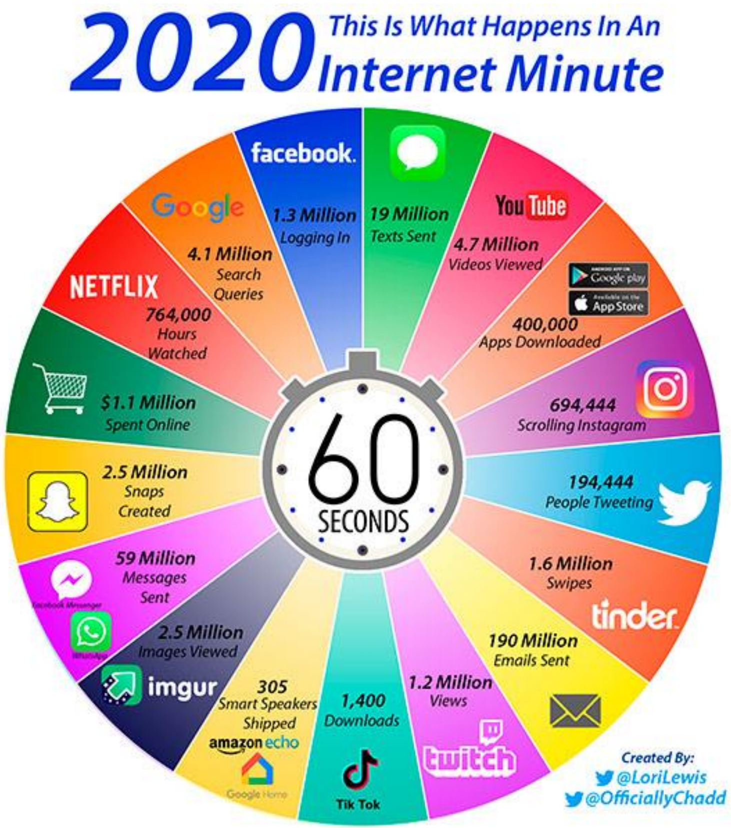


~~Graphene-Silicon Photonic Integrated Devices for~~ **Optical Interconnects**

Internet Traffic

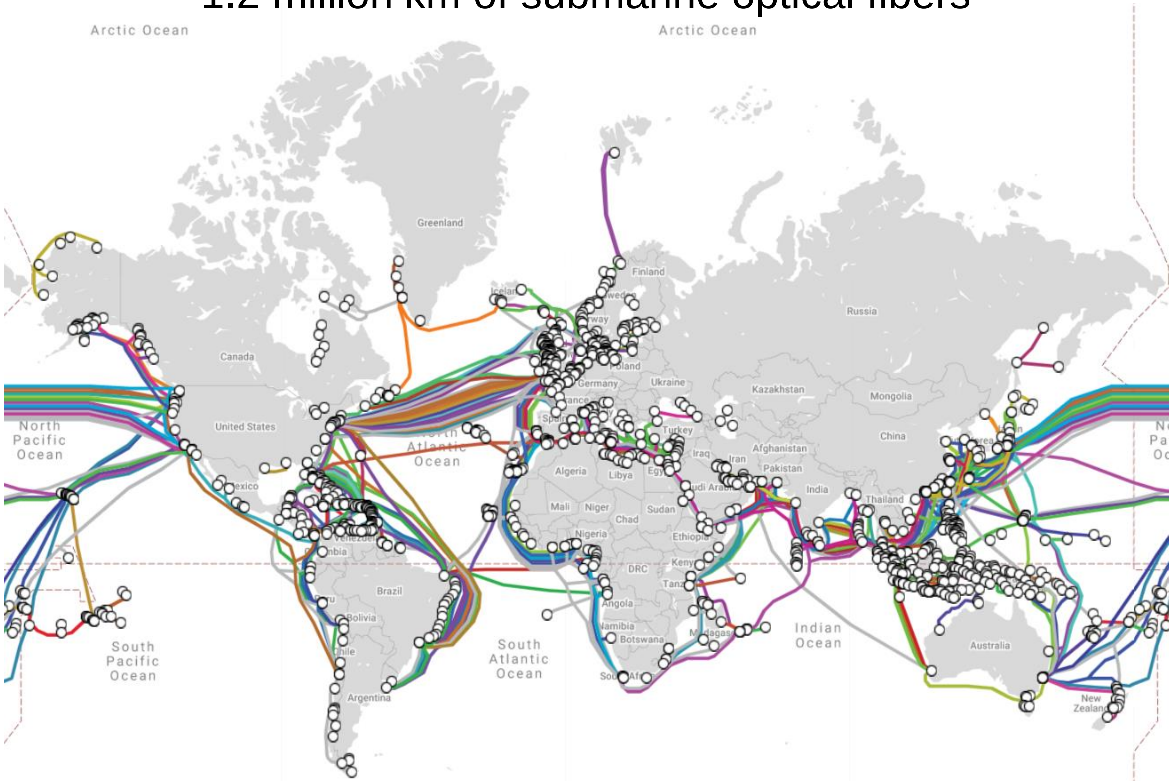






Long Distance Communication: Optical Fibers

1.2 million km of submarine optical fibers



30x

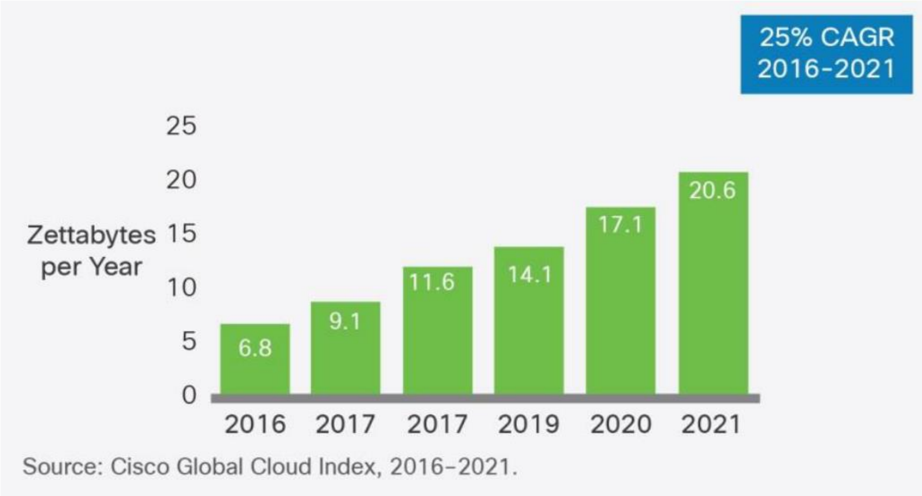
www.submarinecablemap.com

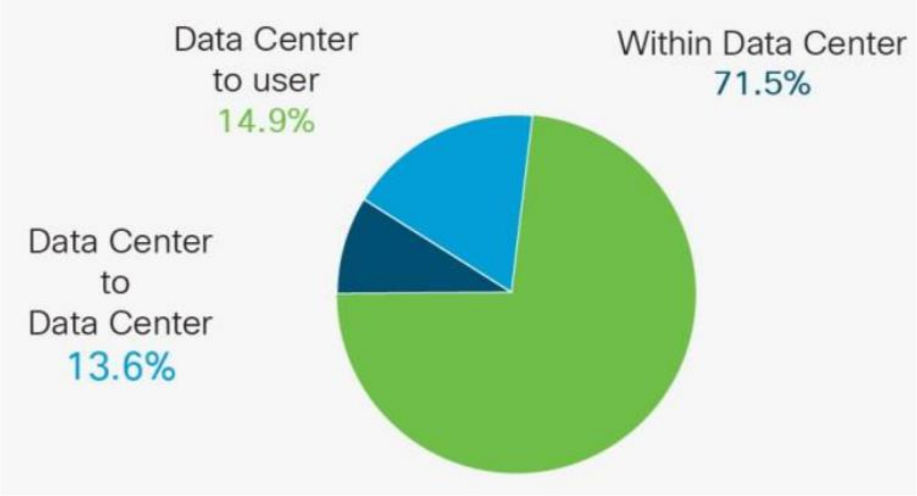
DATA CENTERS

The Citadel, Tahoe Reno, Nevada (USA)

Size = 670,000 m^2 → more than 90 football fields!

INTERNET TRAFFIC





What's a Zettabyte?

1 ZB = 1,000,000,000,000 GB

- Most traffic is for communications within a data center.
- Rack-to-rack traffic is twice the size of the 'within data center' traffic

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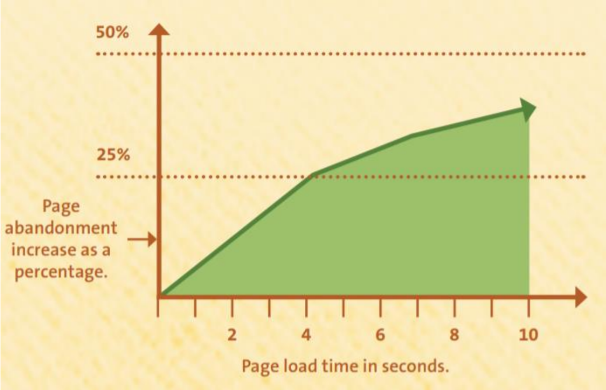
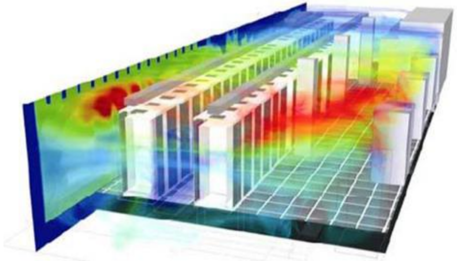
Cisco Global Cloud Index, Forecast and Methodology for 2015-2020, 2016.

Requirements For Data Centers

HIGH SPEED	LOW COST	LOW POWER CONSUMPTION
1. Computation speed 2. Interconnection speed	1. Equipment costs 2. Running and maintenance costs of data centers	1. Nodes 2. Heating, ventilation, cooling



https://blog.kissmetrics.com/wp-content/uploads/2011/04/loading-time.pdf



https://www.independent.co.uk/environment/global-warming-data-centres-consume-three-times-much-energy-next-decade-experts-warn-a6830086.html

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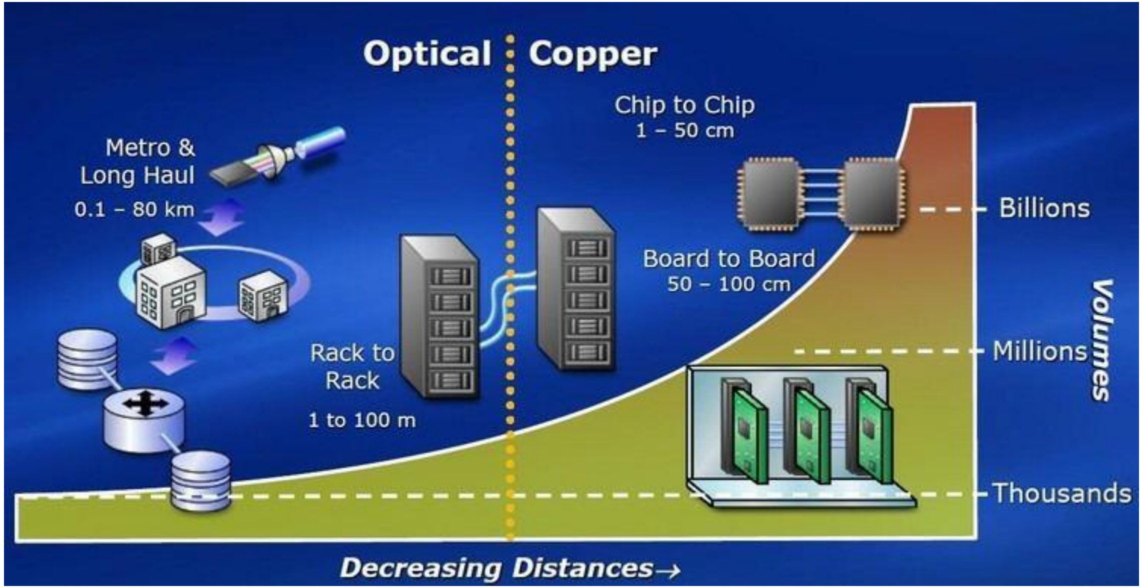
Communication Levels



Fibers (optical) — Bottleneck → Copper (electrical)

- Signal attenuation
- Dielectric losses
- Frequency dependency
- Cross-talk

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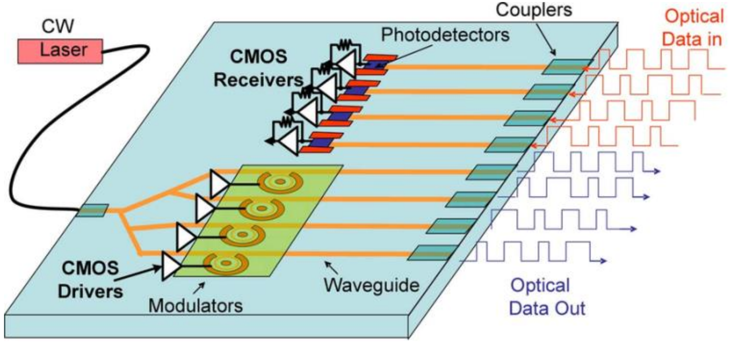
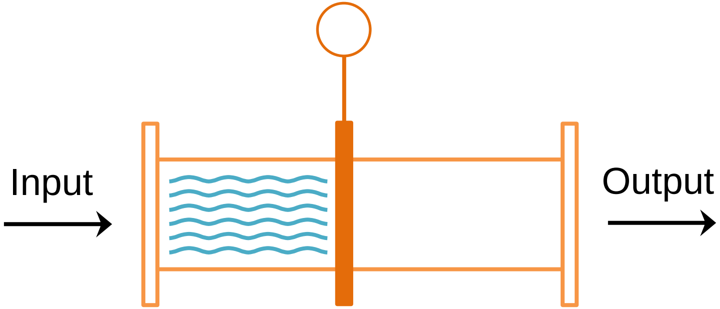
https://alchetron.com/Optical-interconnect

Optical Interconnects

Optical Transceiver



Modulator



Ideal: no losses (no ‘water leaks’)

Modulator:

electrical signal → optical signal

Photodetector:

optical signal → electrical signal

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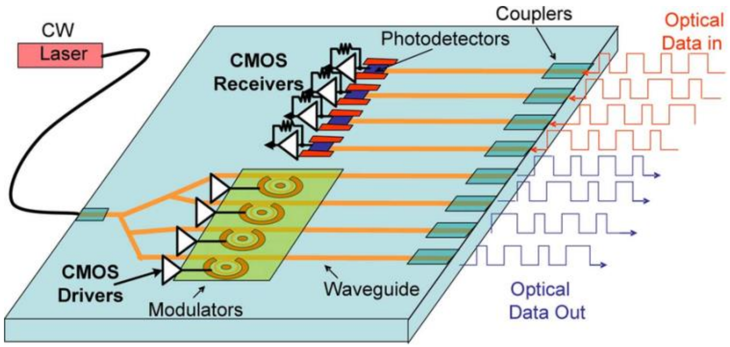
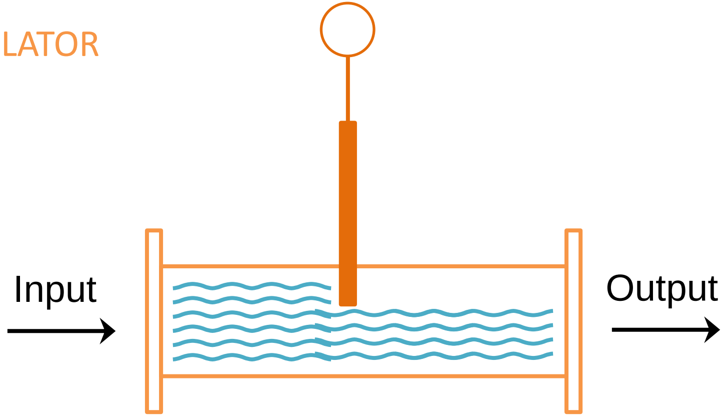
OPTICAL INTERCONNECTS

OPTICAL TRANSCEIVER



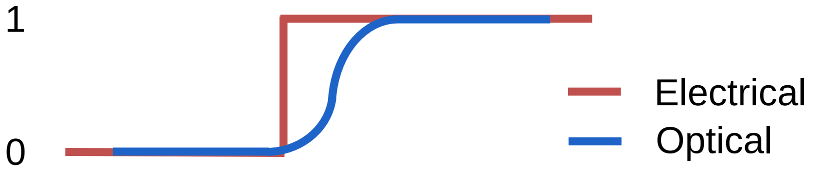
MODULATOR



MODULATOR:

electrical signal → optical signal

Ideal: infinite losses (all the water goes through)

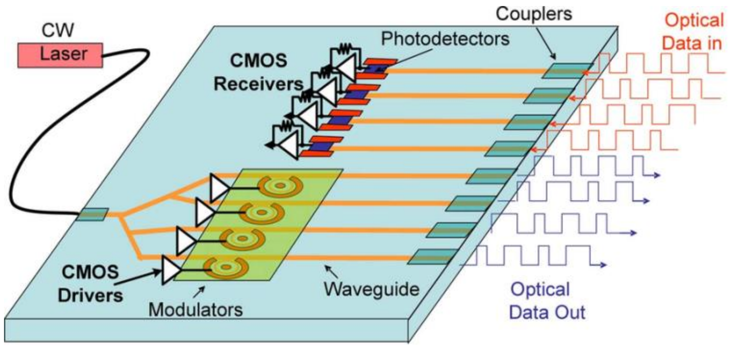


PHOTODETECTOR:

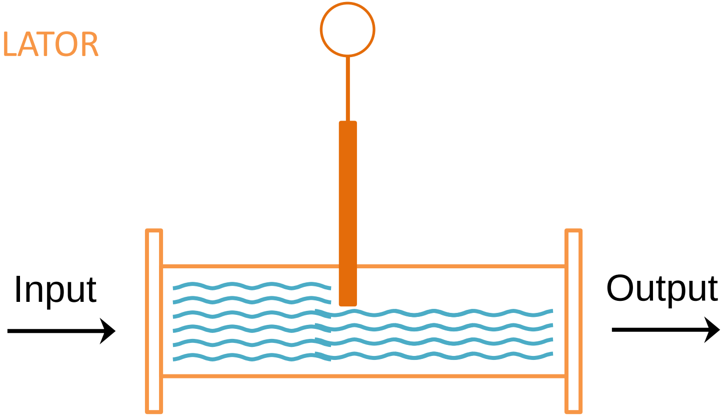
optical signal → electrical signal

Optical Interconnects

Optical Transceiver



Modulator



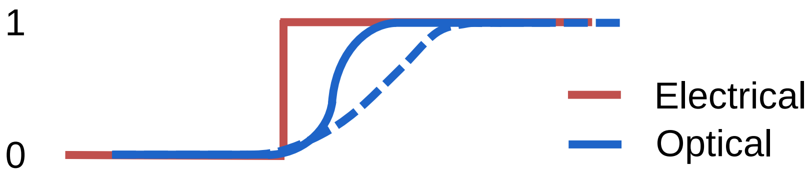
Modulator:

electrical signal → optical signal

Photodetector:

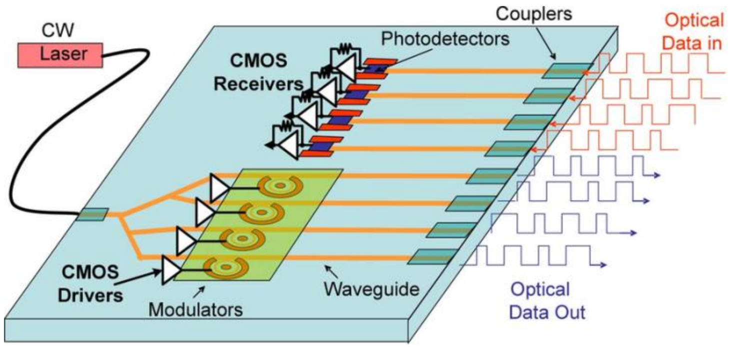
optical signal → electrical signal

Speed is also important!



Optical Interconnects

Optical Transceiver



Modulator:

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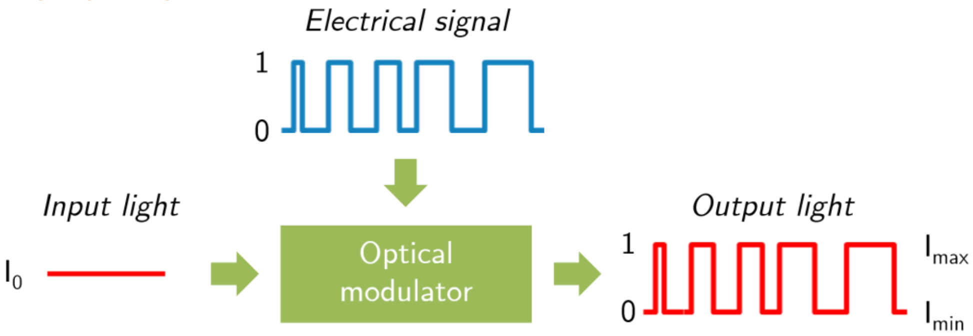
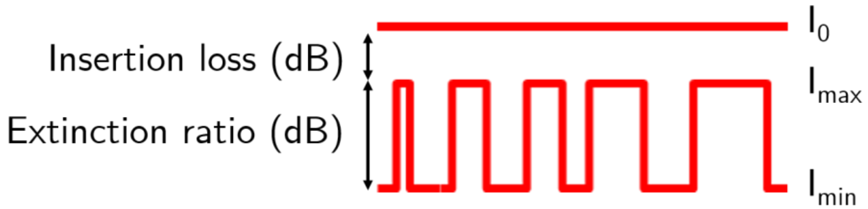
Modulator

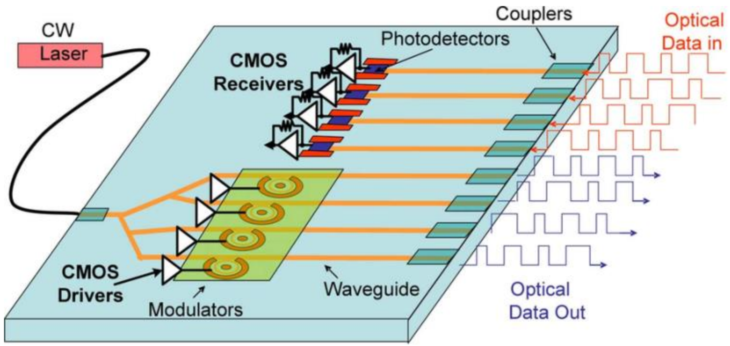


Important Parameters



Optical Interconnects

Optical Transceiver



Photodetector

Modulator:

electrical signal → optical signal

Photodetector:

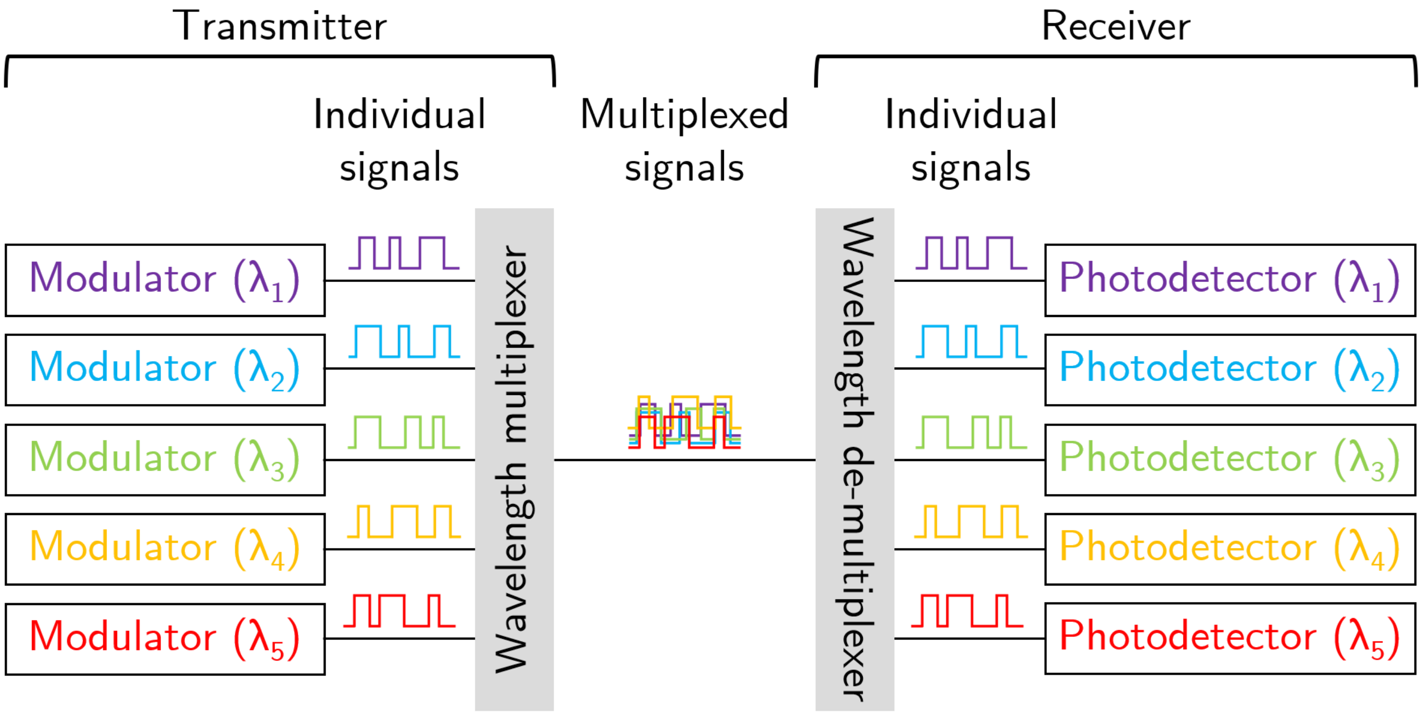
optical signal → electrical signal

Important Parameters

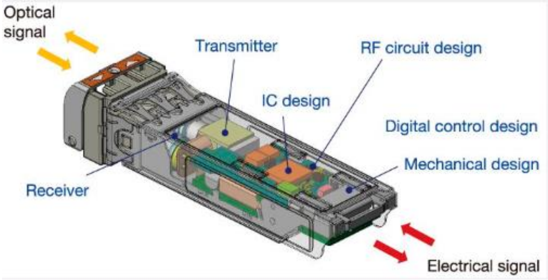
- Responsivity = photocurrent per unit incident optical power
- Dark current = current when input light is off

Optical Interconnects

Wavelength Division Multiplexing



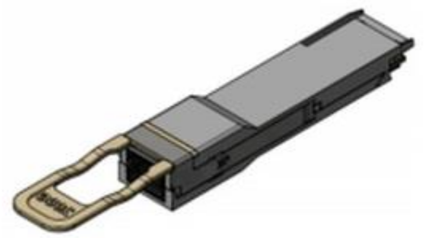
Commercial Optical Transceivers



LUXTERA
FIBER TO THE CHIP

100GbE QSFP28
PSM4

Mellanox
TECHNOLOGIES



200GbE QSFP56
CWDM4

intel

100GbE QSFP28
PSM4

intel

100GbE QSFP28
CWDM4

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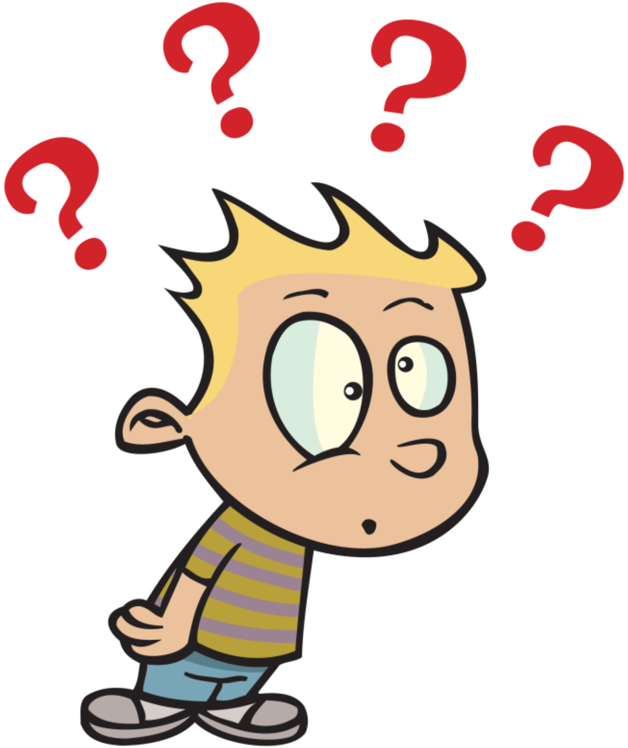


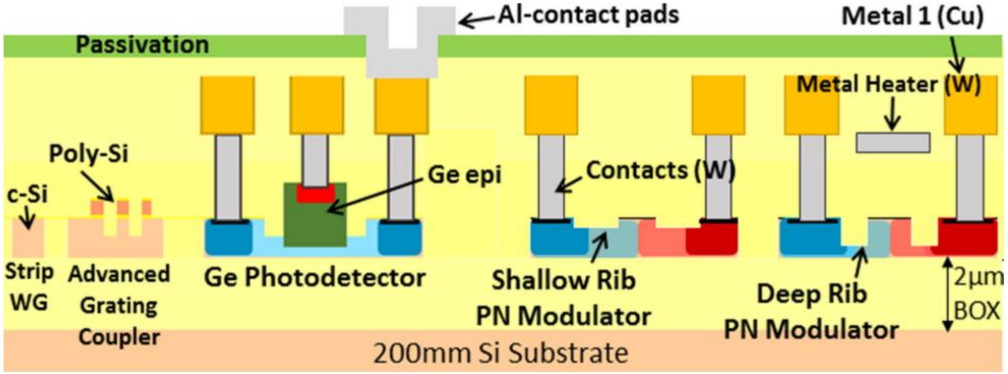
~~Graphene~~ **Silicon Photonic Integrated Devices** ~~for Optical Interconnects~~

Silicon Photonics

- Designing optical devices using silicon
- Light (photons) travels through waveguides made of silicon
- CMOS compatible → low cost

Wavelength Range

- C-band (1530 – 1565 nm)
- O-band (1260 – 1360 nm)



Pantouvaki, M., Srinivasan, ... & Absil, P. (2017). *Journal of Lightwave Technology*, *35*(4), 631-638.

REQUIREMENTS*

For modulators and photodetectors:

- Speed: > 50 Gb/s
- Footprint: < 100 μm^2
- Insertion loss: ≤ 1 dB
- Energy consumption: 100 μW GHz^{-1}

All these requirements can't be satisfied in one system, usually because of trade-offs between electro-optical properties and loss. → New materials need to be continuously researched and tested to push the performance limits.

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*Ethernet roadmap

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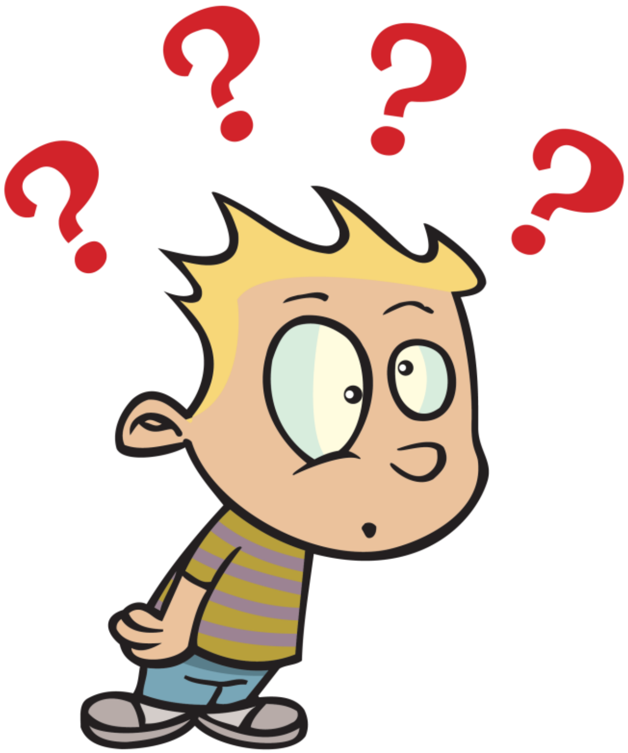
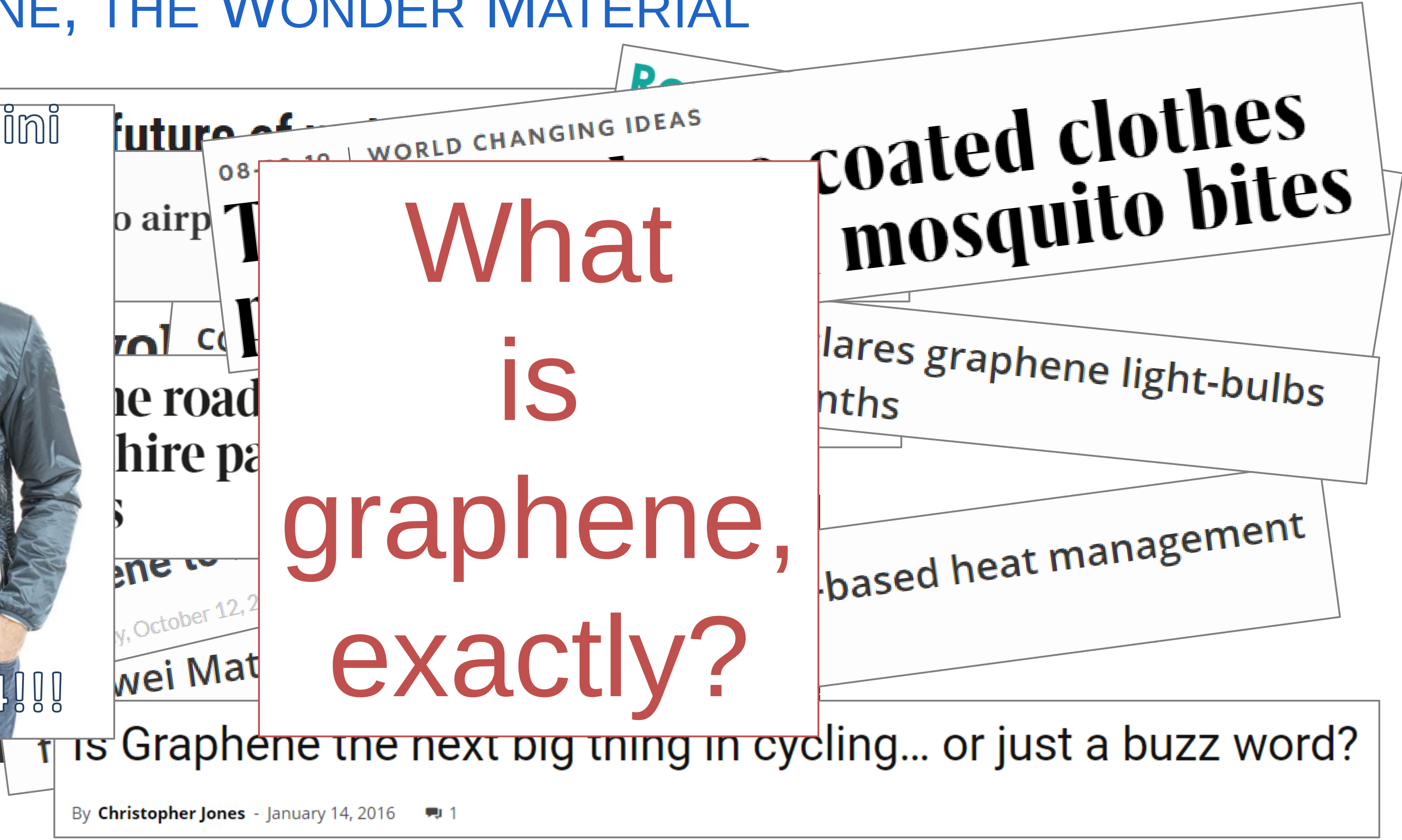


Graphene-~~Silicon Photonic Integrated Devices for Optical Interconnects~~

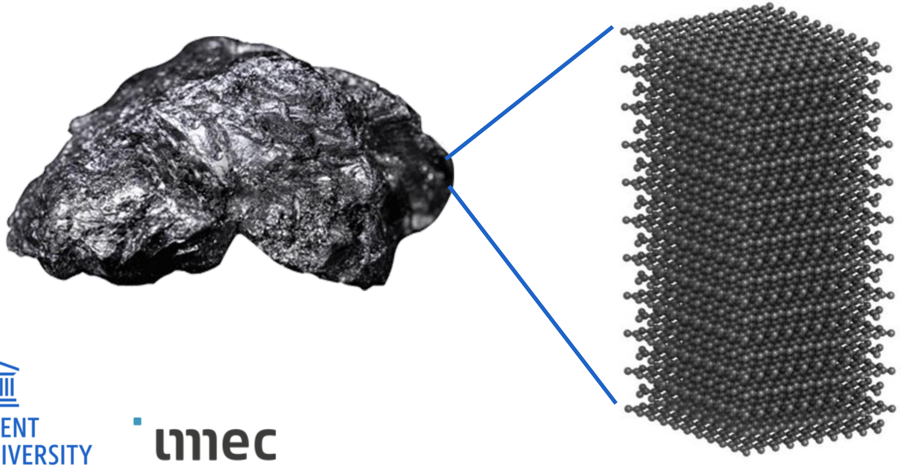
Graphene, the Wonder Material



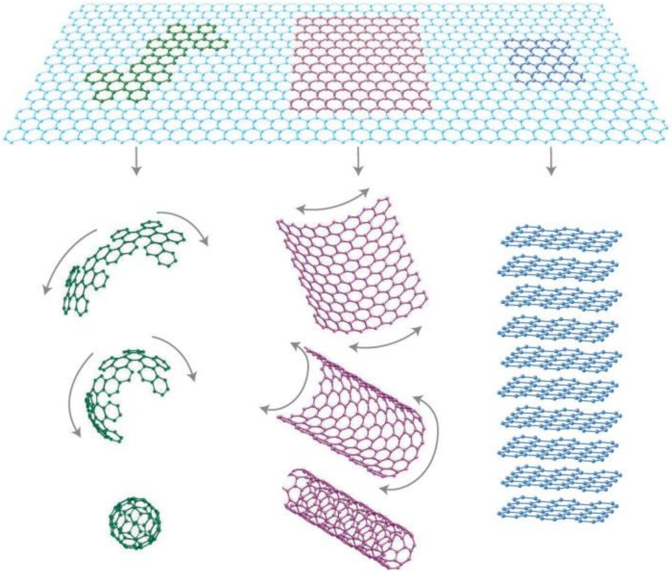
What is graphene, exactly?

Graphene

Graphite



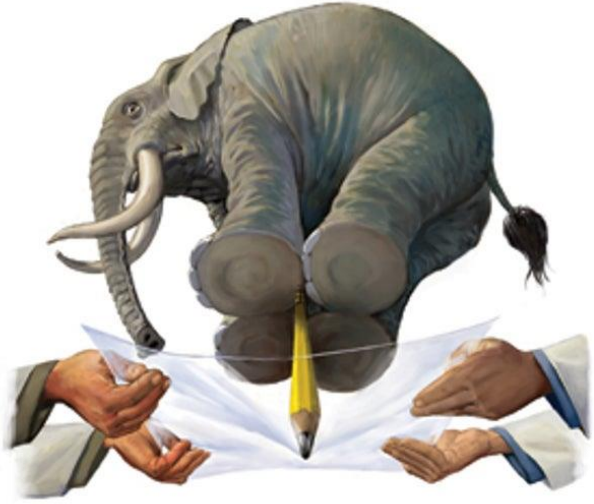
Graphene



HARDER, BETTER, FASTER, STRONGER

HIGH TENSILE STRENGTH

It would take an elephant balanced on a pencil to break a (perfect) graphene layer.
100x stronger than steel



HIGH CONDUCTIVITY

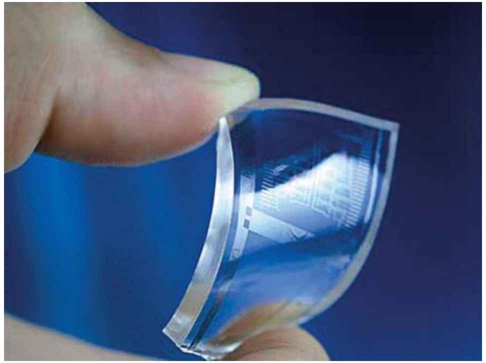
Perfect thermal conductor
High electrical conductivity

IMPERMEABILITY

Less permeable to gases than a one-mm-thick wall of glass

FLEXIBILITY

Graphene can stretch by 20%, like rubber



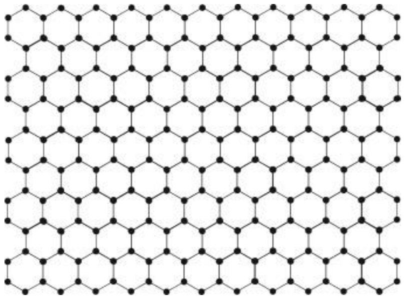
TRANSPARENCY

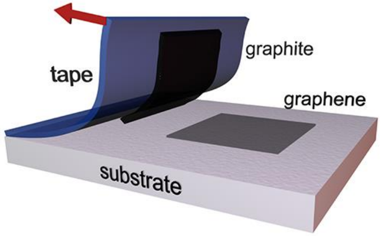
From visible to infrared

GRAPHENE PROPERTIES

Graphene: the "original" 2D material

- Single layer of σ-bonded carbon atoms arranged in a hexagonal lattice.
- The exfoliation of a single layer was first demonstrated by Novoselov et al. [1] (Nobel prize in Physics 2010).

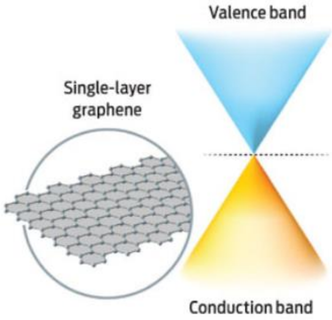




The scotch-tape method

Properties:

- Very high mobilities (>300 000 cm^2/Vs @ 300 K)[2]
- Exceptional temperature stability
- High optical absorption: 2.3% per atomic layer
- Broadband absorption (no bandgap)
- Tunable light absorption



[3]

Zero bandgap

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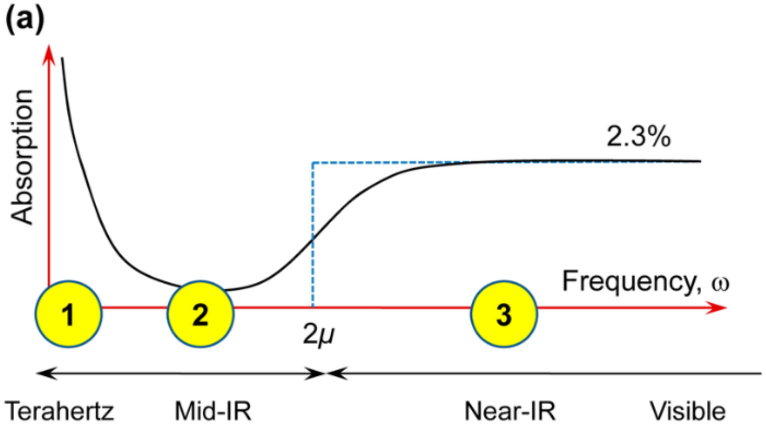
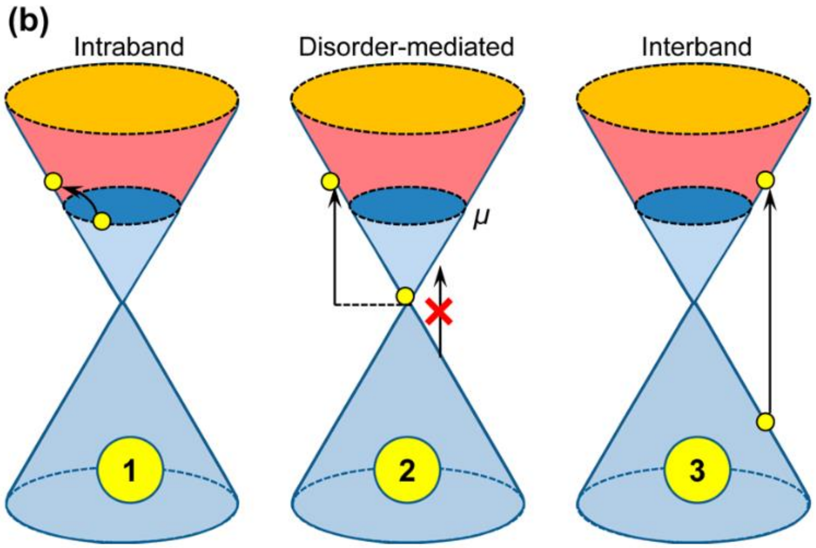
[1] 10.1038/nmat1849
[2] 10.1016/j.ssc.2008.02.024
[3] 10.1109/mspec.2009.5210033

Graphene Optical Properties

Constant 2.3% absorption beyond the far-infrared



Optical transition processes



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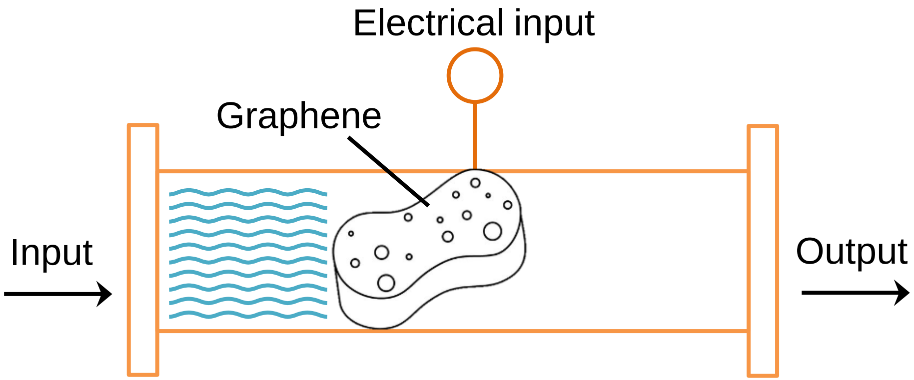
Graphene Electro-Absorption Modulators



The sponge absorbs all the water → no output

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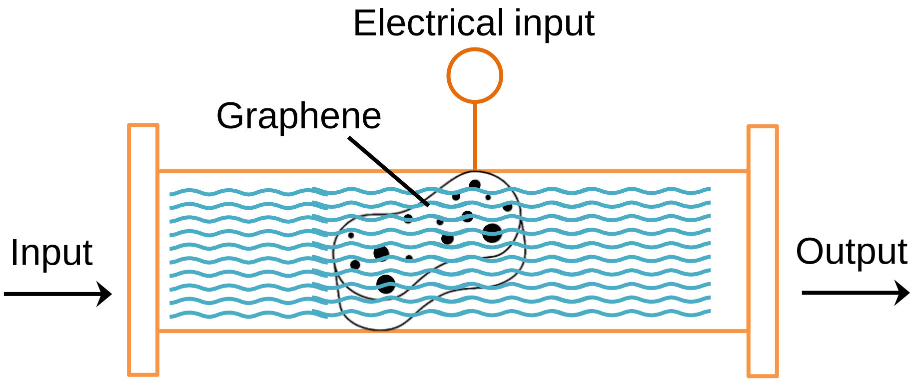
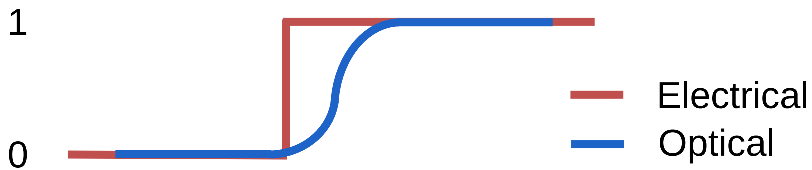
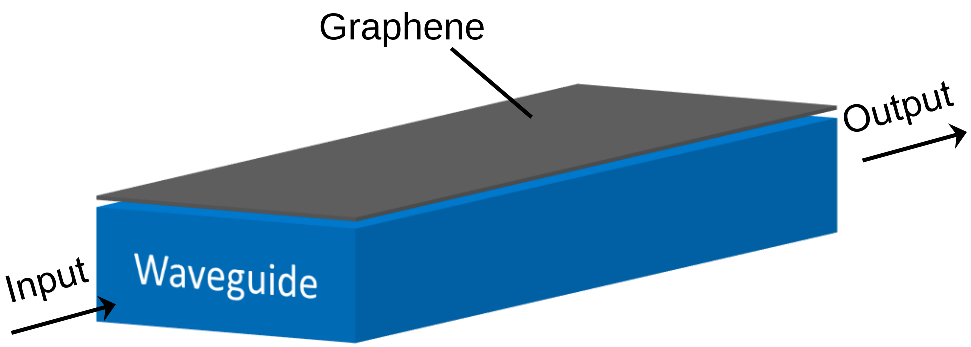
Graphene Electro-Absorption Modulators

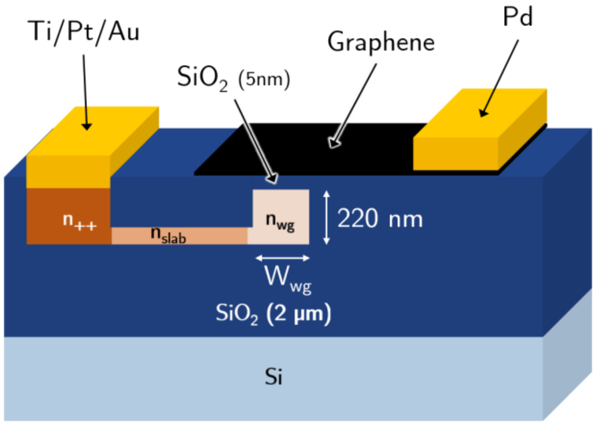


All the holes in sponge are filled in with ‘dirt’ → the sponge does not absorb anymore → all the water goes through



In Practice:





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Research Objectives

Evaluate the potential of graphene-based photonics devices for use in future datacom applications.

1. Optimisation of the process flow used to fabricate graphene-based devices
2. Optimisation of graphene modulators, in particular with single-layer graphene, to achieve high-speed operation.
3. Fabrication and characterisation of graphene-based photodetectors to assess their potential and challenges.

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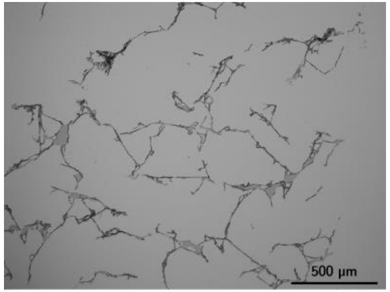
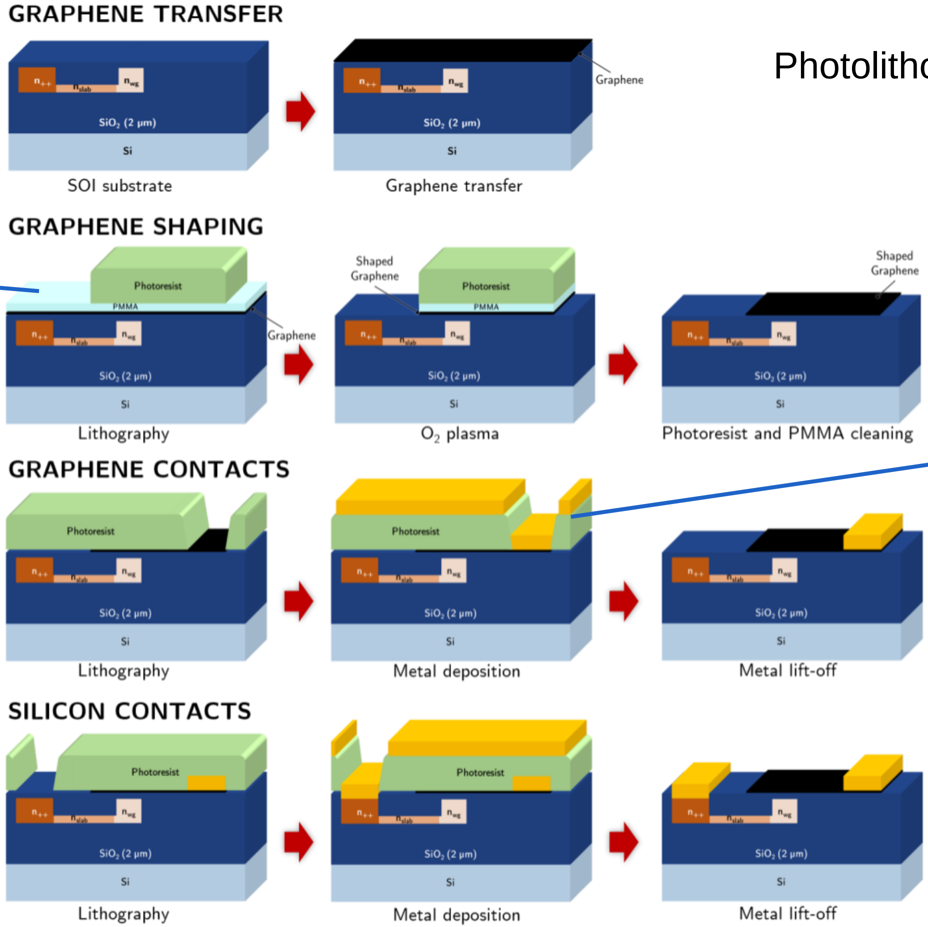
PROCESS FLOW – STANDARD

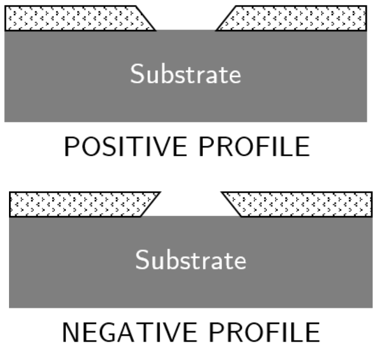
Photolithography (resolution ~ 1 µm)

PMMA layer used to protect graphene from solvents, to avoid delamination





Positive profile (IX845 photoresist) used to for metallisation



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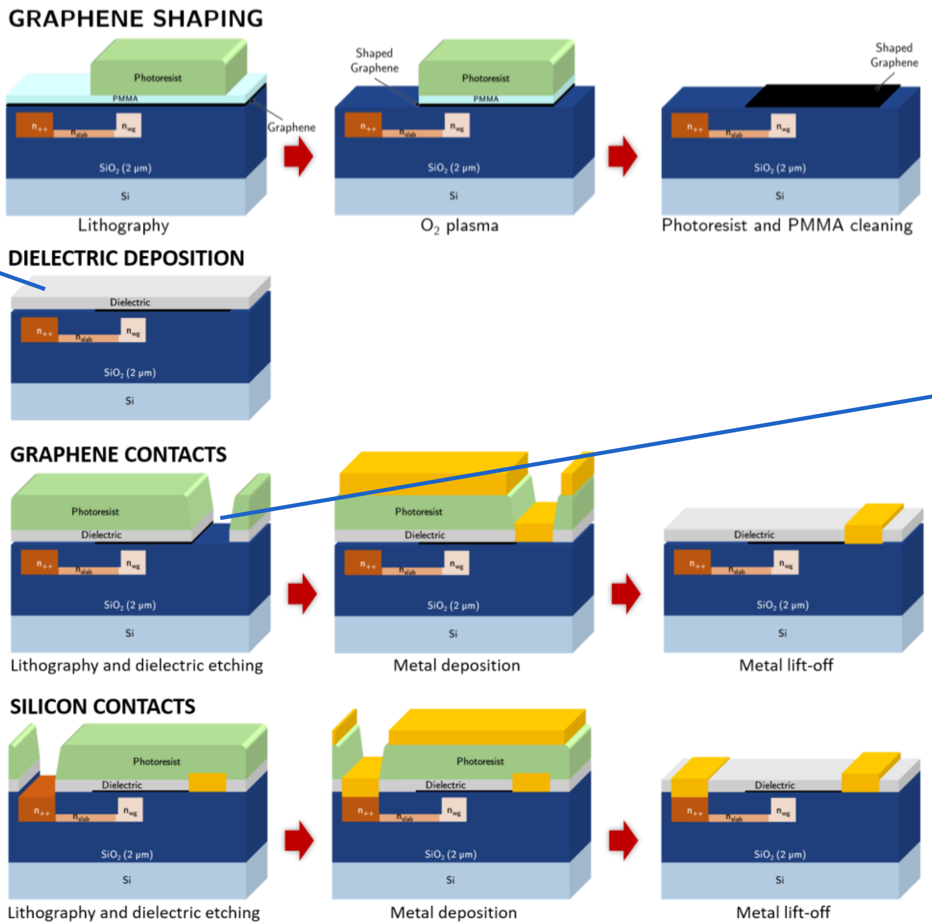
Process Flow – Passivation First

Experimental



Dielectric deposition after graphene shaping → it protects graphene from intercalation of solvents

Dielectric etching also removes the graphene layer underneath → graphene-metal edge contact

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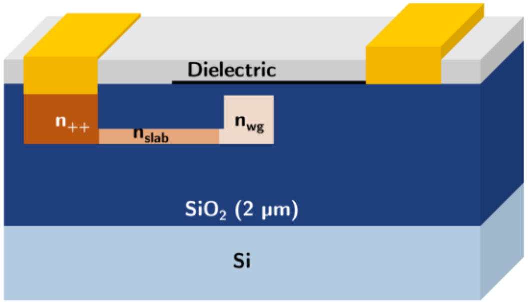
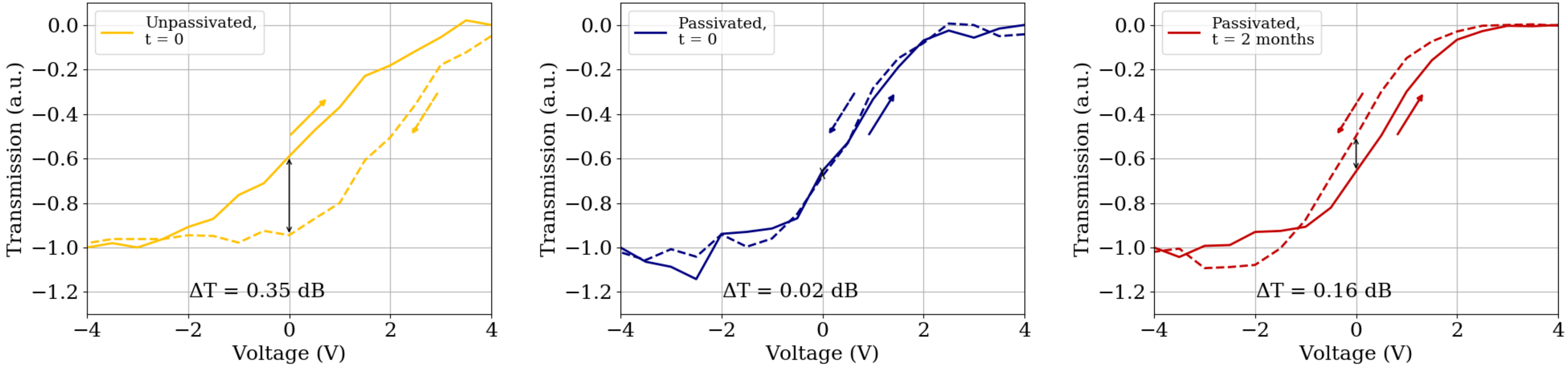
EXPERIMENTAL

PASSIVATION FIRST - RESULTS

- Si (1 nm) / Al_2O_3 (30 nm)
- Single-layer graphene (SLG) EAMs with passivation show reduced hysteretic behaviour





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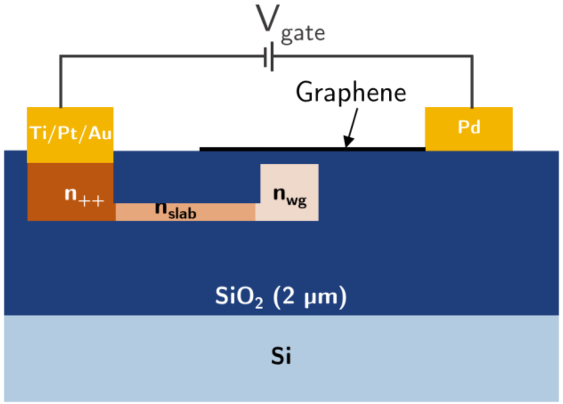
Single-Layer Graphene EAM

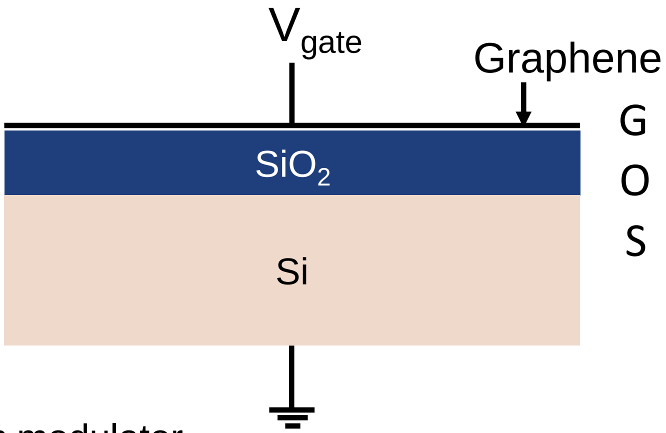


- Planarized, doped Si waveguide
- Doped Si connection “slab”
- Highly doped Si for metal contact
- SiO_2 for light confinement
- Metal contact to Si (Ti) and to graphene (Pd)
- Graphene (on top of the waveguide, for absorption effect)

Graphene + SiO_2 + Si waveguide

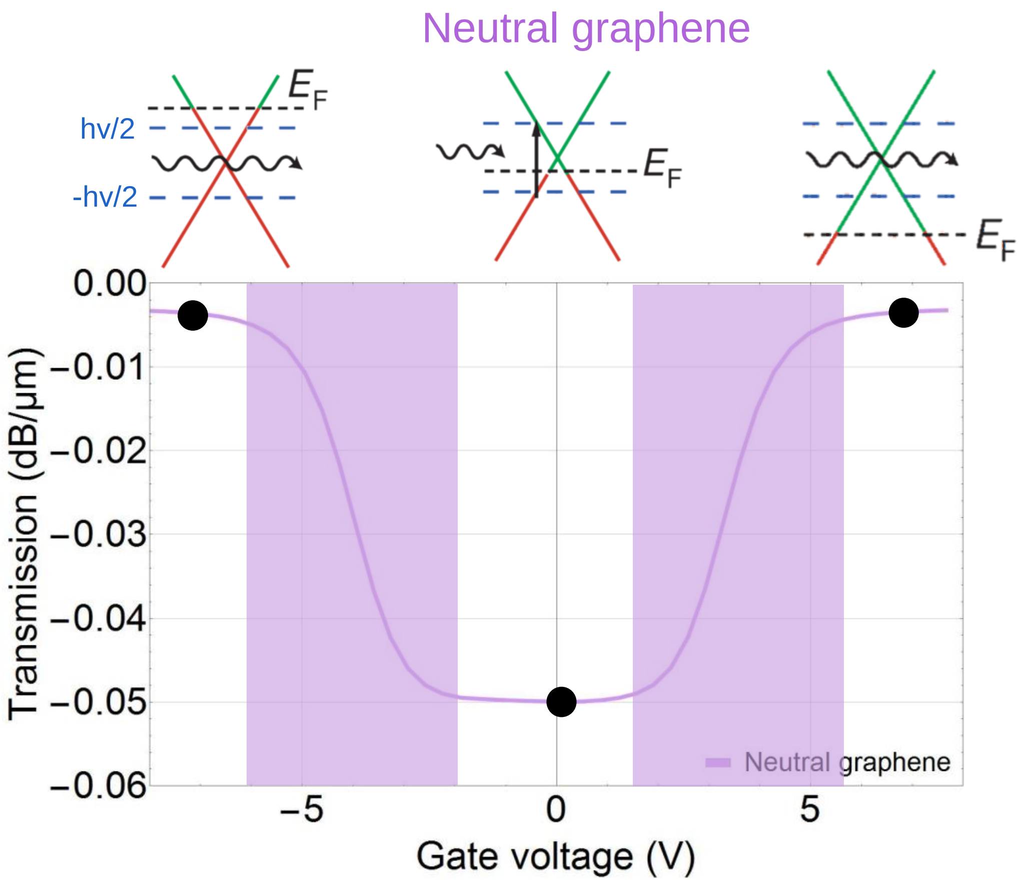
↓

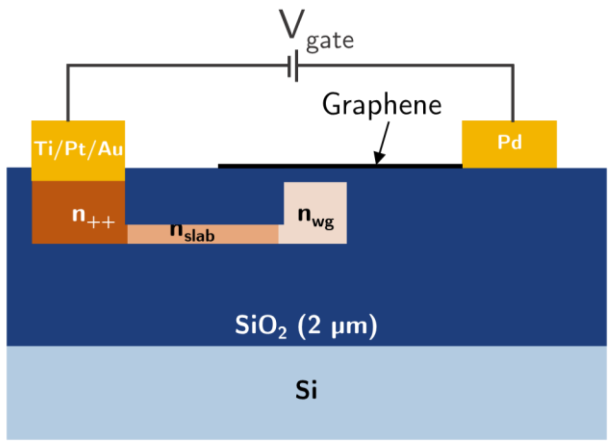
Graphene – Oxide - Silicon (GOS) capacitor



EAM = Electro-absorption modulator

WORKING PRINCIPLE OF A SLG EAM



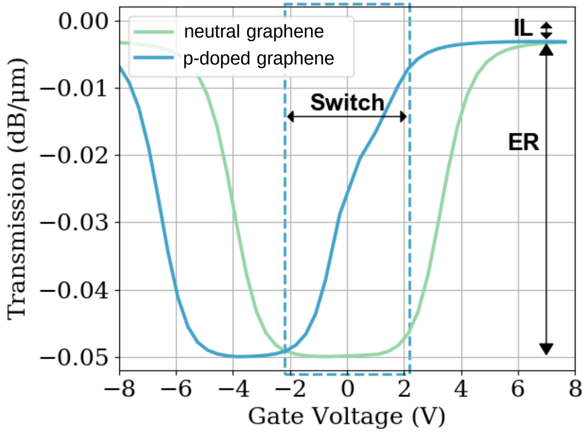


$$V_g = \frac{q\left(n_0 + n_s\right)}{C_{GOS}} = \frac{q}{\pi\left(\hbar v_F\right)^2}\frac{\mu^2}{C_{GOS}}$$

SLG = Single-Layer Graphene
EAM = Electro-absorption modulator

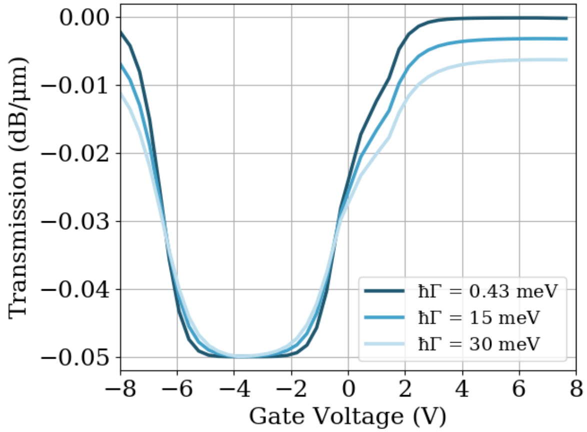
STATIC ELECTRO-OPTICAL BEHAVIOUR

1.



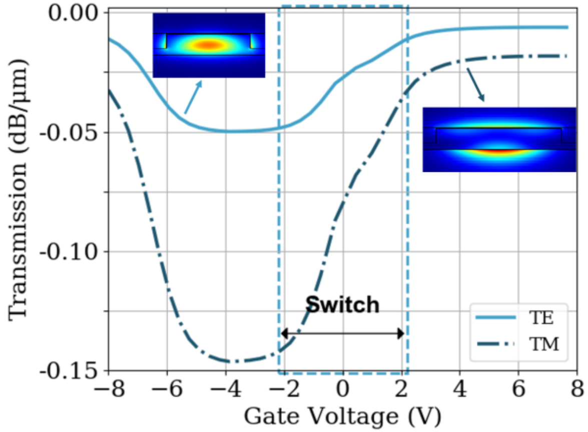
P-doped graphene → switch around 0 V

2.



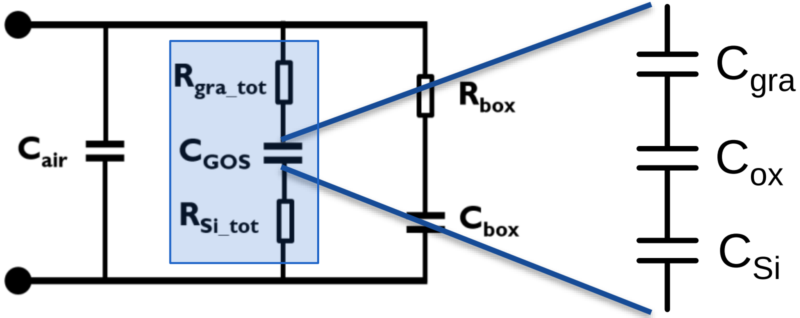
Higher mobility (lower) → higher extinction ratio

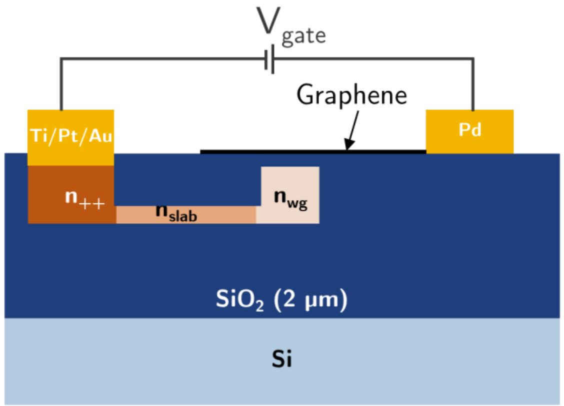
3.



TM mode → higher extinction ratio than TE mode

Speed Limitation: The RC Constant





1. $$C_{gra} = \frac{2q^2}{\hbar v_F \sqrt{\pi}} \sqrt{|n_s + n_0| + |n^*|}$$

2. $$C_{ox} = \frac{\varepsilon_0 \varepsilon_{ox}}{d_{ox}}$$

3. $$C_{Si} = \frac{\varepsilon_0 \varepsilon_{Si}}{W_{dep}} \propto \sqrt{N_{D/A}}$$

Silicon doping

- The capacitance can be reduced by playing with the Si doping

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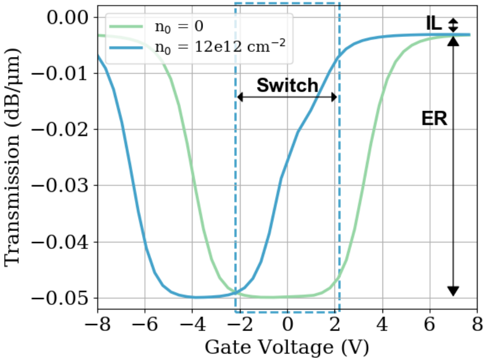
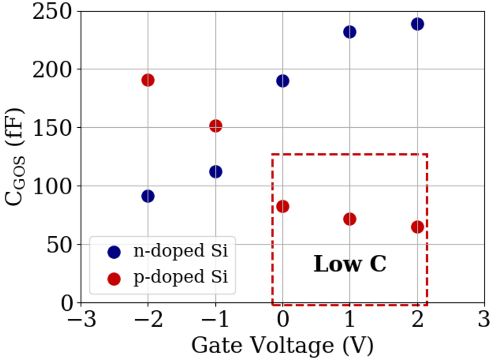
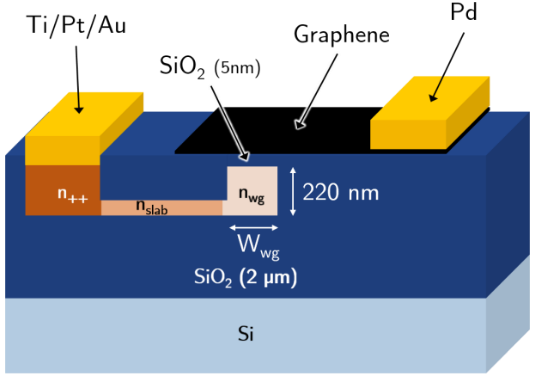
STUDY OF SI DOPING INFLUENCE ON SLG EAMS

DC CHARACTERISTIC (P-SI)

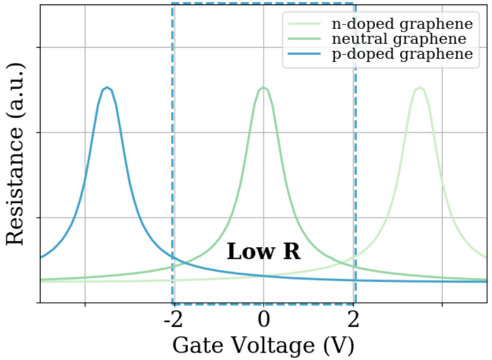


CAPACITANCE GOS

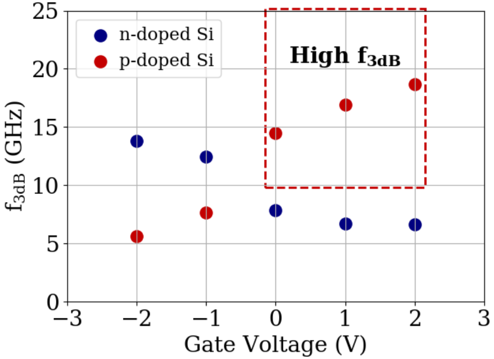




GRAPHENE RESISTANCE



3DB BANDWIDTH



Waveguide

- p-doping → low capacitance at forward bias ✓
- n-doping → high capacitance at forward bias ✗

↓

When combined with p-doped graphene, p-doped Si is preferable

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EXPERIMENTAL

SI DOPING EFFECT ON EAM PERFORMANCE

STATIC PERFORMANCE

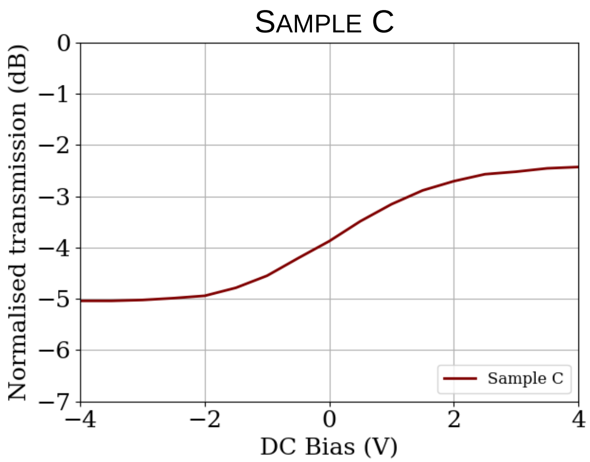
DESIGN OF EXPERIMENTS

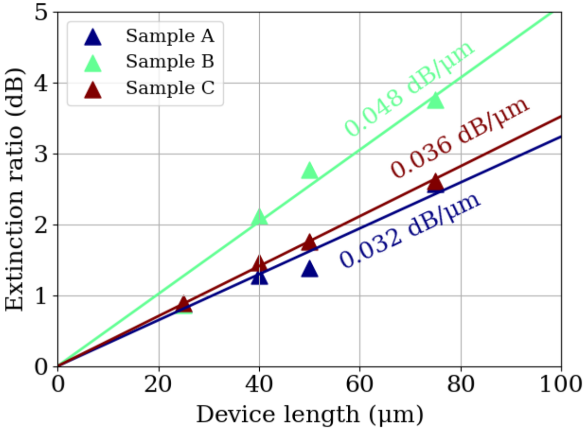
- Three samples fabricated with different silicon doping

	Si doping type	Si doping level
Sample A	n-doped	Low
Sample B	n-doped	High
Sample C	p-doped	High

RESULTS

- Graphene is p-doped (minimum of transmission at negative bias)
- Extinction ratio increases with device length





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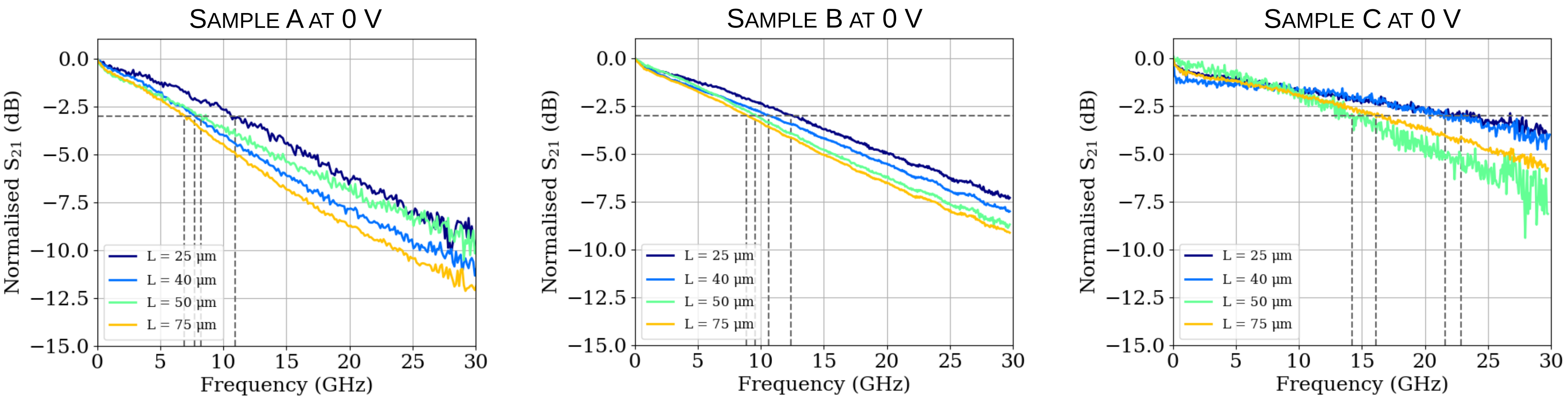
Experimental

Si Doping Effect on EAM Performance

Electro-Optical S-Parameters measurements



	C-band 3db Bandwidth (GHz) at 0 V			
	L = 25 µm	L = 40 µm	L = 50 µm	L = 75 µm
Sample A (n-Si, low)	10.9	7.7	8.2	6.9
Sample B (n-Si, high)	12.4	10.6	9.6	8.9
Sample C (p-Si, high)	22.8	21.6	14.2	16.1

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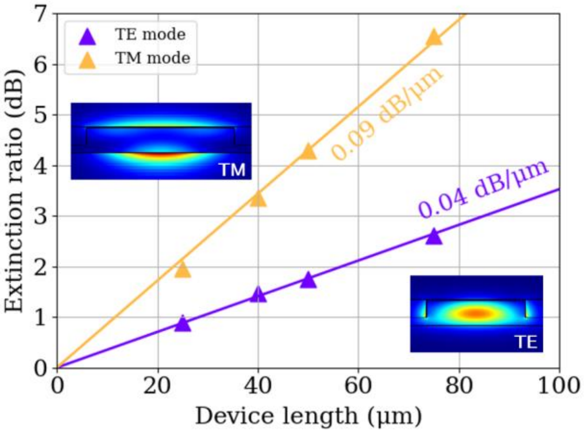
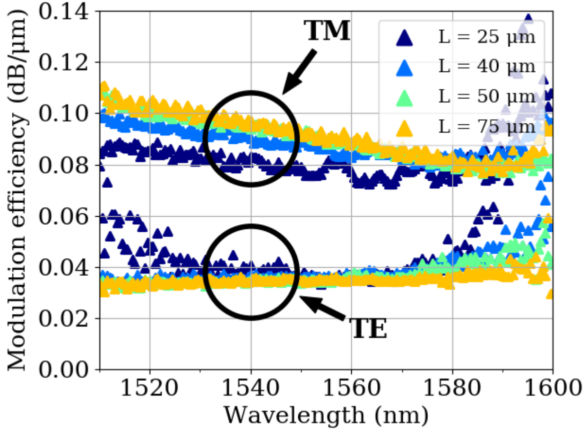
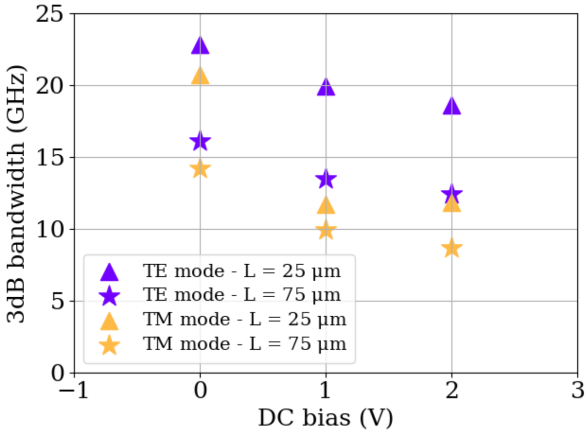
TE VS TM EAMS WITH P-DOPED SI







- TM modulators need a wider waveguide in order to keep the mode confined
- TM modulators have higher mode overlap with the graphene layer
- This results in a double modulation efficiency (ME)
- Similar 3dB bandwidth

$$ME = \frac{ER}{L_{device}}$$

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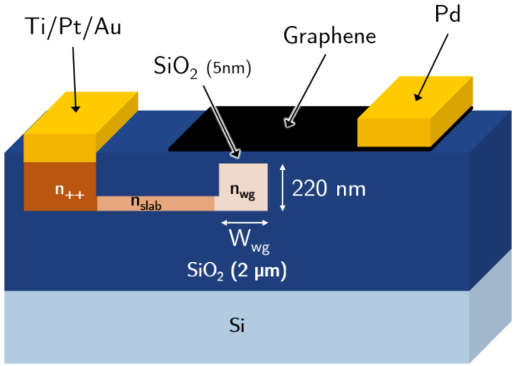
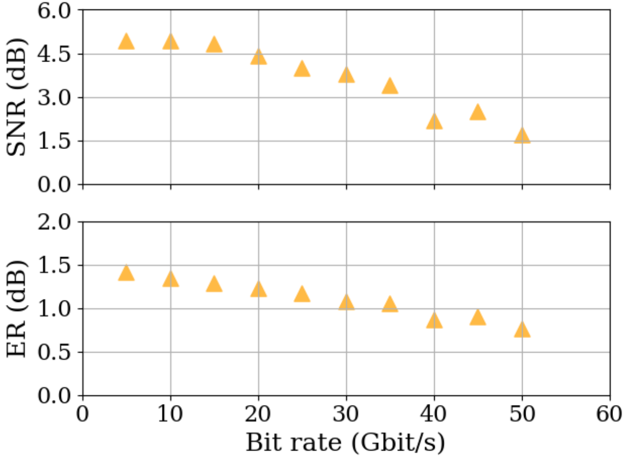
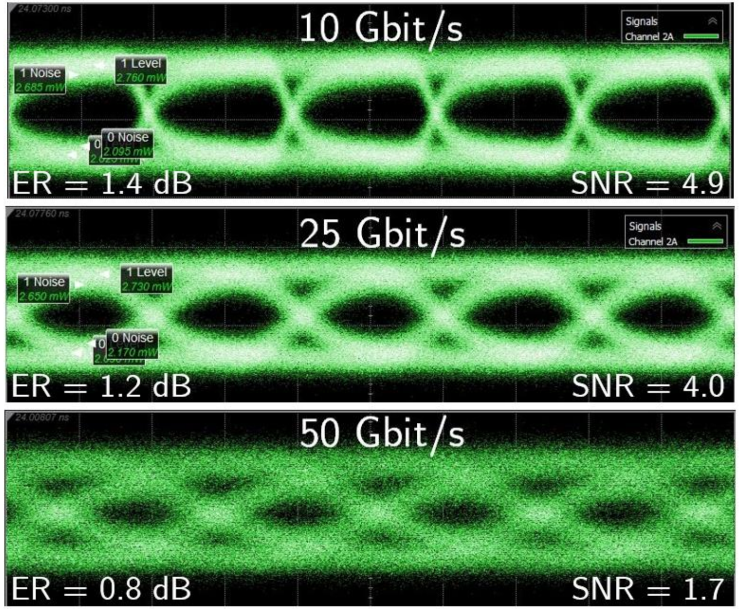
EXPERIMENTAL

50 GBIT/S SLG EAM WITH P-DOPED SI



- TM, C-band, pSi EAM
- L_{device} = 75 μm
- Static ER = 6.6 dB
- DC bias: V = -0.5 V
- 2.5 V_{pp}
- 2^{23}-1 PRBS





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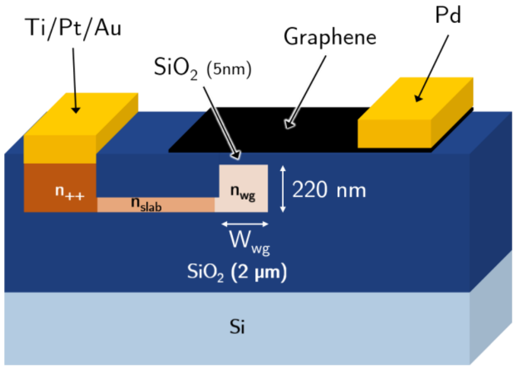
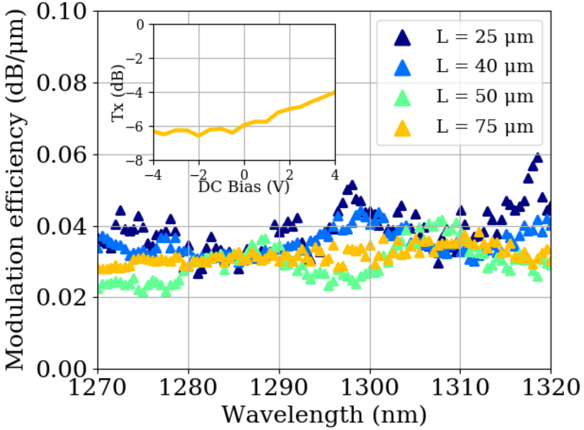
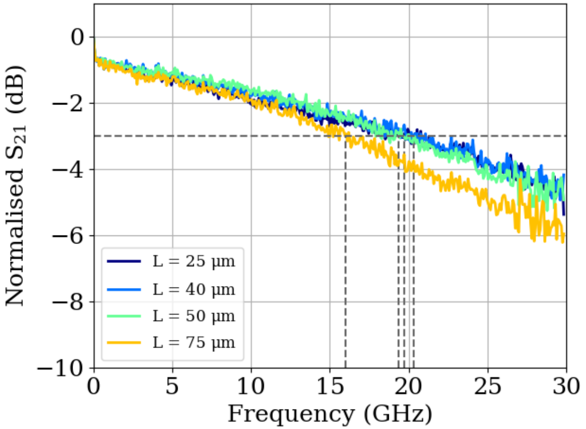
O-BAND OPERATION OF SLG EAMS

EXPERIMENTAL



O-BAND (TM)





- High-speed operation in the O-band and in the C-band using the same fabrication process
- First time demonstration of graphene O-band modulators

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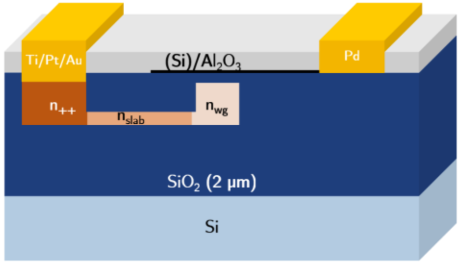
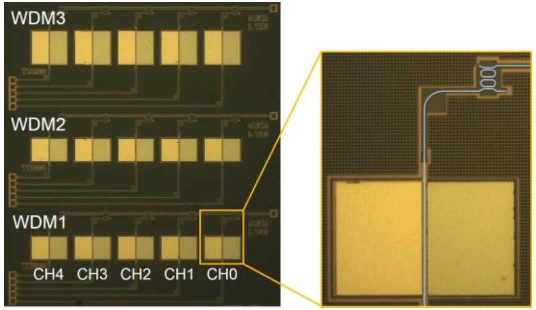
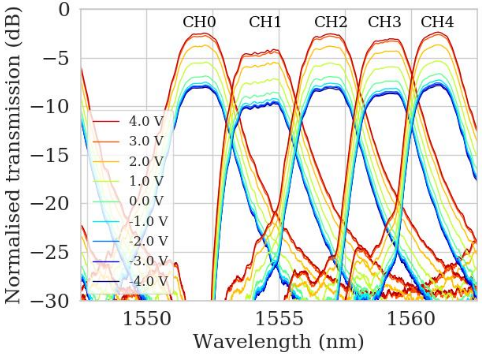
WDM TRANSMITTERS WITH SLG EAMS (N-SI)

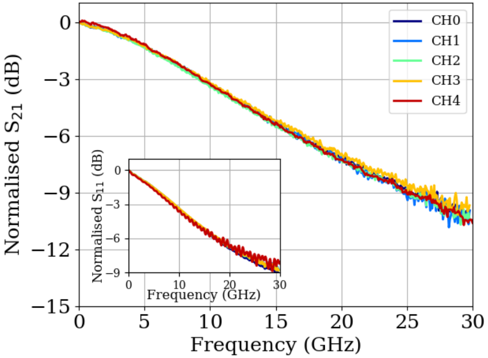
CROSS SECTION AND TOP VIEW



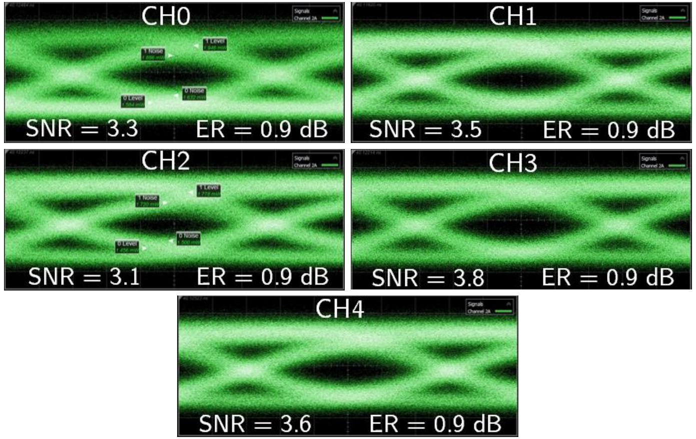


STATIC AND S-PARAMETER MEASUREMENTS ON WDM2





LARGE SIGNAL CHARACTERISATION



5 x 25 Gbit/s

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

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Research Objectives

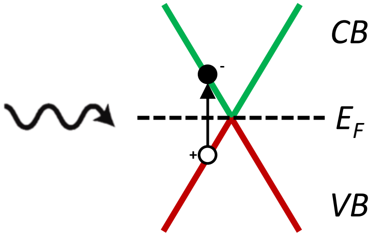
Evaluate the potential of graphene-based photonics devices for use in future datacom applications.

1. Optimisation of the process flow used to fabricate graphene-based devices
2. Optimisation of graphene modulators, in particular with single-layer graphene, to achieve high-speed operation.
3. Fabrication and characterisation of graphene-based photodetectors to assess their potential and challenges.

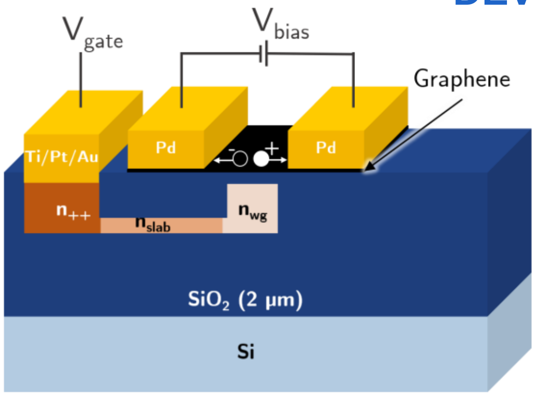
Graphene Photodetectors

GOAL

1. Photons absorption
2. Generation of e^--h^+ pairs
3. Collection of e^- (or h^+) before recombination occurs



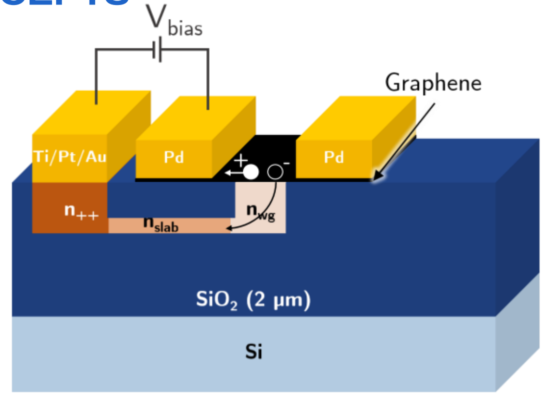
DEVICE CONCEPTS



GRAPHENE PHOTORESISTOR

With oxide between graphene and Si

- The light induces a resistance change in the device: the resistance becomes lower and the current increases
- Dark current too high

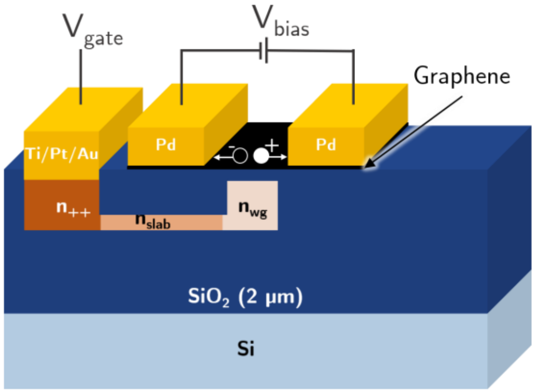


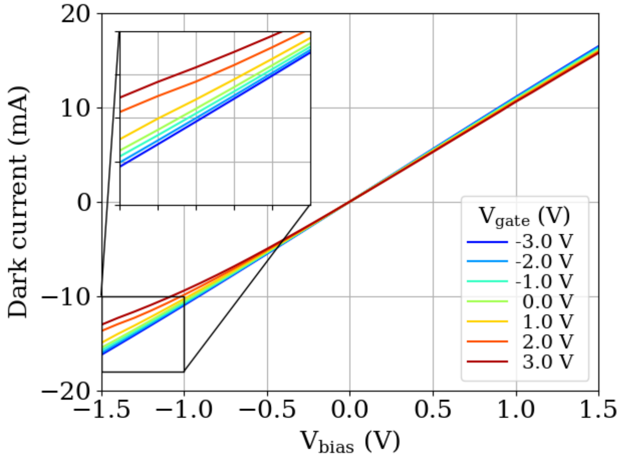
GRA/Si SCHOTTKY JUNCTION

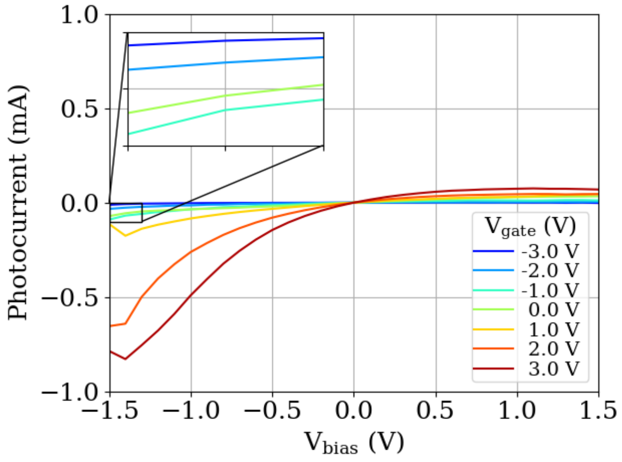
No oxide between graphene and Si

- Si acts as an electrode: carriers are collected directly where they are generated→ more efficient carrier collection
- Carrier dynamics at the interface play an important role

GRAPHENE PHOTORESISTOR







- Laser power = 12 dBm
- Photocurrent = Light current – Dark current
- At V_{bias} = -1.5 V, V_{gate} = 3 V → I_{dark}/I_{photo} ~ 16.4
- Dark current is too high

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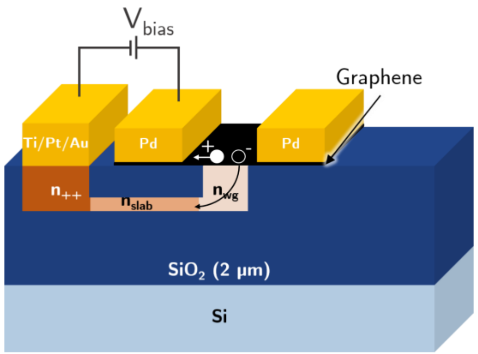
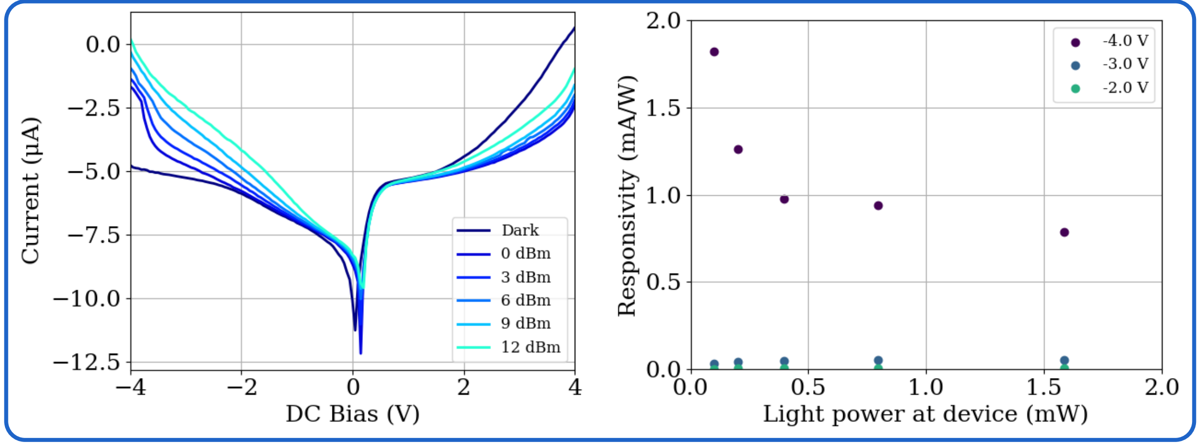
Graphene/Si Schottky Junction

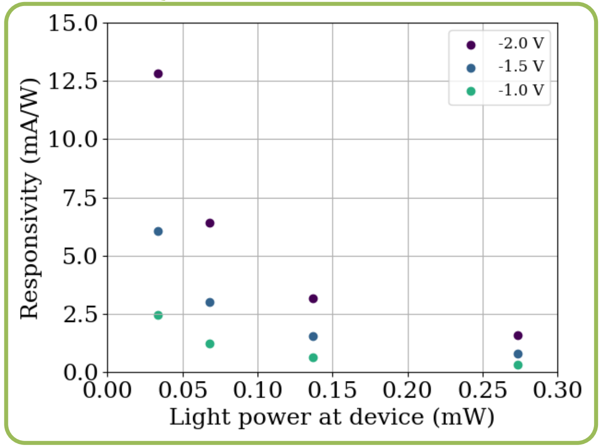
Experimental

Best in literature (for similar geometry):
R = 370 mA/W*



Device type	Wg mode	L_{device} (µm)	R (mA/W)	I_{dark}	V_{bias} (V)	V_{gate} (V)
Schottky diode (n-Si)	TE	150	1.8	-8.6 nA	-4	-
Schottky diode (p-Si)	TE	150	0.4	-1.5 µA	-4	-
Schottky diode (n-Si)	TM	50	9.7	-1.9 µA	-2	-
Schottky diode (n-Si)	TM	100	12.8	-3.5 µA	-2	-





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*Goykhman et al., Nano Lett. **16**(5), 3005-3016 (2016)

CONCLUSIONS

Conclusions: Graphene for Optical Interconnects

Modulator type	Optical BW (dB)	Insertion Loss (dB)	Static ER (dB)	Power consumption (fJ/bit)	Speed (GHz)	Bit Rate (Gb/s)
Si MRR	< 1 nm	3.8	4.4	-	42	60
Si MRR	< 1 nm	1.2	-	600*	50	112
Si MZM	80	5.6	2.3	720	27	56
GeSi EAM	10	4.4	4	-	> 50	100
Ge EAM	22.4	4.9	4.6	12.8	> 50	56
SLG EAM (C-band)	> 90 nm	4.2	6.5	112	14.2	50
SLG EAM (O-band)	> 90 nm	4.0	3.1	-	16.0	-

*includes power consumption of CMOS drivers

Conclusions and Outlook

1. A stable processing flow was achieved, but further improvements are necessary
   - Fabrication of graphene offers advantages to III-V or Ge (BEOL)
   - Graphene transfer process is an important part of up-scaling graphene devices fabrication
   - Improved fabrication process for passivation layers on graphene
2. Graphene modulators show potential for high-speed data transmission
   - 50 Gbit/s SLG EAM
   - 5x25Gbit/s WDM transmitter
3. Graphene photodetectors studied in this thesis need further improvement, but results in literature show that they could be competitive

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