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Graphene based integrated photonics for optical interconnect

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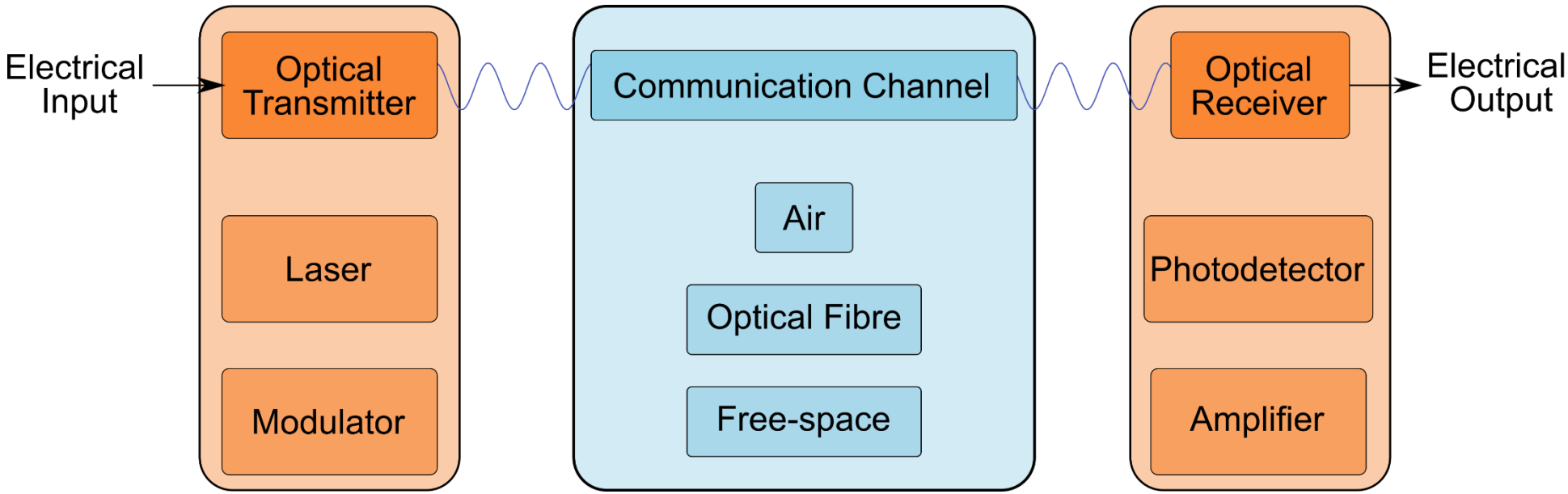
Cambridge Graphene Centre

Electrical Engineering

Outline

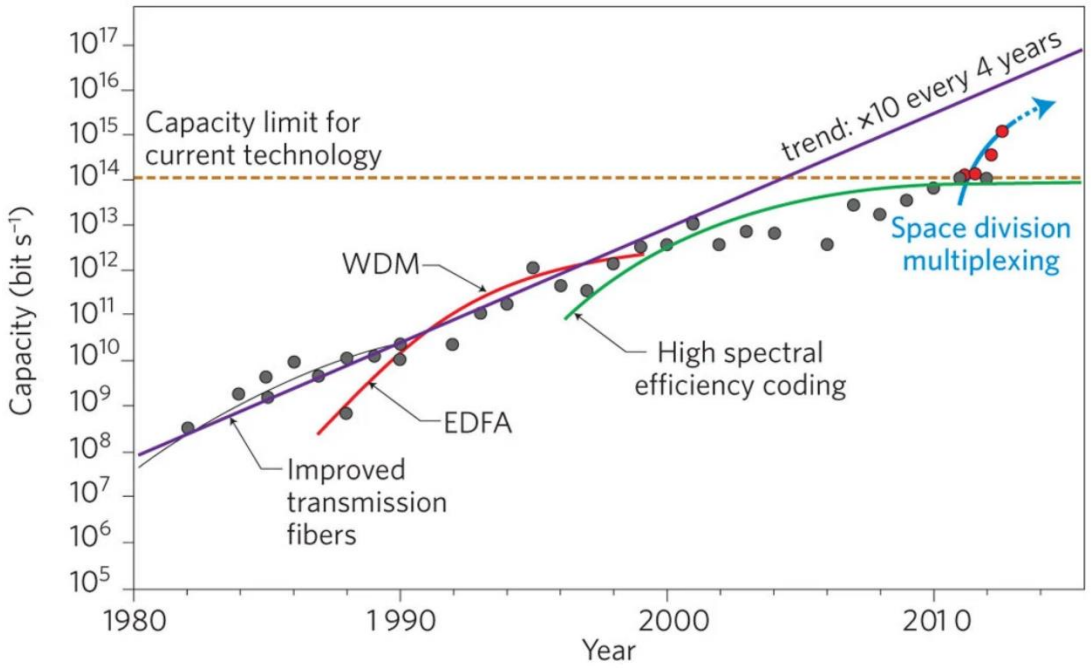
- Optical Links
  - Long-reach optical networks
  - Short-reach optical networks
- Si Photonics
- Graphene for opto-electronics
- Graphene transceiver
- Outlook

Optical Links



- Optics enables high-bandwidth and low-power data transmission
- Most expensive component is electro-optic conversion (usually discrete component)

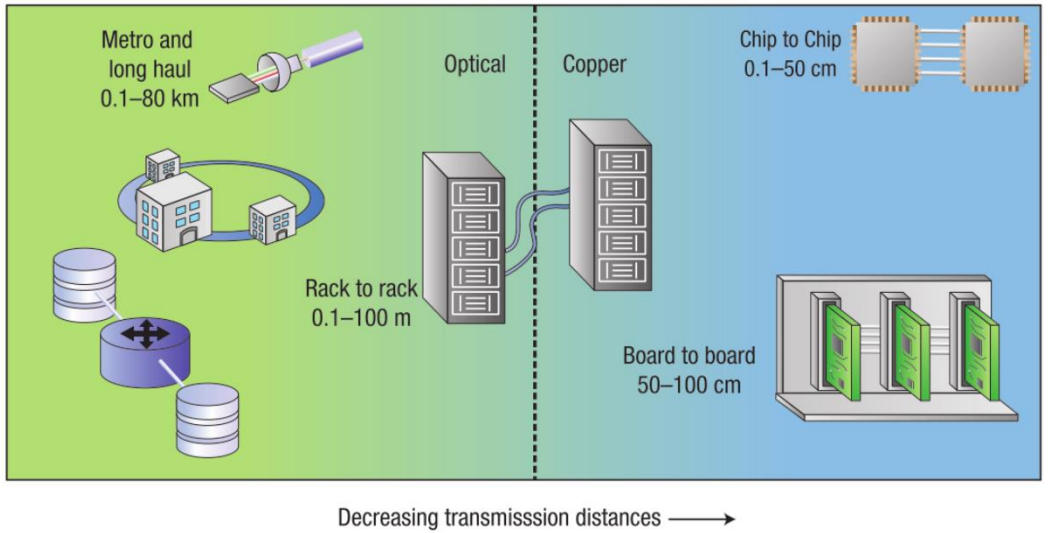
Long-haul Optical Networks



Richardson, D. J., *et al*. *Nature Photonics*, *7*(5), 354–362 (2013)

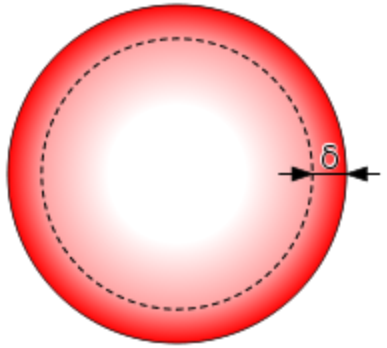
- Optical transmission since 1980s to overcome loss of electrical cables over long distances
  - Driven by the development of low-loss optical fibre and optical amplifiers
- Data rates have continued to rise with adoption of wavelength division multiplexing (WDM), and complex modulation formats
- Hitting the limit to how much data you can send down a single optical fibre (10 Pb/s in 2017)
- **Low-power** optical transceivers needed

Short-reach Optical Networks



Alduino, A., *et al*. *Nature Photonics*, *1*(3), 153–155 (2007)

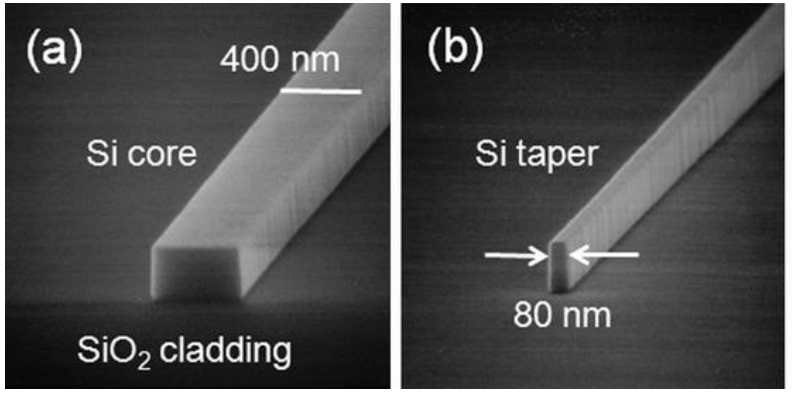
Resistance of electrical interconnects $\propto \sqrt{f}$ due to the skin effect

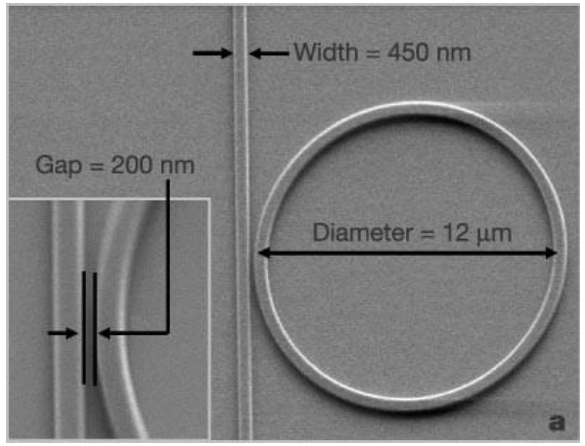


- Losses of electrical interfaces will become unmanageable at Tb/s data rates, making optical interconnect worth the cost
- **Low-power** and **compact** optical transceivers needed

Si Photonics

- Photonic circuits made of submicron Si waveguides guide light on-chip
- Fabricated with existing CMOS technology
- Si band gap (1.1 eV at 300 K) makes Si transparent for λ = 1.3 – 1.55 μm
- Ideal for guiding light with low optical loss, but not good for modulators and photodetectors that interact with light…





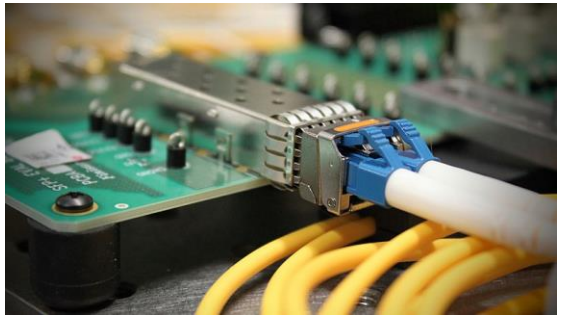
Xu, Q., *et al. Nature* **435,** 325–327 (2005)

Si Photonics

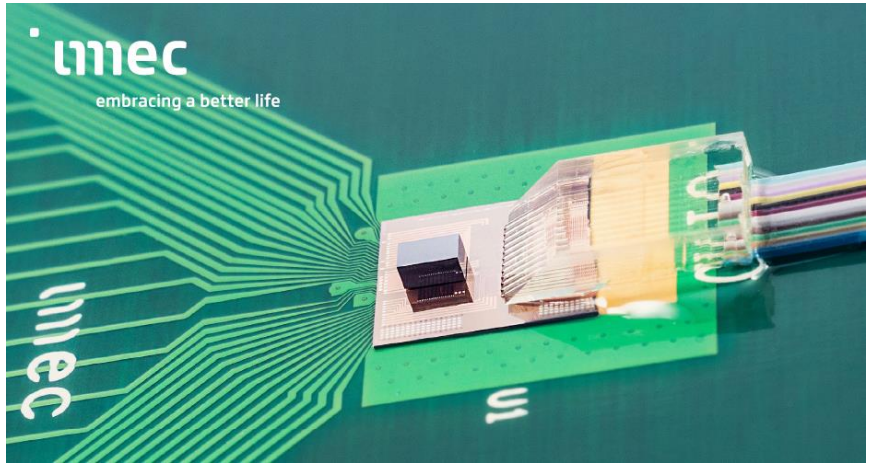
Pluggable Optics

Intel Si Photonics platform announced 400 Gb/s transmission in 2019

Intel 100G CWDM4 QSFP28



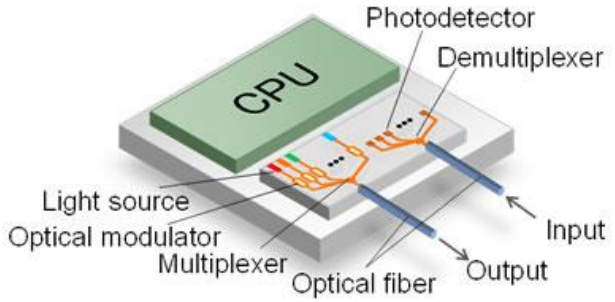
On-board Optics



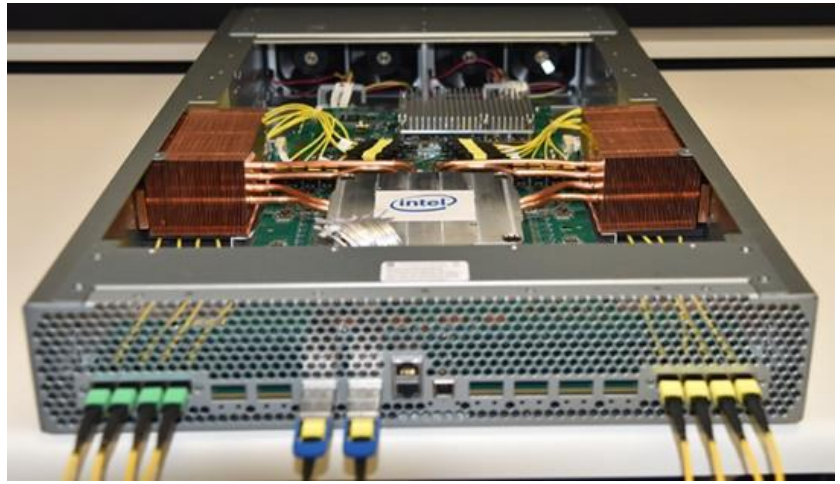
Intel Co-packaged 12.8 Tb/s Switch (2020)

SiPh engine @ 1.6 Tb/s

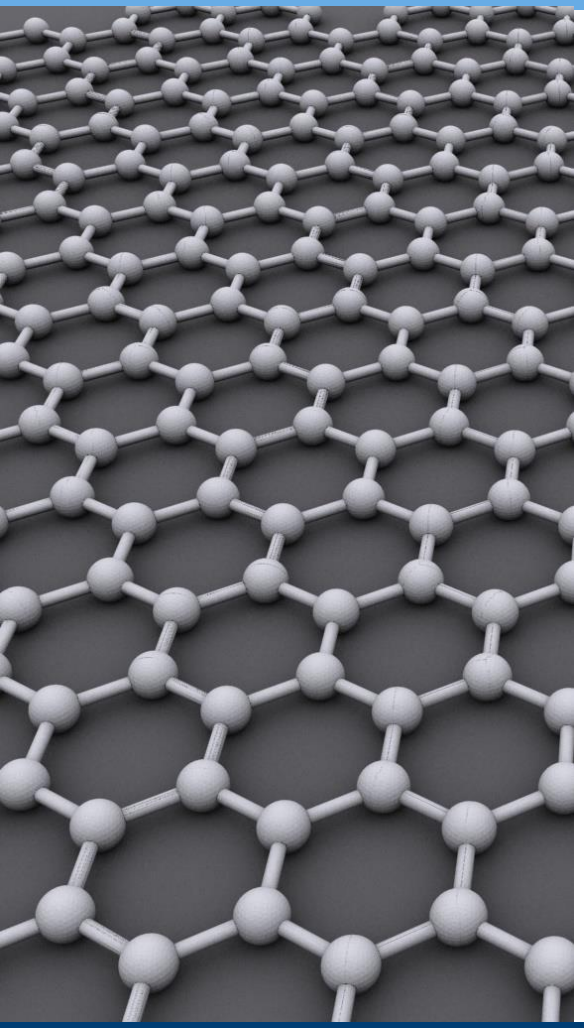
Co-packaged Optics



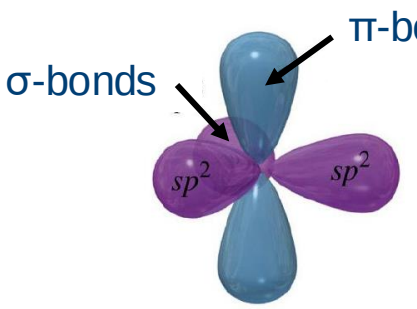
Tanaka, S *et al*. *Fujitsu Scientific and Technical Journal*, ***50*(1)**, 123–131, (2014)

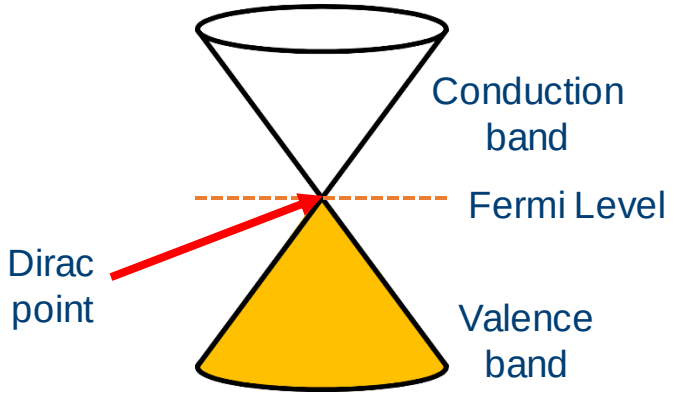


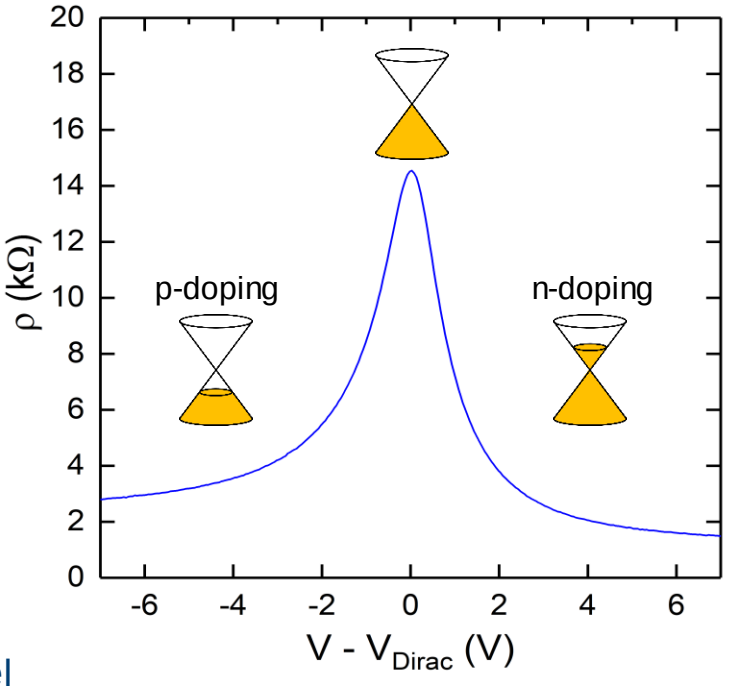
Graphene: Electrical Properties



- Strong in-plane σ-bonds between C atoms
- Carriers become delocalised by overlapping out-of-plane π-bonds
- In-plane confinement leads to a linear band structure

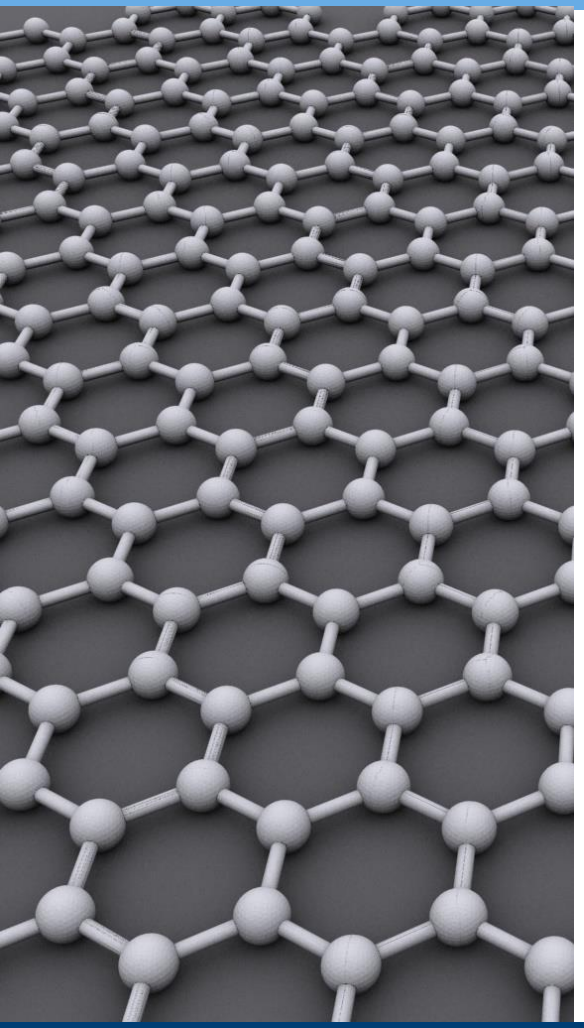




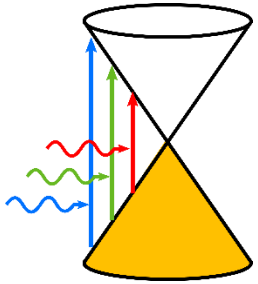


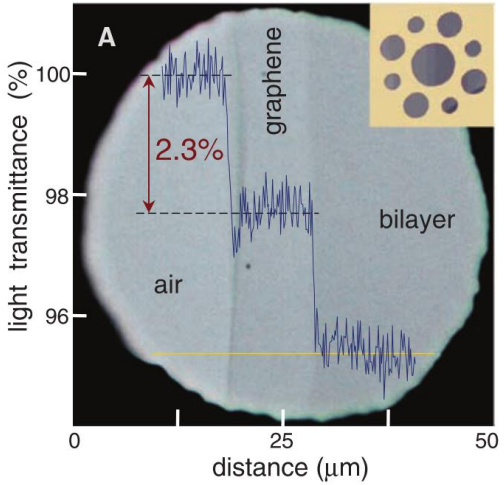
High carrier mobility (>100,000 cm^2/Vs) at room temperature

Graphene: Optical Properties

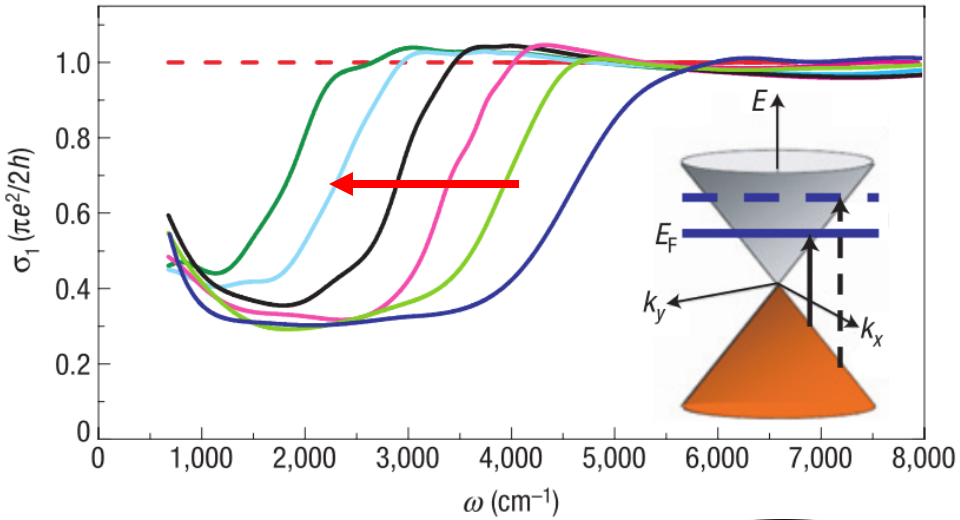


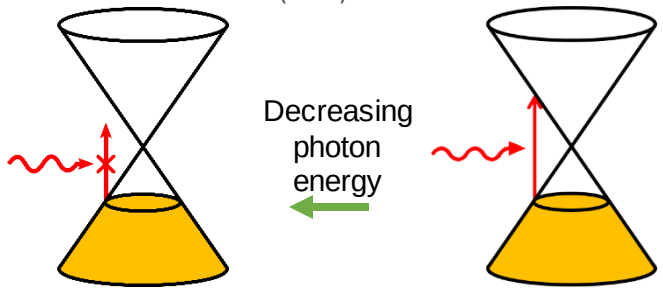
Wavelength independent absorption





Electrostatically tuneable optical conductivity





Nair, R. R., *et al. Science*, *320*(5881), 1308–1308 (2008)

Li, Z. *et al. Nature Physics*, 4(7), 532–535 (2008)

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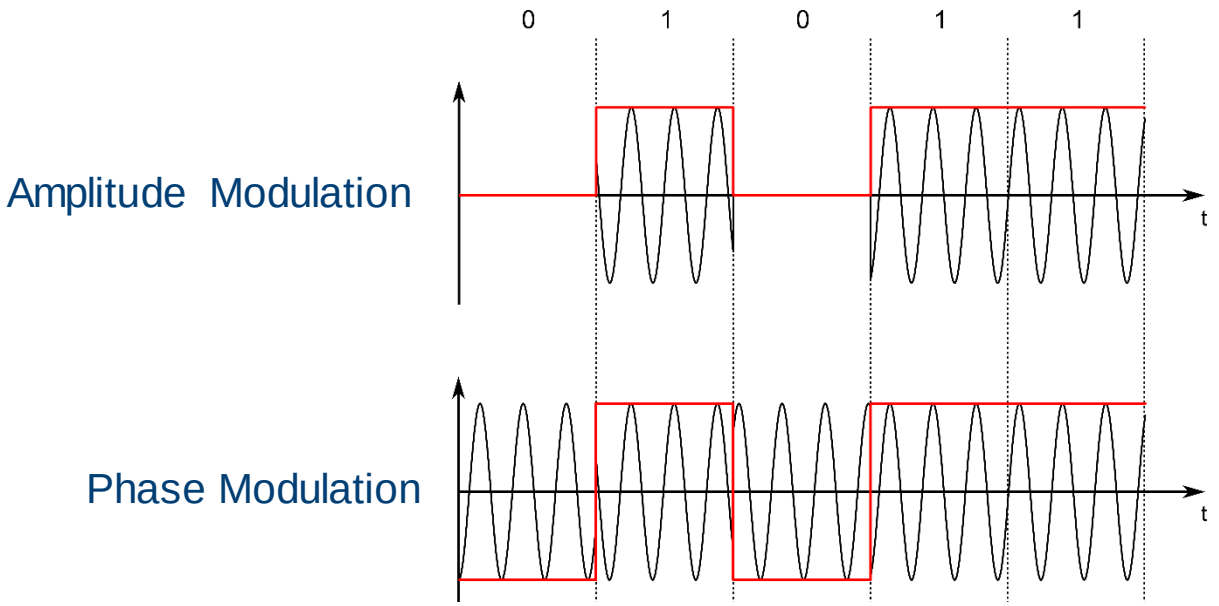
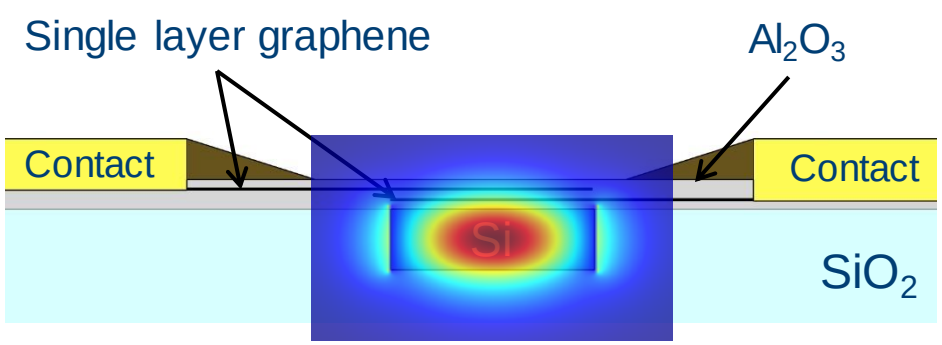
Integrated Modulators

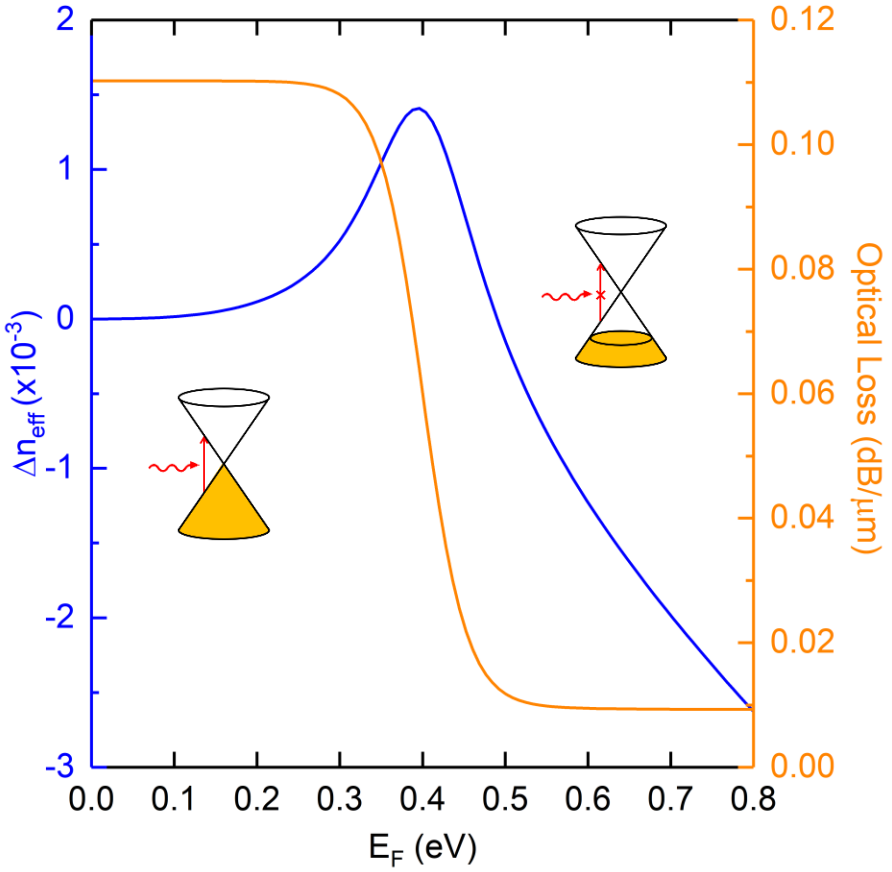


- Converts electrical data stream into an optical signal
- Encodes information in the amplitude and/or phase of the optical signal
- Typically uses Si, Lithium Niobate, or III-V material

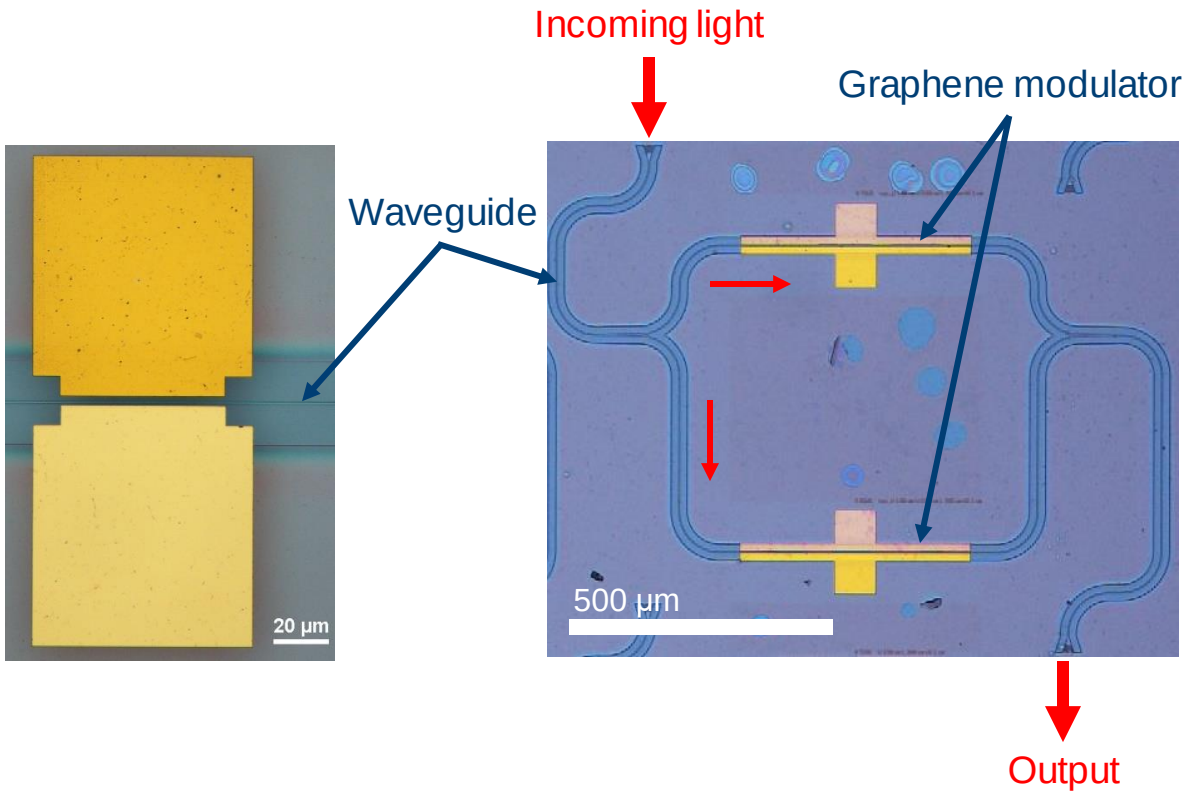
Graphene Modulators

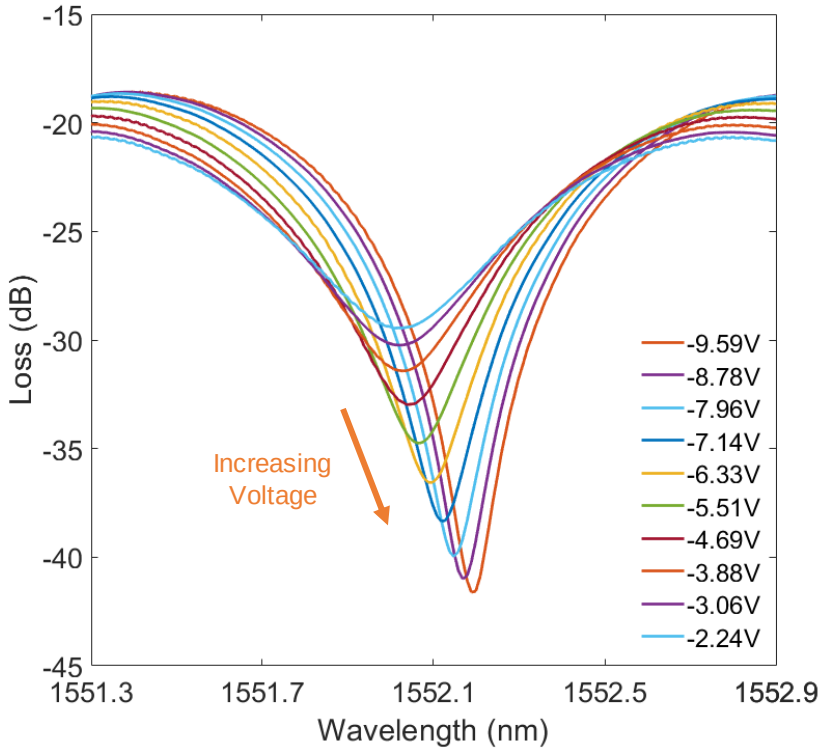


- Applied voltage changes the doping of each SLG and therefore the optical conductivity
- Changes the refractive index and optical losses of the propagating light
- Can be used as a phase or amplitude modulator



Graphene Phase Modulator



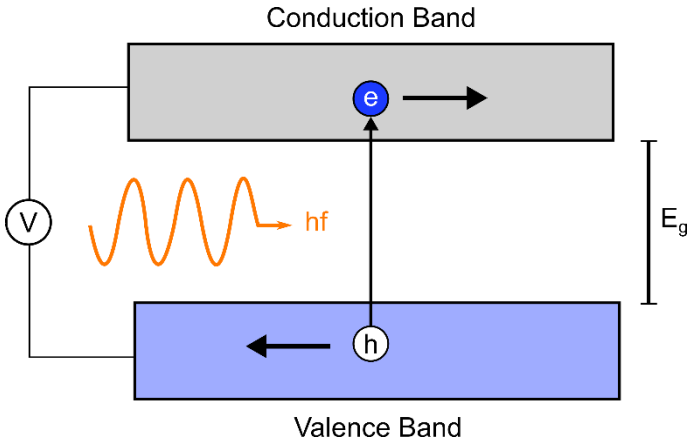


- Millimetre device length for π-phase shift in V_{DD} = 1V
- >20 GHz bandwidth

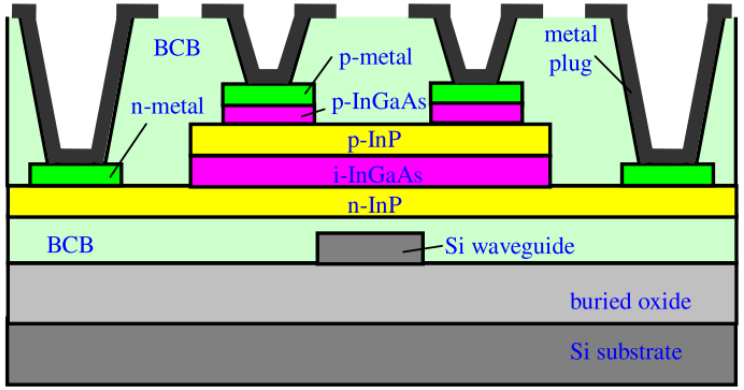
Watson, H. F. Y., *et al.* (2020) Manuscript in preparation

Integrated Photodetectors

- Converts an optical signal back into an electrical signal at the receiver
  - Photons are absorbed and produce an electron-hole pair
  - Electron-hole pairs are separated by an electric field and generate a photocurrent
- Limited by carrier recombination and dark current



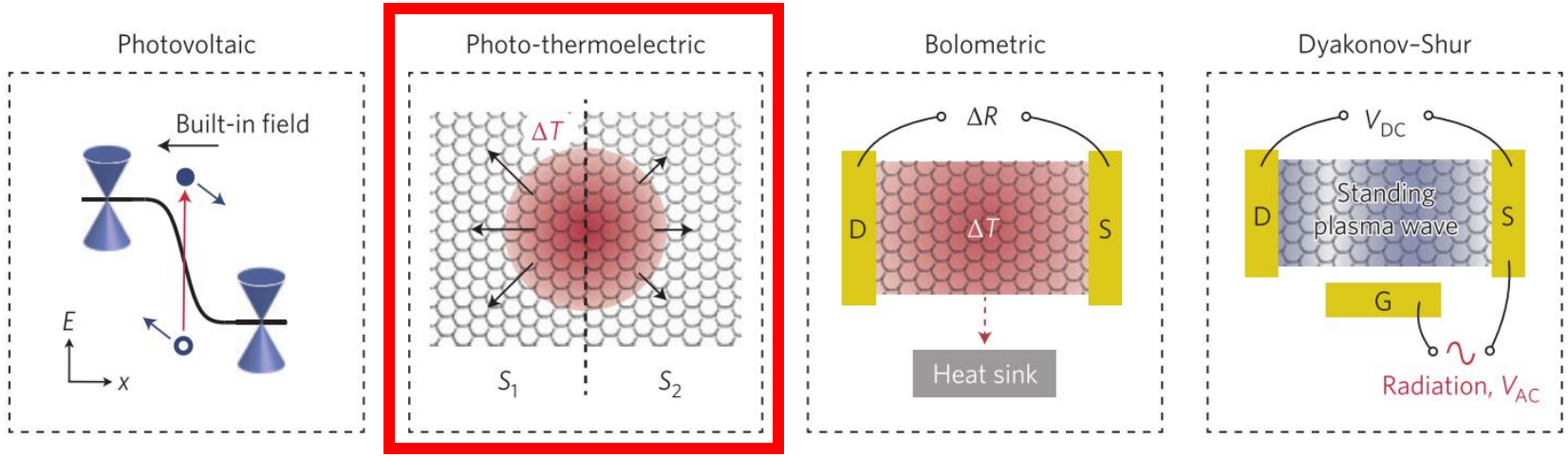
40 μm III-V PD



Sheng, Z., *et al. Optics Express*, *18*(2), 1756 (2010)

- Typically use p-i-n junctions based on Ge-on-Si or bonded III-V wafers

Graphene Photodetectors



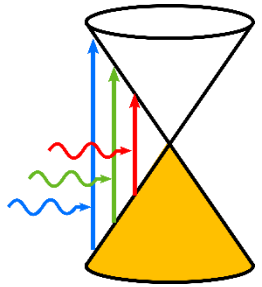
Koppens, F. H. L., *et al*. *Nature Nanotechnology*, *9*(10), 780–793 (2014)

<u>Advantages</u>

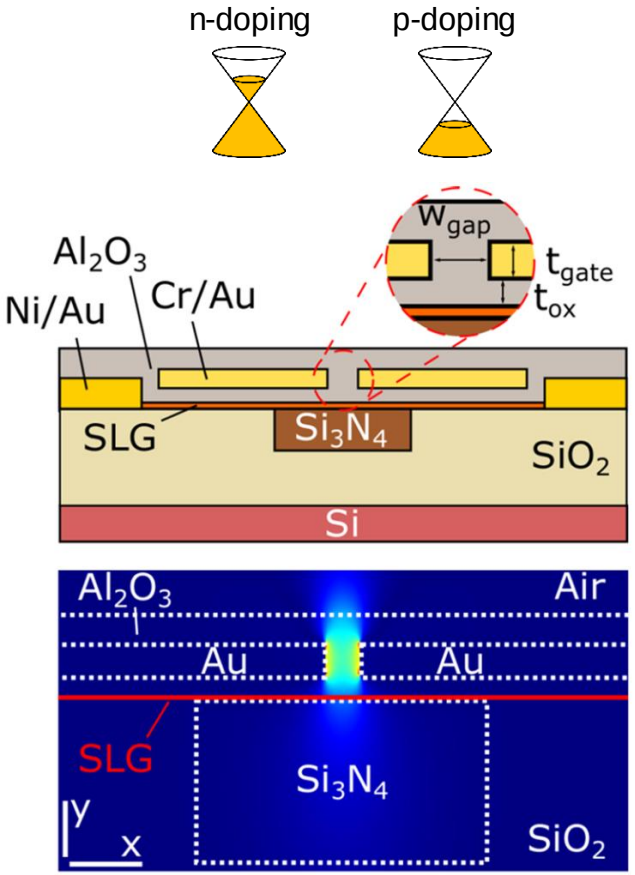
- Wavelength independent absorption
- High mobility = fast operation

<u>Disadvantages</u>

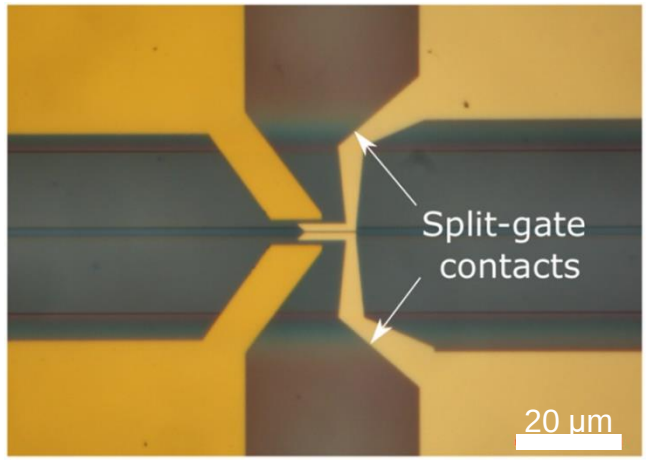
- Limited by dark current because of a zero band gap

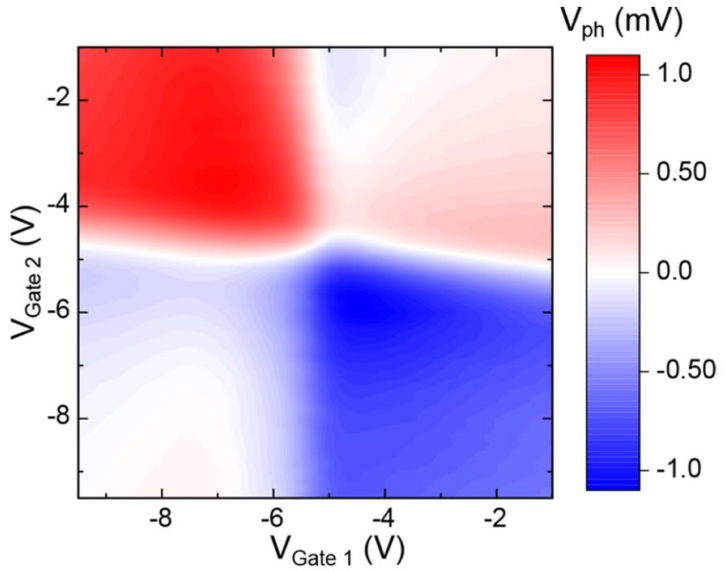


Graphene PTE Photodetector



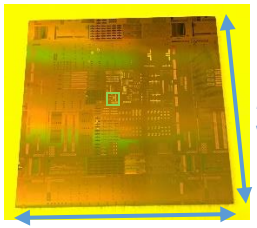
- Split-gates used to create a p-n junction in the SLG channel
- Efficiency increased due to plasmonic-enhanced optical field
- 12.2 V/W, 42 GHz bandwidth
- Zero bias operation = zero dark current



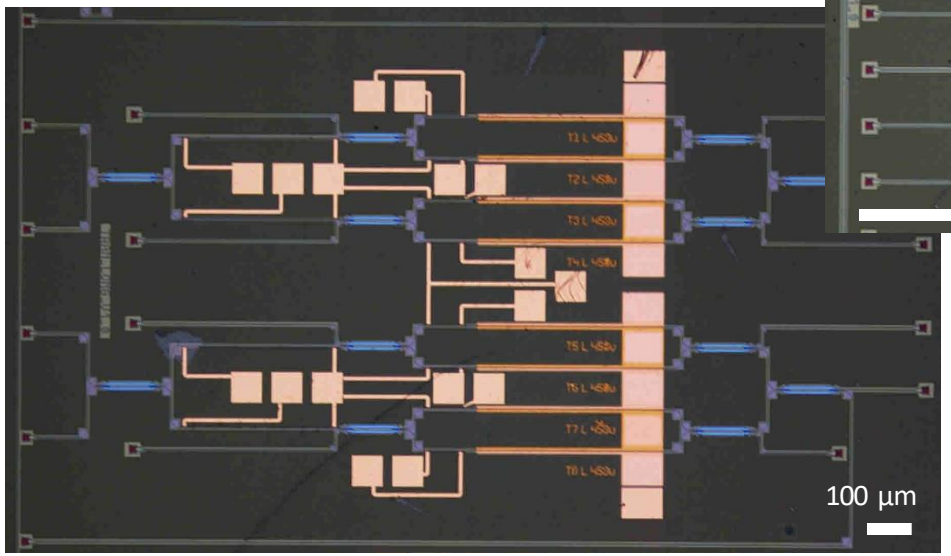


Muench, J. E., *et al. Nano Letters*, *19*(11), 7632–7644 (2019).

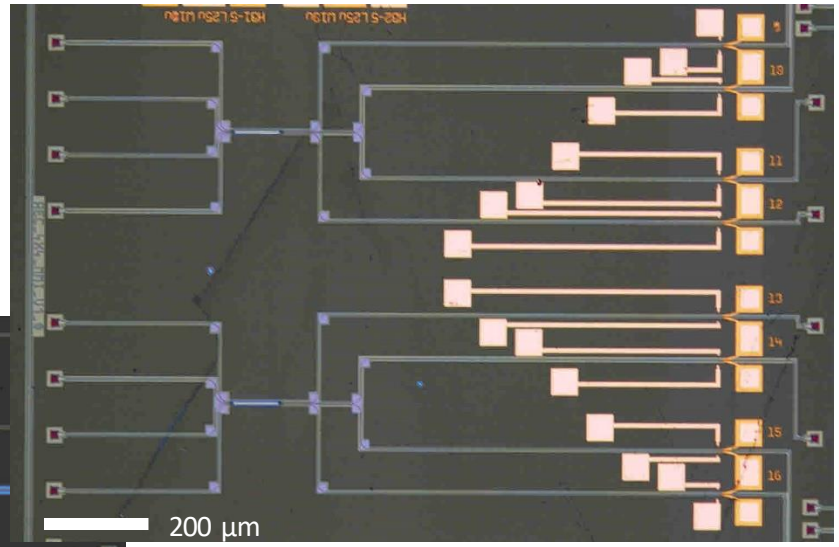
Graphene IQ Transceiver

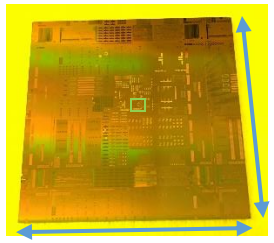


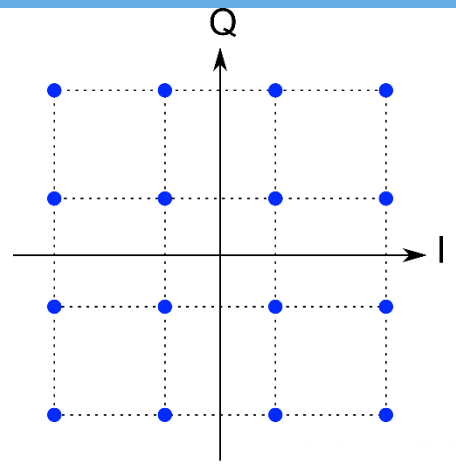
Graphene Transmitter



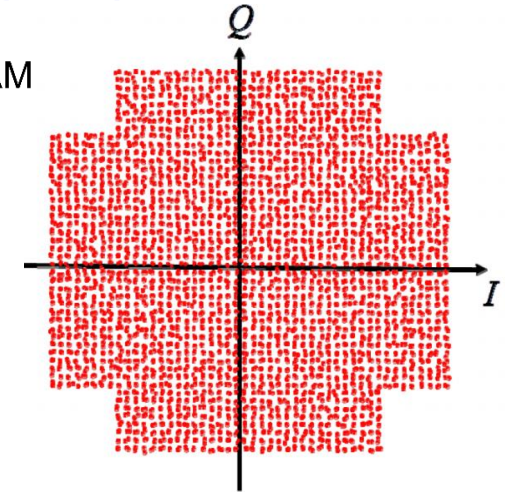
Graphene Receiver







16-QAM

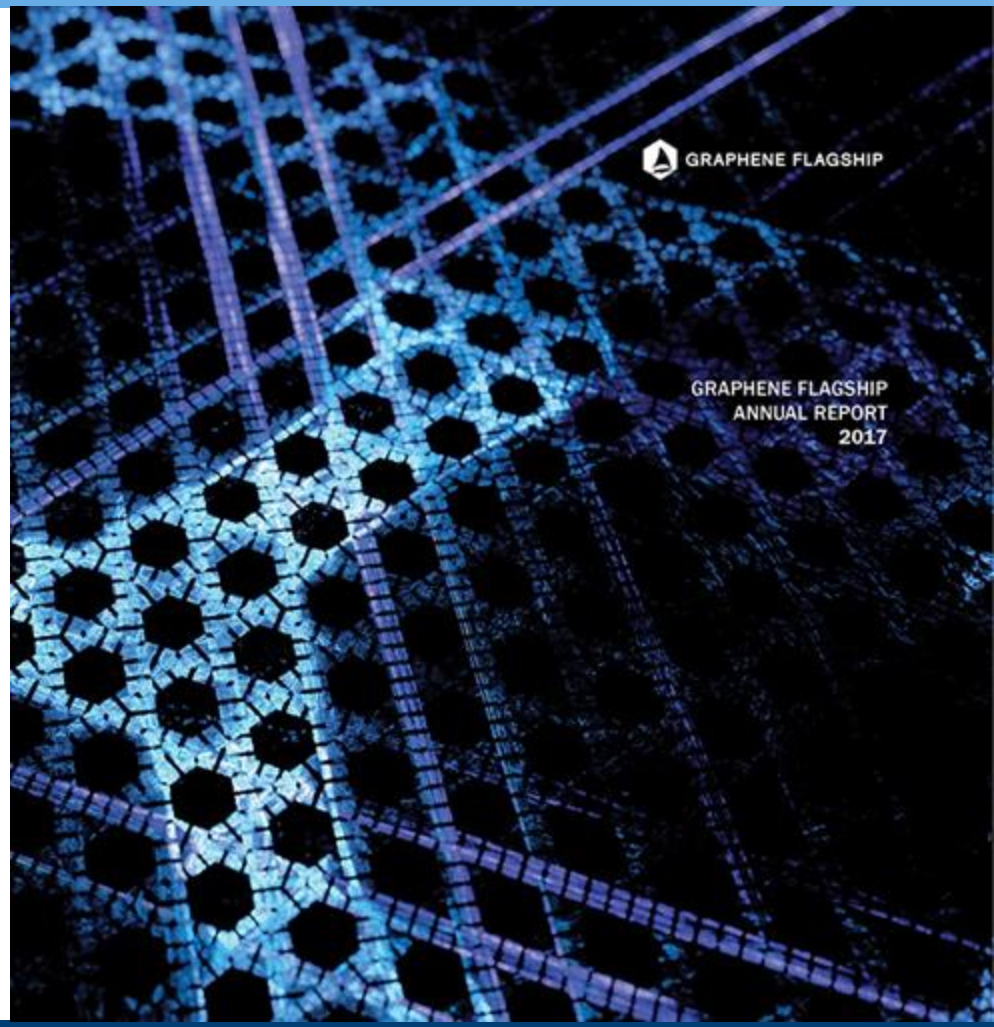


2048-QAM

Beppu, S, *et al. Optics Express,* 23(4), 4960-4969 (2015)

Outlook

- Power efficiency is key for Tb/s data transmission
- Si Photonics technology enables integrated photonic circuits
- Graphene offers a combined and efficient modulation and photodetection platform that can be fabricated in the CMOS back-end-of-line
- Work still needs to be done to improve the uniformity and mobility and reduce optical loss in order to realise simulated device performances

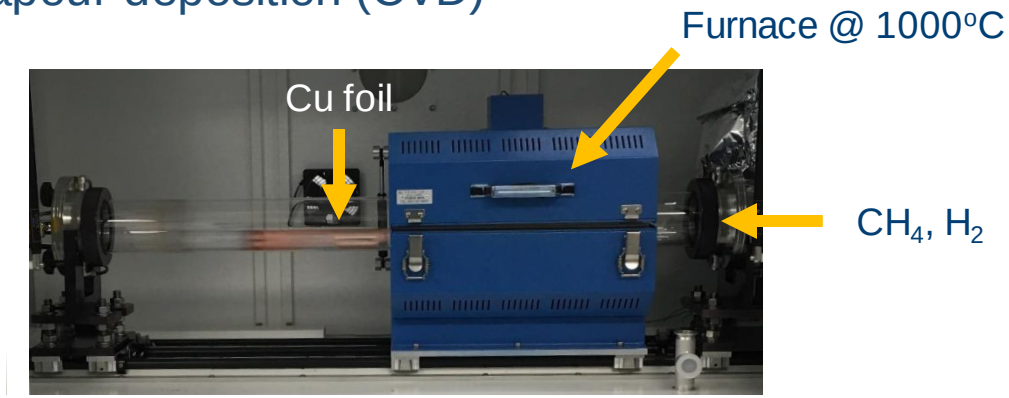


Acknowledgements

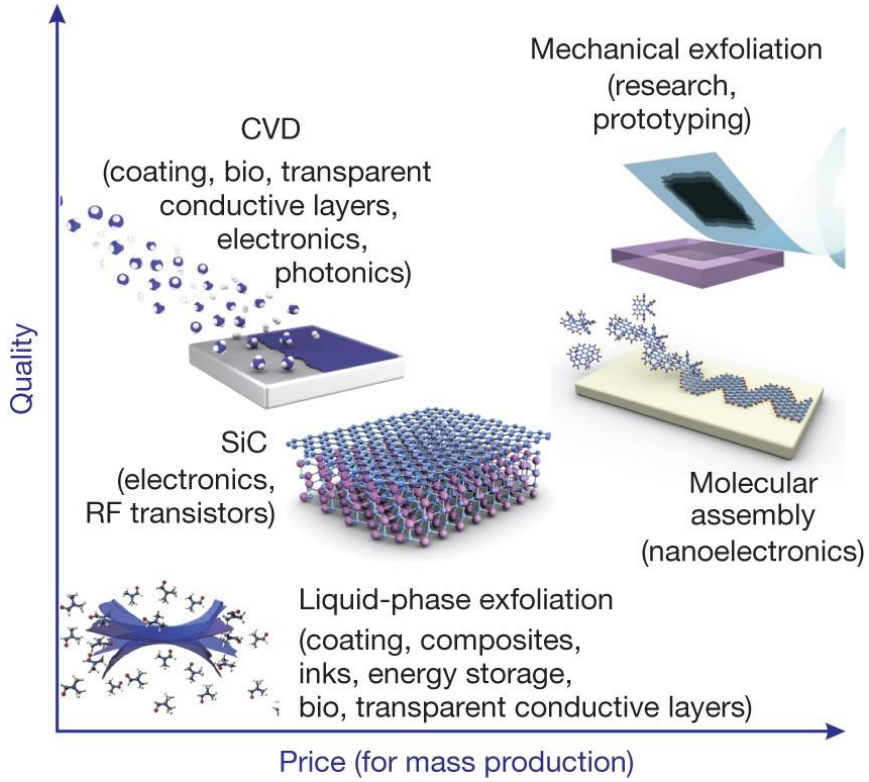
Back up Slides

Graphene Production

- Best electrical properties from mechanical exfoliation (Scotch tape method)
- Worst electrical properties from liquid phase exfoliation
- Combination of good electrical properties and scalability is chemical vapour deposition (CVD)



- Large area growth up to 30 inch films (roll-to-roll)
- Can be transferred onto any substrate



Novoselov, K *et al. Nature* **490,** 192–200 (2012)

Mach Zehnder Interferometer

- To detect a change of phase in an optical signal an interferometric device is required
- Usually this is with a Mach-Zehnder interferometer or ring resonator