Integrated Photonic Modulators Based on Graphene and Other 2D Materials for Optical Interconnects

Chenghan (Kenny) Wu

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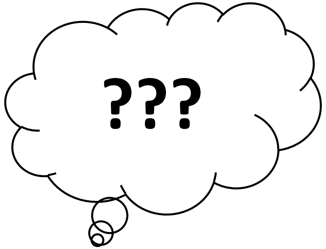
WHAT IS…?



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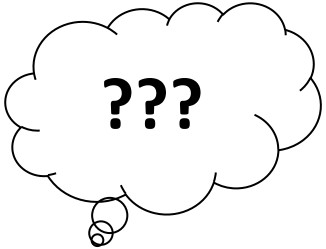

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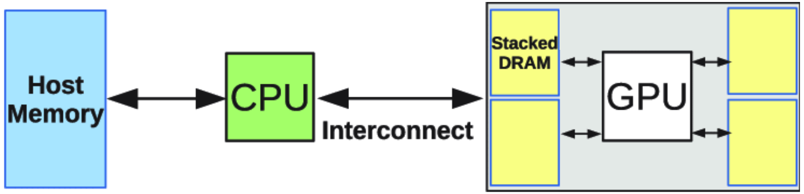
INTERCONNECT



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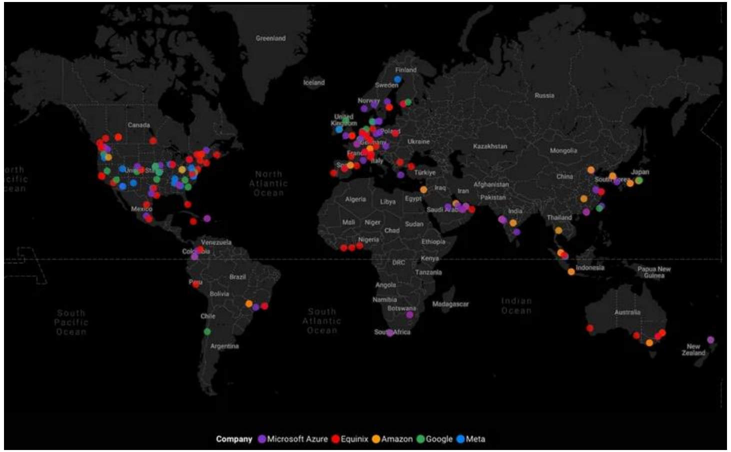
Interconnect Network

This interconnected network enables seamless communication and access to various online services.

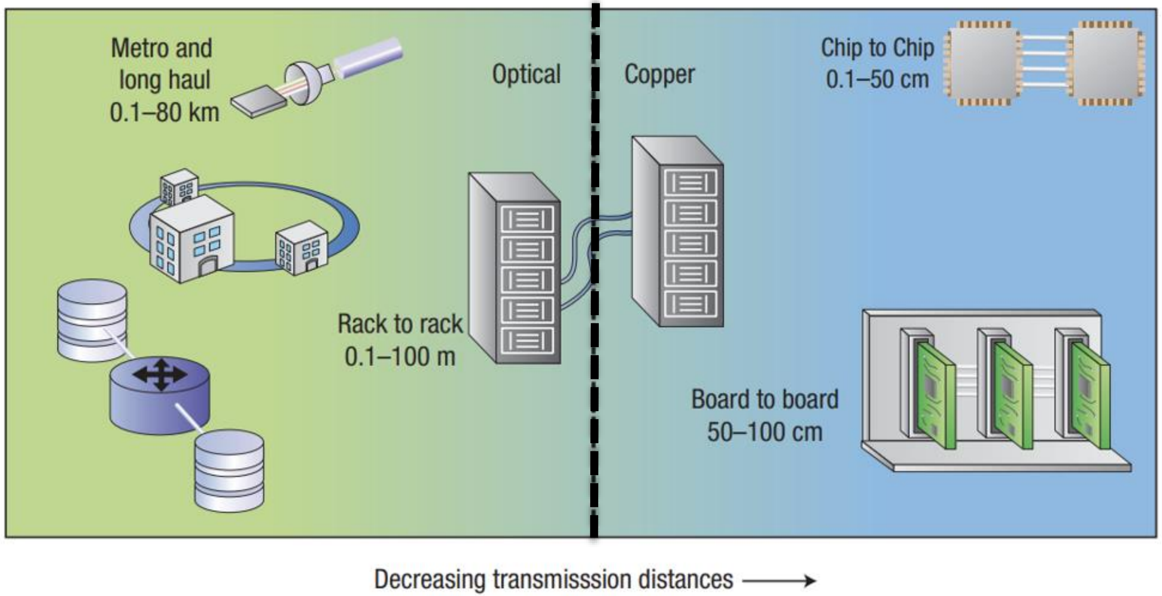
DATA CENTER


Company Microsoft Azure Equinix Amazon Google Meta


The Citadel, Tahoe Reno, Nevada (USA) Size ~ 70 football fields
8
switch
TSC
1000

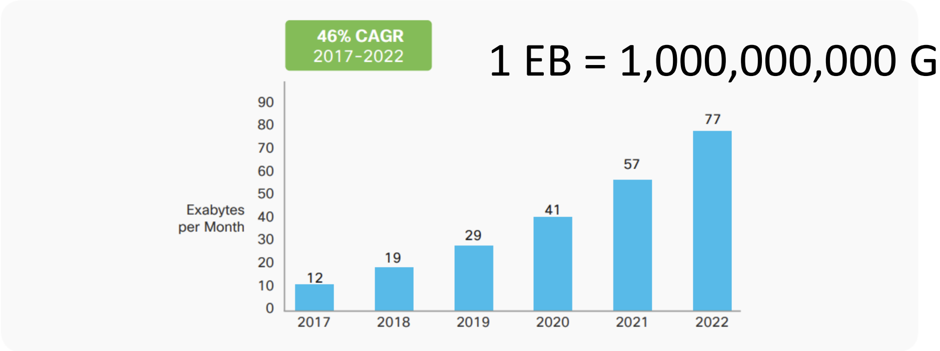
COMMUNICATION LEVEL

Fiber (optical interconnect) | Copper (electrical interconnect)



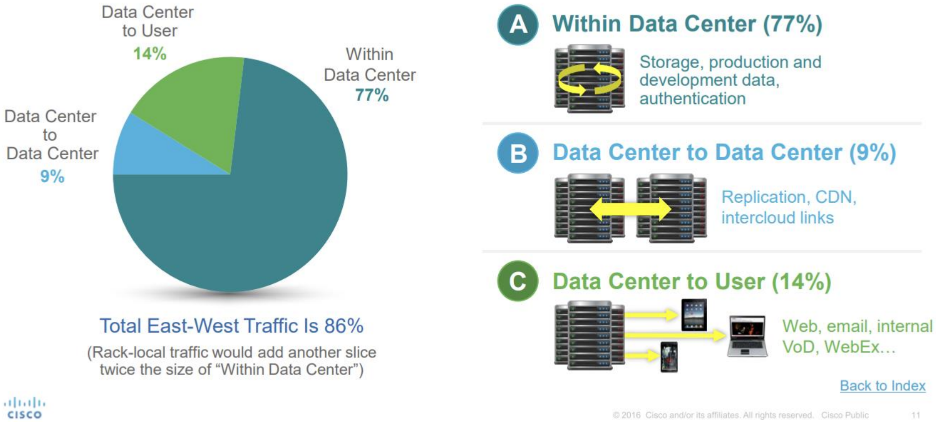
INCREASED DATA TRAFFIC

Figure 2. Cisco Forecasts 77 Exabytes per Month of Mobile Data Traffic by 2022



1 EB = 1,000,000,000 GB

Source: Cisco VNI Mobile, 2019



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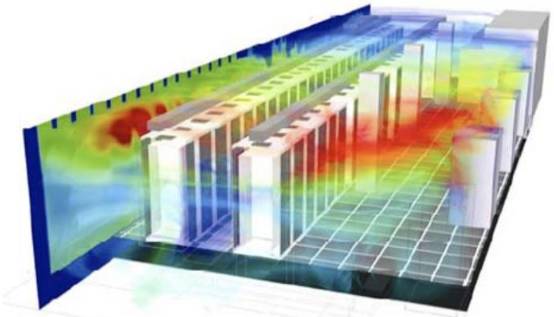
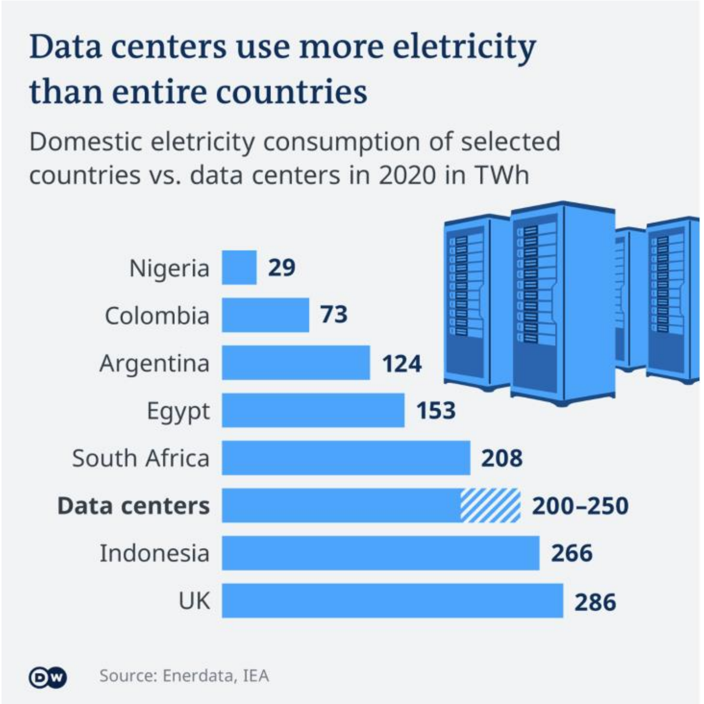
Challenges for data center

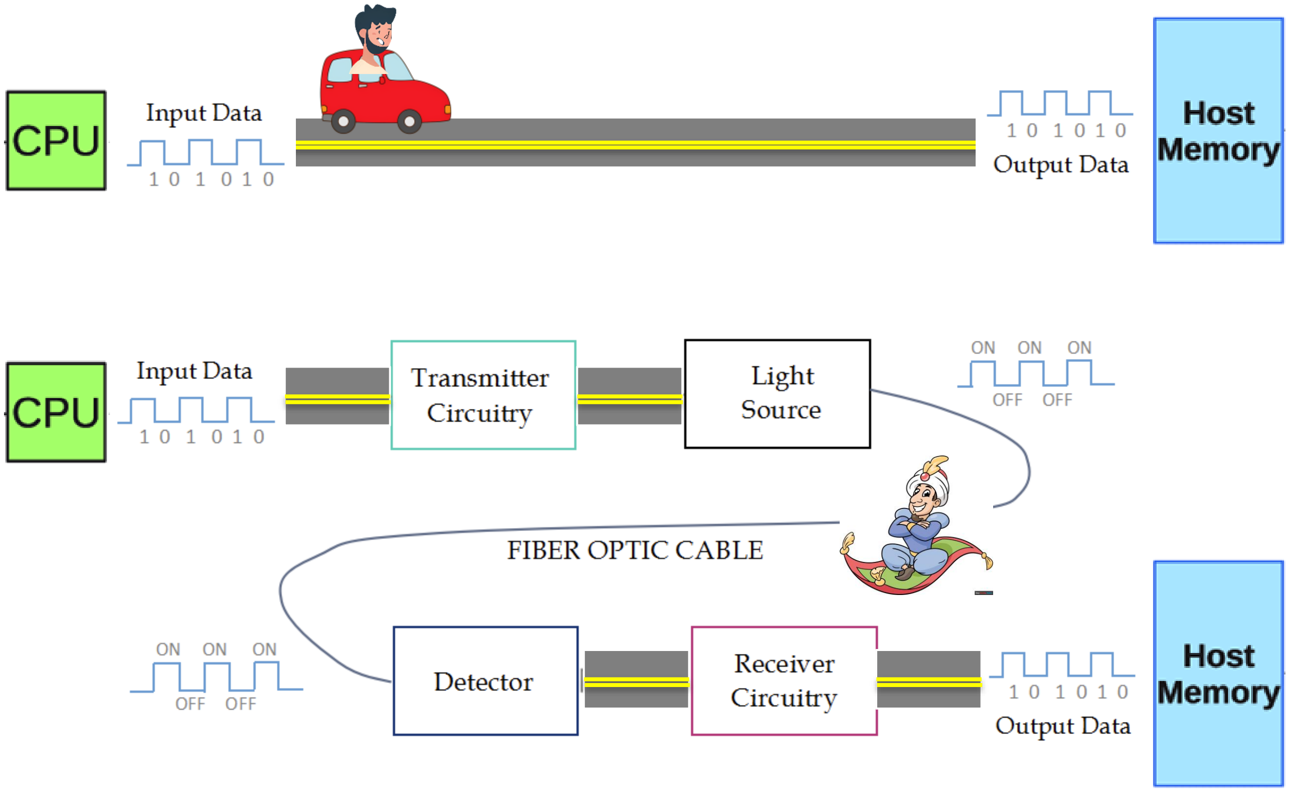




Electrical and Optical Interconnect

	Electrical interconnect	Optical interconnect
Bandwidth / data rates	☹	☺
Power consumption	☹	☺
Cost	☺	☹
Compatibility with existing data center	☺	☹

Optical Interconnect



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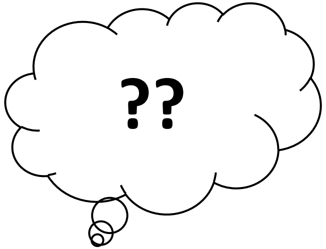

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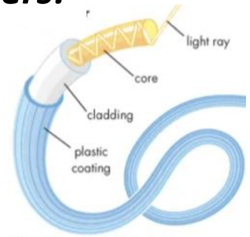
SILICON WAVEGUIDES = FIBERS IN CHIP

Fibers:



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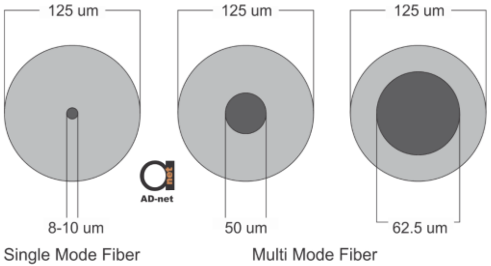
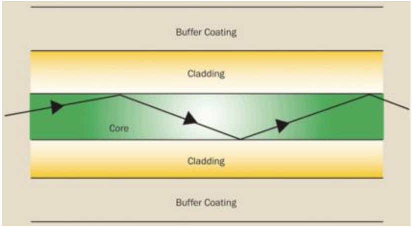
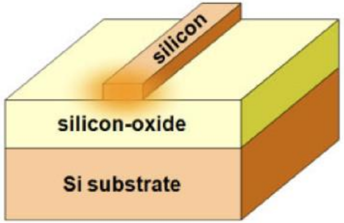
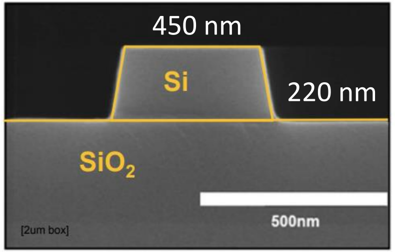
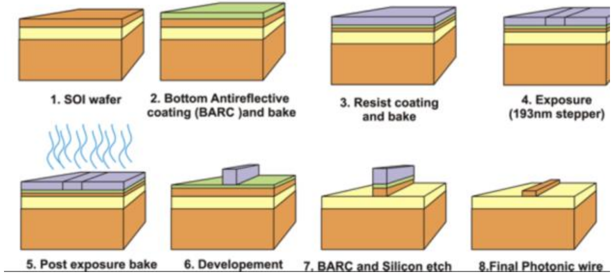




Waveguides:







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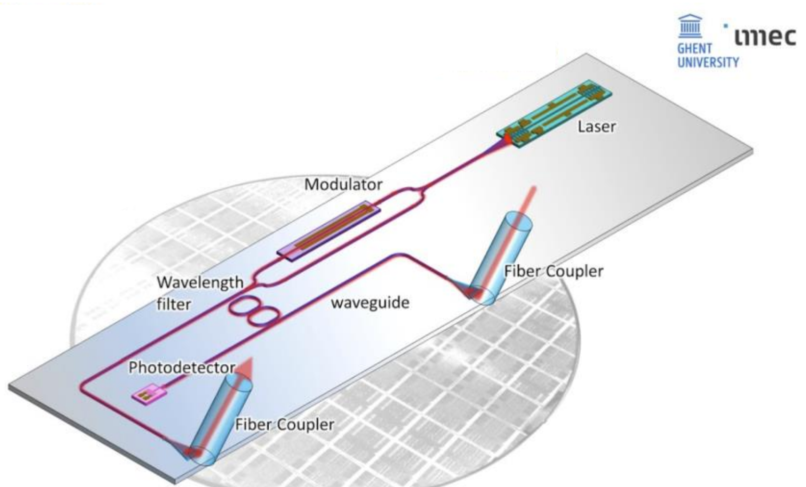
INTEGRATED SILICON PHOTONICS



Circuits connect elements together with waveguides

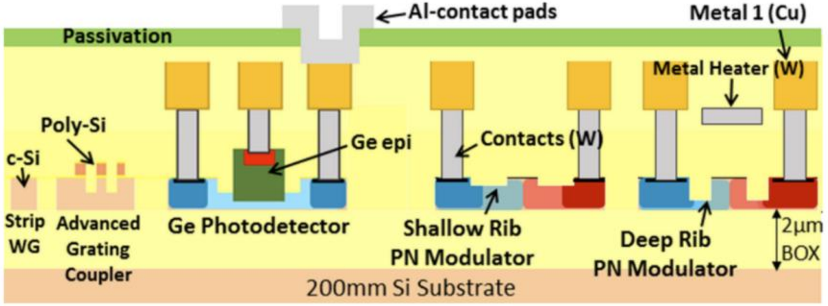
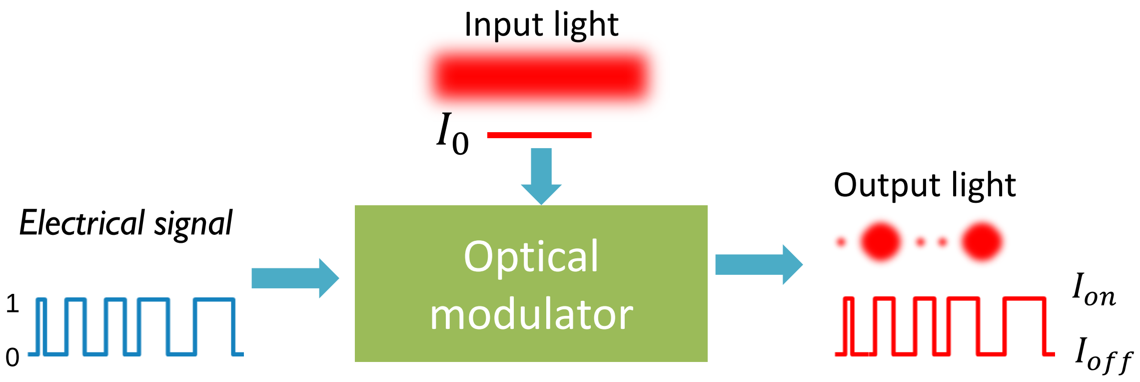


Figure 1.2: Schematic cross-section of imec's silicon photonics platform, with the basic passive and active devices. Taken from [2].

MODULATOR



Amplitude modulation (AM)

Phase modulation (PM)

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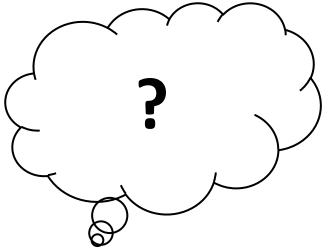
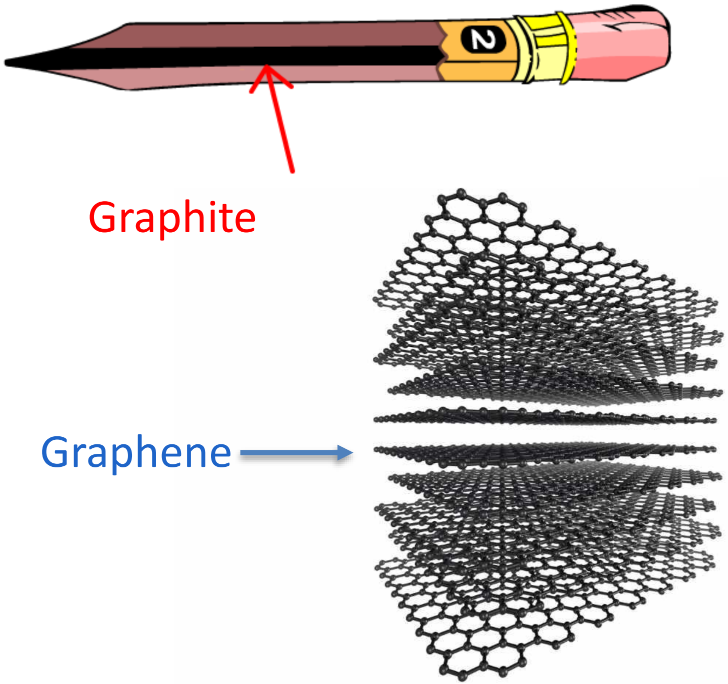
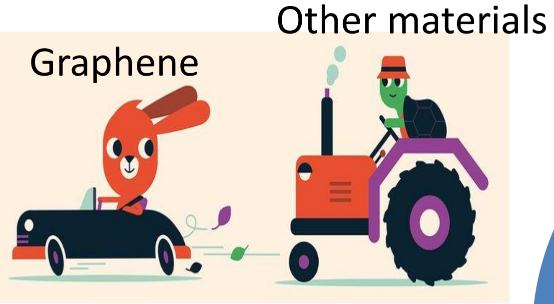


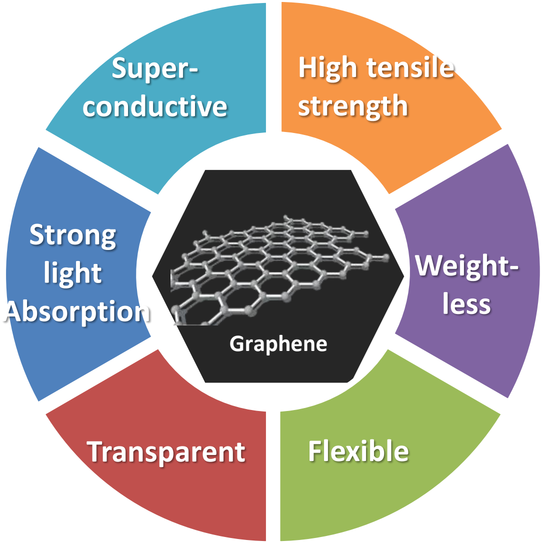
Integrated Photonic Modulators Based on **Graphene and Other 2D Materials** for Optical Interconnects

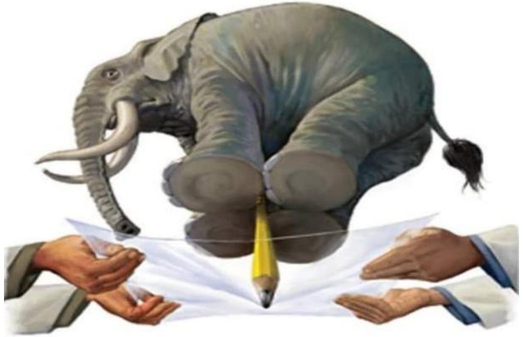
THE FIRST 2D MATERIAL : GRAPHENE

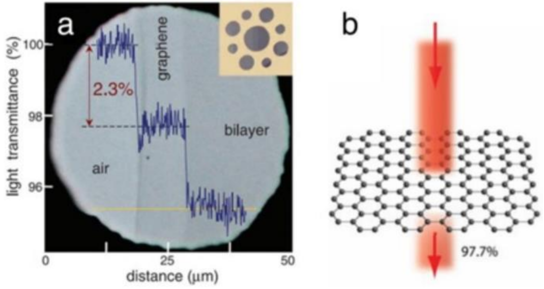


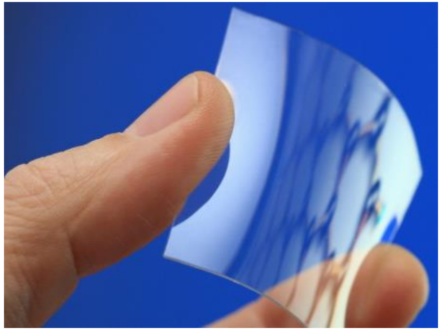
Graphene: Super hero in materials



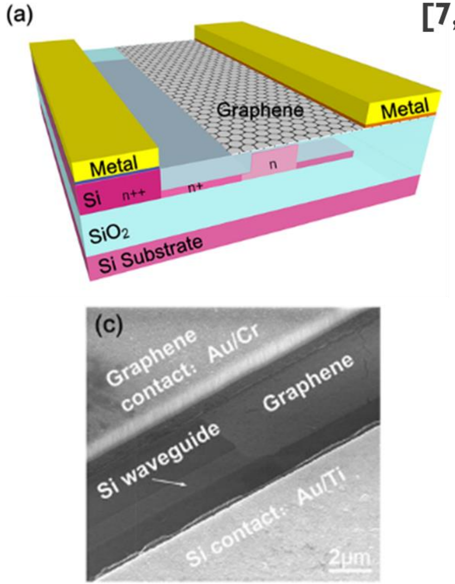




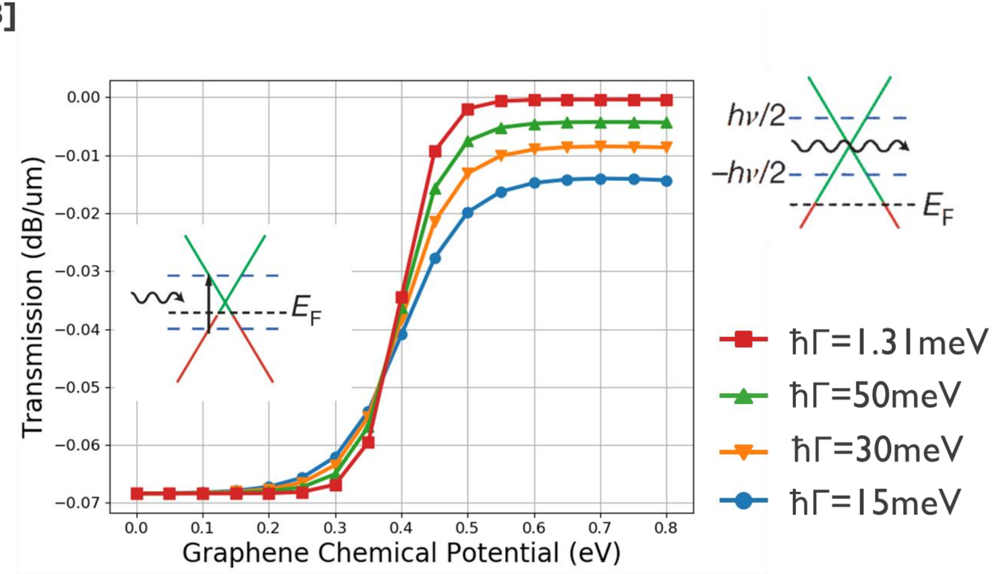




GRAPHENE + INTEGRATED PHOTONICS MODULATORS



[7,8]



OTHER 2D MATERIALS

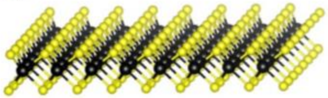
Atomically Thin

Flexible

Bandgap

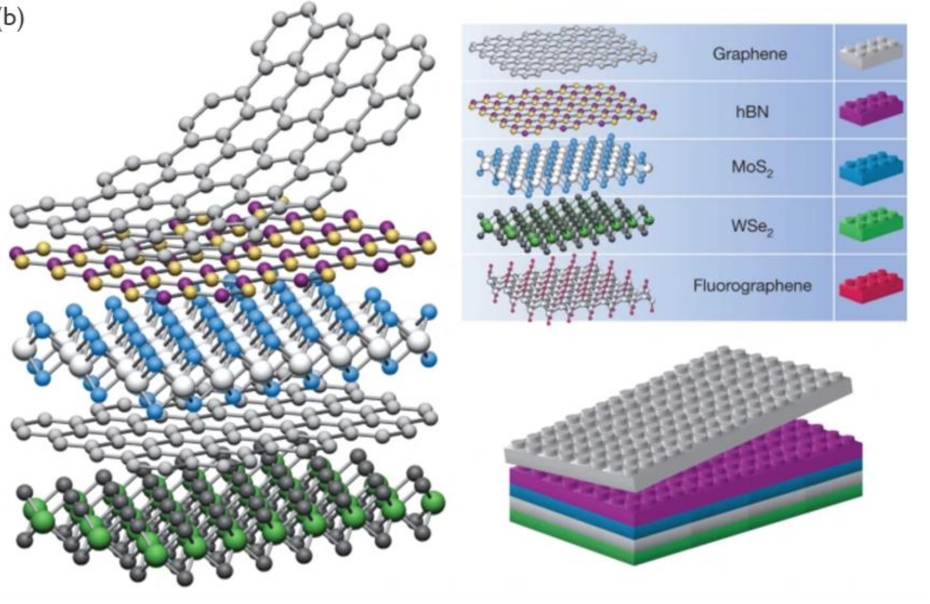
Large phase change

(a)



MX2
M: transition metal (Mo, W)
X: chalcogen (S, Se, Te)

(b)



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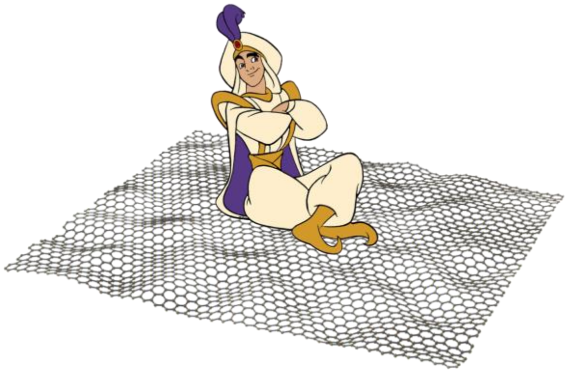

Research Objectives

Can 2D material based photonic devices be adopted in industry for the next generation of data communication and telecommunications applications?

SCALABILITY	PERFORMANCE	EXPLORATORY
	 	
- Establishment of inline integration - 3 optimization directions	- Electro-absorption Modulators - Mach-Zehnder Modulators - Ring Modulators	- Doped-Si/Oxide/MoS_2 - Graphene/Oxide/MoS_2 - MoS_2/Oxide/MoS_2

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Scalability!

Wafer-scale Integration of Graphene EAM in 300 mm CMOS Pilot Line

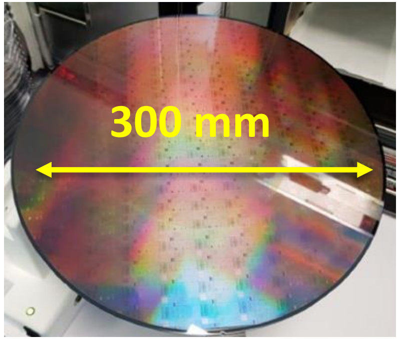
Motivation

Most research studies on small coupons without CMOS-compatible technology, which are not compatible with high-volume industrial manufacturing.

Small coupons
2x1 cm^2

Develop robust inline integration flow in a 300mm pilot CMOS foundry environment.

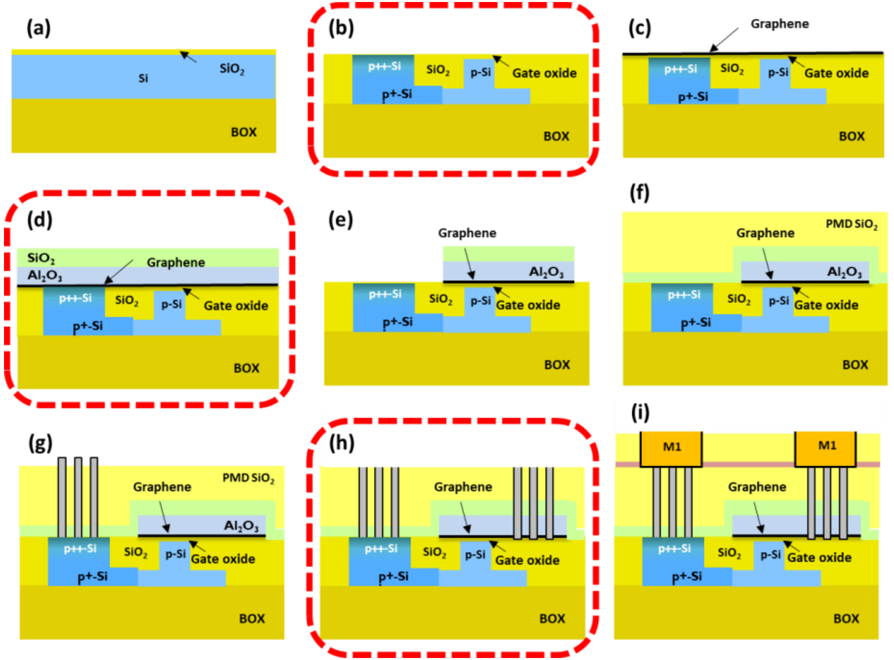
300 mm wafer
(>50 dies)



CHALLENGES AND STRATEGY

The challenges:

1. Developing CMOS-compatible processes for lithography and contact.
2. Scaling up graphene growth and transfer methods for large-scale production.
3. Designing an efficient capping layer to safeguard graphene from delamination.
4. Minimizing contact resistance to enable high-speed performance in graphene-based devices.



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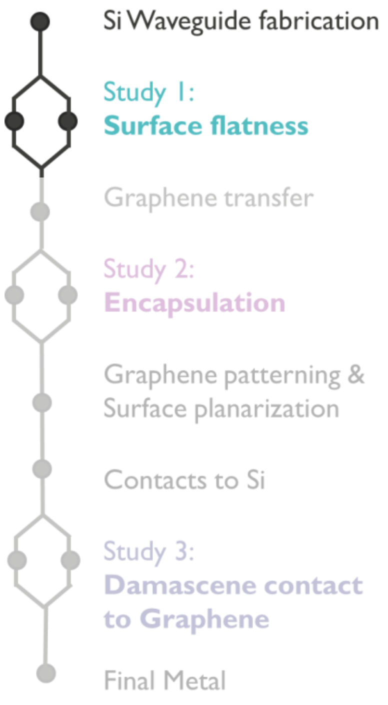
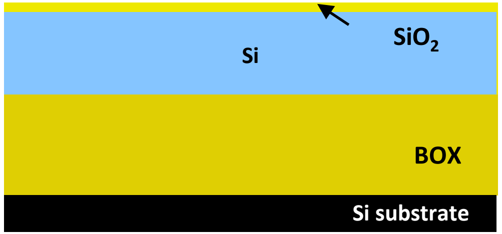
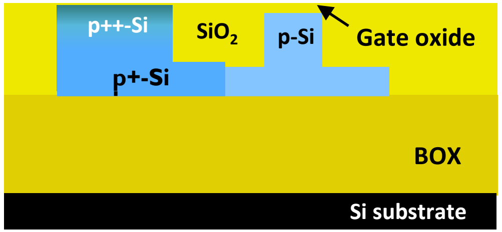
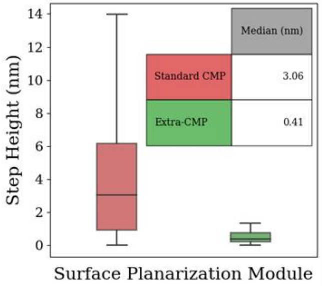
PHASE 1 STUDY: FAB-LEVEL INTEGRATION FLOW

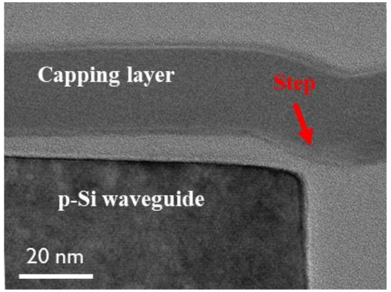




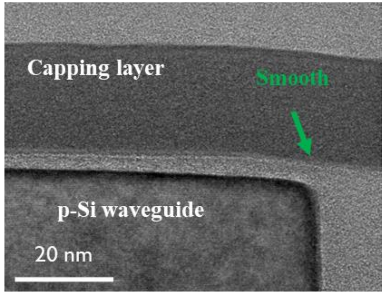




Standard CMP



Extra CMP



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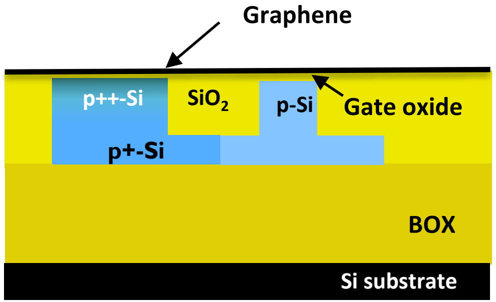
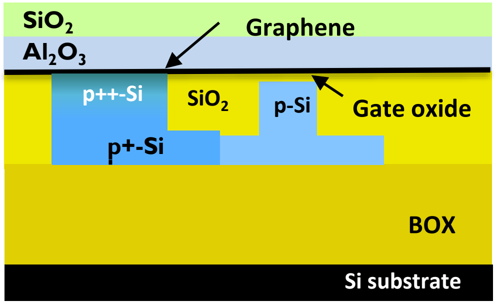
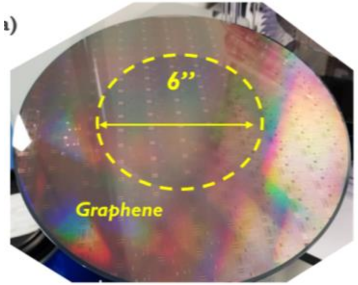
PHASE 1 STUDY: FAB-LEVEL INTEGRATION FLOW

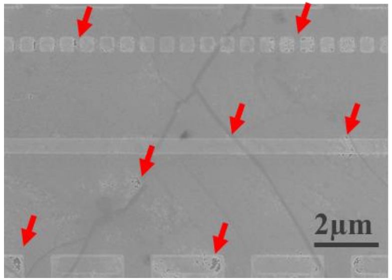
- Si Waveguide fabrication
- Study 1: **Surface flatness**
- Graphene transfer
- Study 2: **Encapsulation**
- Graphene patterning & Surface planarization
- Contacts to Si
- Study 3: **Damascene contact to Graphene**
- Final Metal



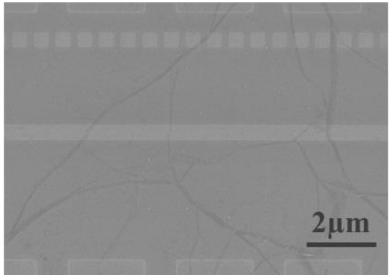




Non-optimized Al_2O_3



Optimized Al_2O_3



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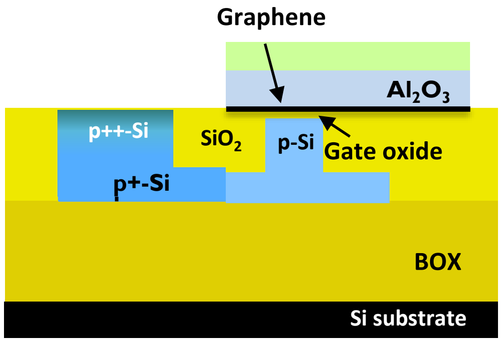

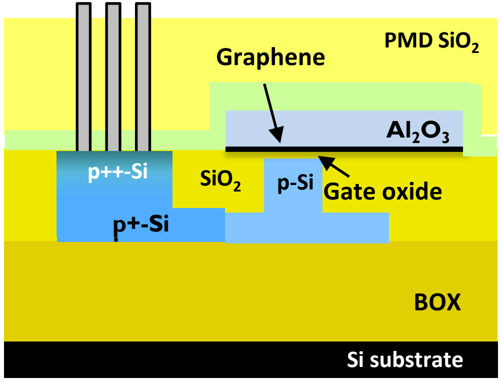

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Phase 1 study: FAB-level integration flow

- Si Waveguide fabrication
- Study 1: **Surface flatness**
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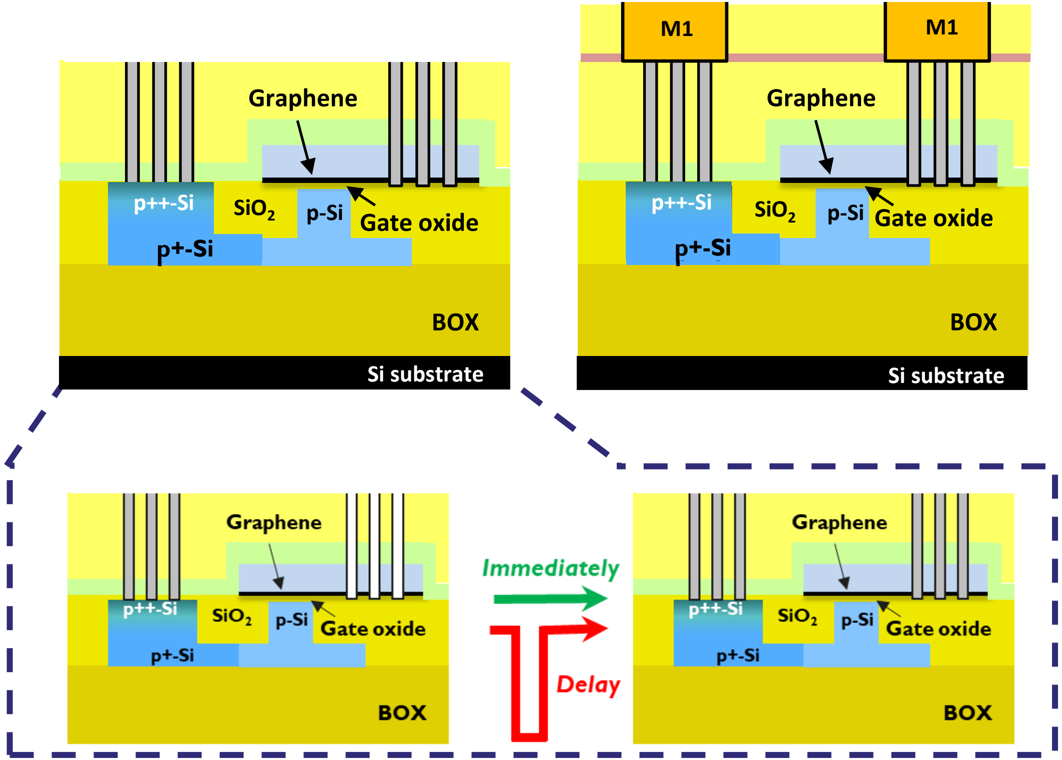
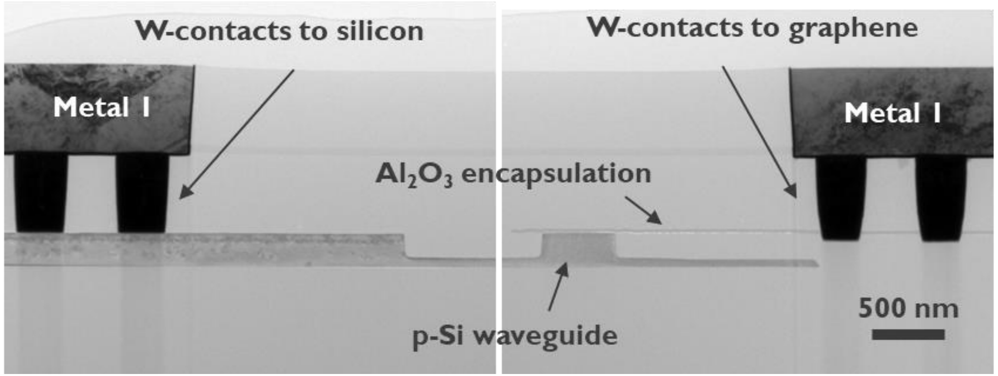
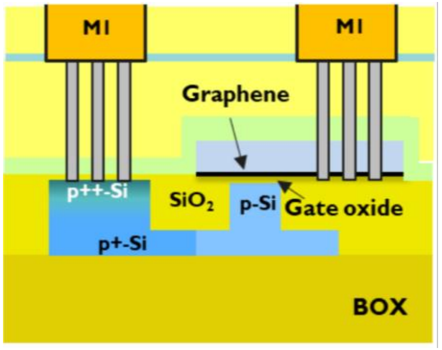
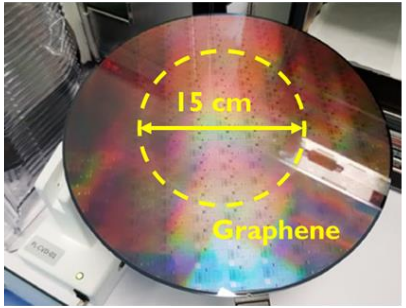
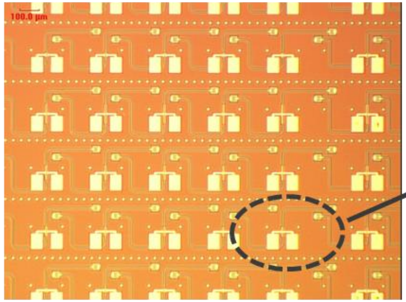


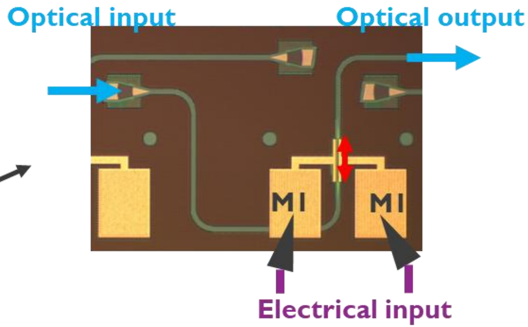
DEVICES' LOOK



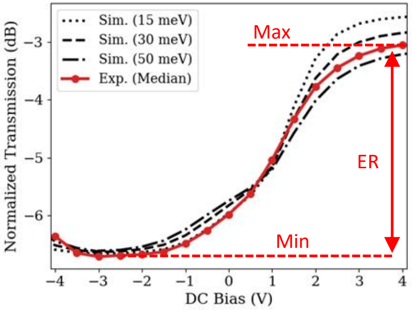








CHARACTERIZATION



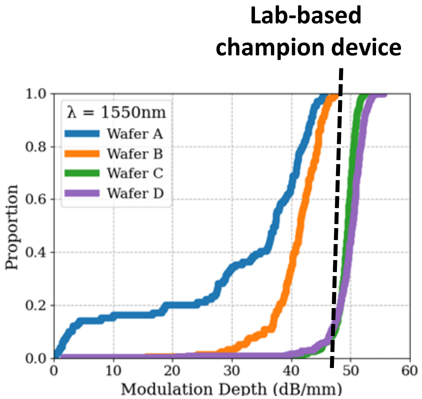
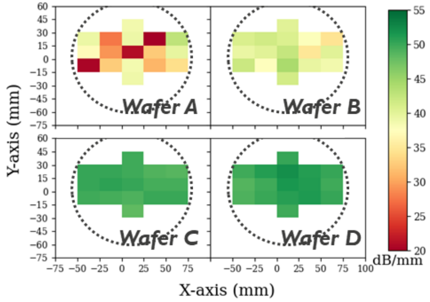
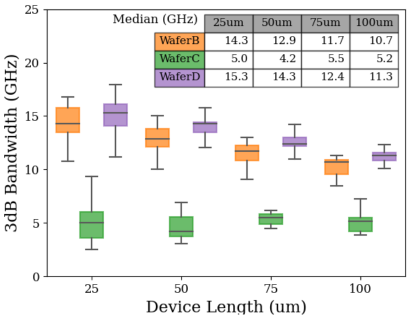


Table 1: DOE summary of four wafers reported in this paper

DOE	Wafer A	Wafer B	Wafer C	Wafer D
Surface planarization	Standard STI	Standard STI	Extra CMP	Extra CMP
Encapsulation soaking	Short	Long	Long	Long
Contact metal deposition	No delay	No delay	2 days delay	No delay





Study 1 on surface planarization: (Wafer B vs Wafer D)
Devices with Extra CMP modules results in a better modulation depth.

Study 2 on encapsulation soaking: (Wafer A vs Wafer B)
Devices with longer soaking results in a better device yield.

Study 3 on contact metal: (Wafer C vs Wafer D)
No difference is observed in static characterization. In dynamic characterization, Devices with no-delay contacts results in larger bandwidth.

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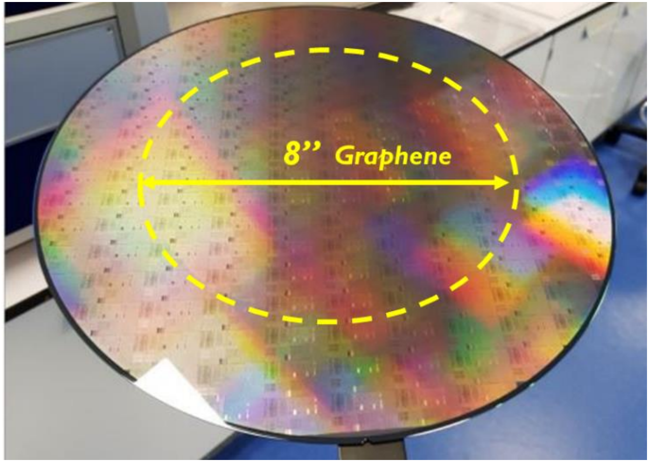
Wrap-up



Graphene photonics devices are now fully integrated with CMOS technology on 300 mm wafers!

Technology		Wafer-scale SLGEAM - Wafer D		Lab-based Champion SLGEAM	
		This work		[1]	
Active length	um	50	75	75	75
Working band & mode	-	C-band TE		C-band TE	
Oxide stack(s)	-	SiO2		SiO2	
Peak-to-peak Voltage	V	5		~5	
IL @highV	dB	2.0 ± 0.7	3.5 ± 1.5	~2.5	3
ER	dB	2.5 ± 0.1	3.7 ± 0.3	3.6	2.7
Modulation depth	dB/mm	50 ± 4.0		48	36
FOM(ER/IL)	-	1.28 ± 0.23	1.30 ± 0.31	1.52	0.87
Transmission Penalty	dB	7.39 ± 0.76 Best device: 6.44	7.90 ± 1.70 Best device: 6.76	8	9.4
3dB bandwidth	GHz	14.1 ± 1.4	12.6 ± 0.9	8.9	16.1
Number of devices	-	> 400		1	1

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PERFORMANCE!

HIGH-EFFICIENCY DUAL SINGLE LAYER GRAPHENE MODULATORS WITH STRIP AND SLOT WAVEGUIDES

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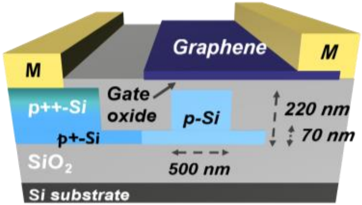
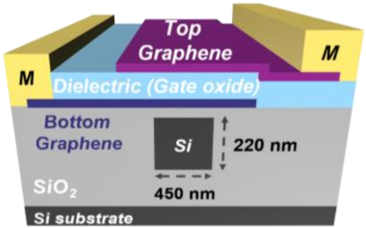
GRAPHENE FLAGSHIP

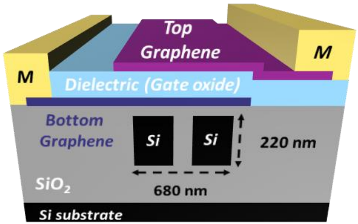
Motivation

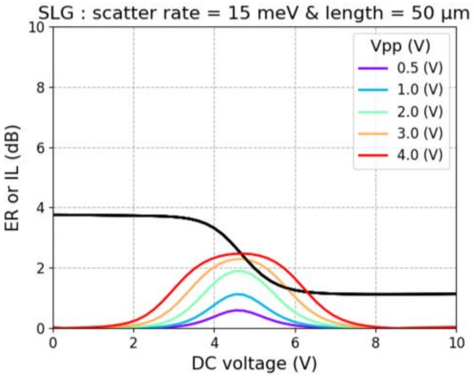


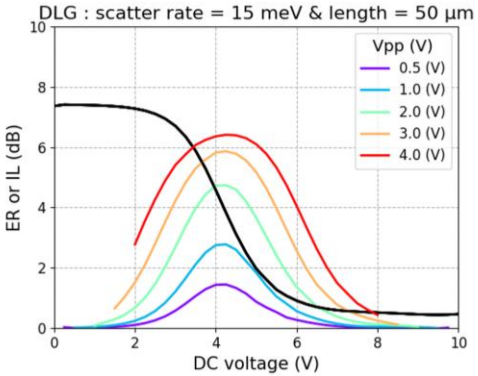
Increase modulation
No need Si implantation
Any passive WG

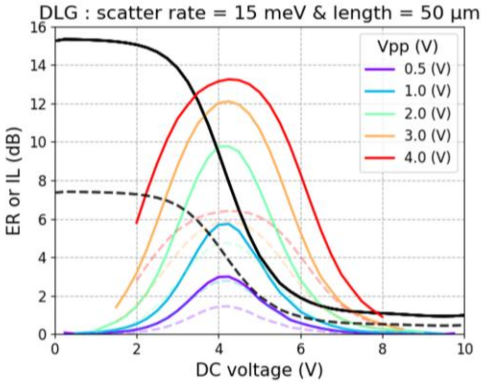
More complicated integration





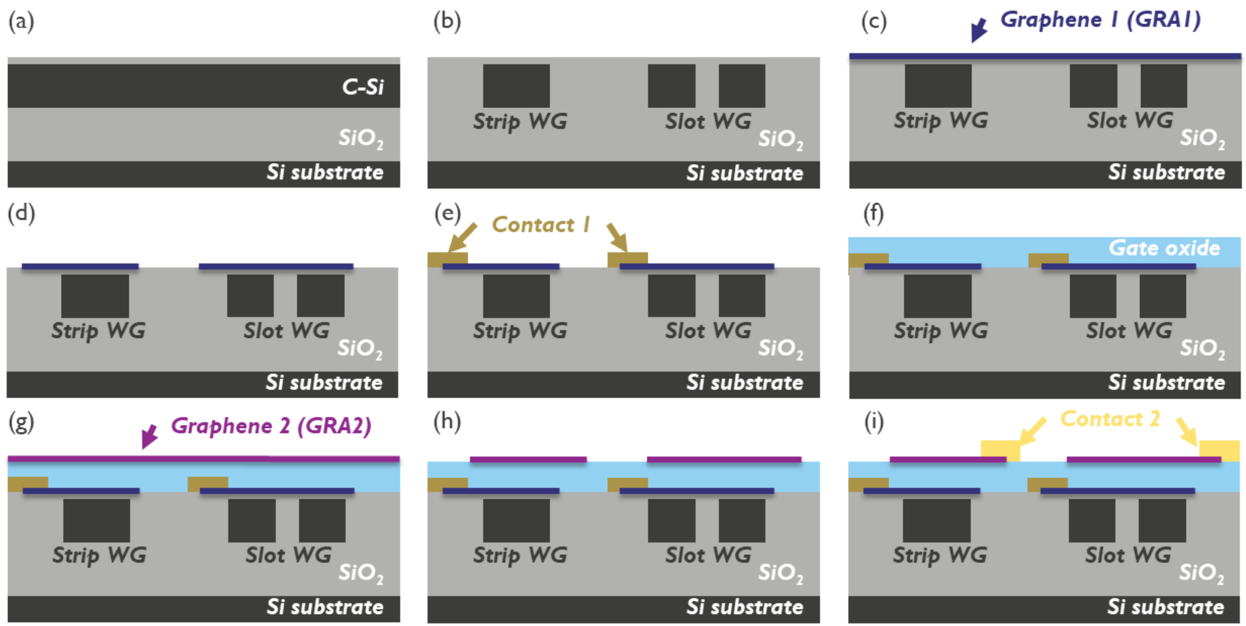






Strip waveguide-based
Slot waveguide-based

LAB-LEVEL INTEGRATION FLOW



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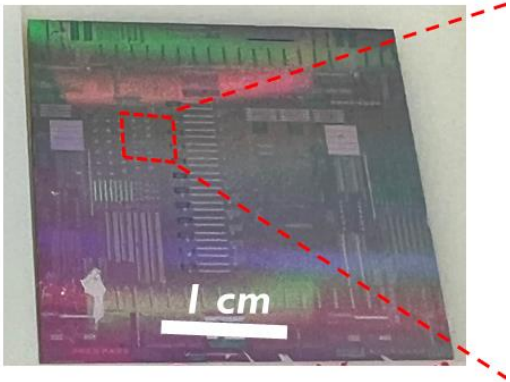
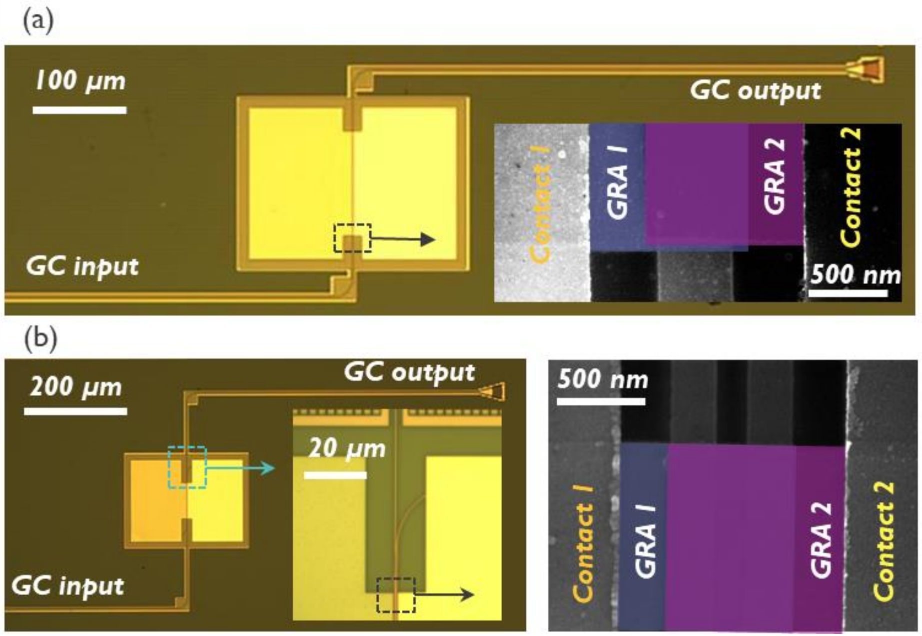
DLG EAMs

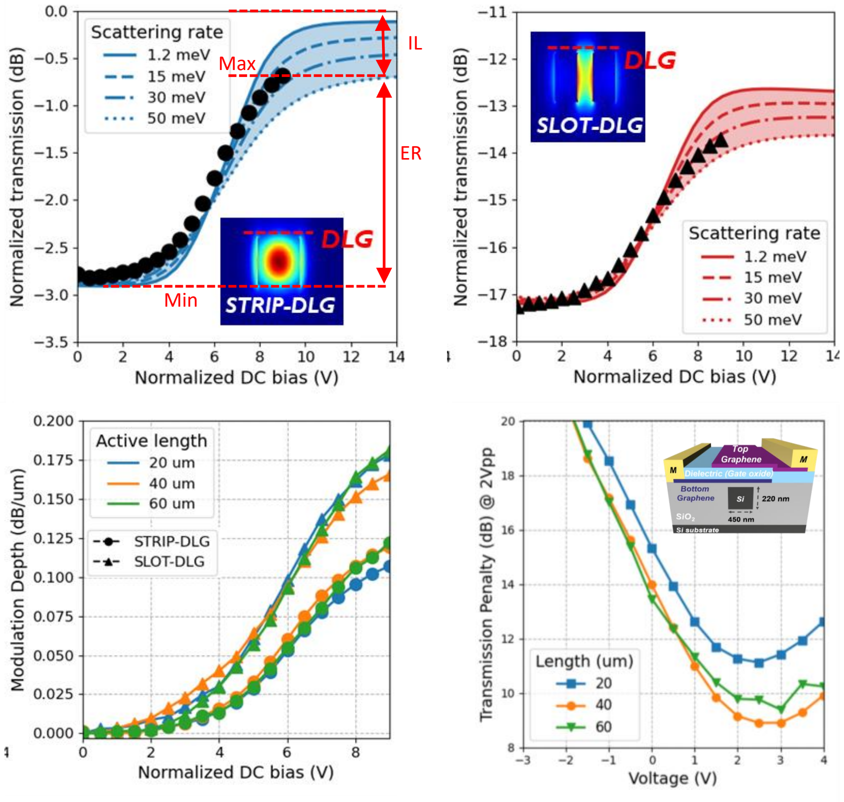


1 cm



(a)
100 µm
GC output
GC input
Contact 1
GRA 1
GRA 2
Contact 2
500 nm
(b)
200 µm
GC output
GC input
20 µm
500 nm
Contact 1
GRA 1
GRA 2
Contact 2

DLG EAMs DC PERFORMANCE



$$Transmission\ Penalty\ [dB] = \frac{P_1 - P_0}{2Pin} = -10\ log_{10}\left(\frac{1-\frac{1}{ER}}{2\ IL}\right)$$

- **Strip**: MD = 0.125 dB/um; TP = 8.9 dB @ 2 V_{pp}
- **Slot**: MD = 180 dB/um; TP > 20 dB @ 2 V_{pp}
- TP = 8.9 dB is best reported for graphene-based modulator and comparable with Ge device.

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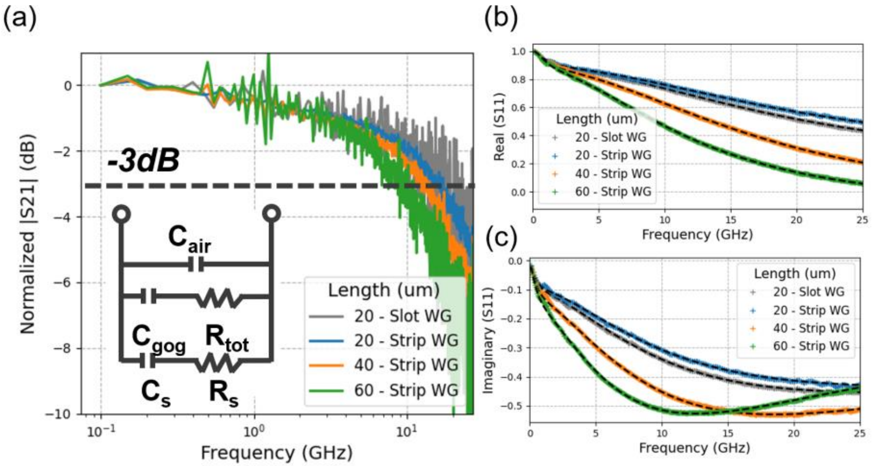
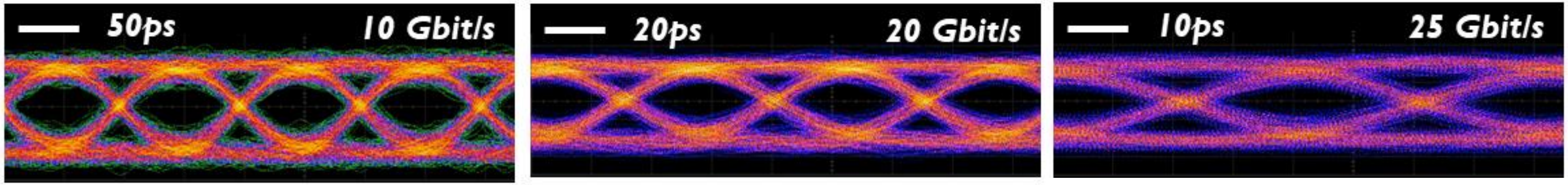
DLG EAMs AC PERFORMANCE



WG Type	Length	f_{3dB}	C_{gog}	R_{tot}
	[um]	[GHz]	[fF]	[Ω]
Strip WG	20	15.9	45	116
	40	12.5	92	47
	60	9.2	139	43
Slot WG	20	15.9	53	101



DLG EAMs Benchmarking Table

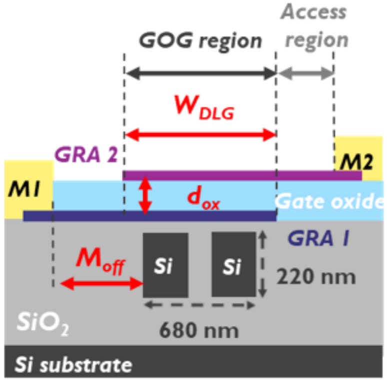
Graphene-based EAMs		DLGEAM Strip WG	DLGEAM Slot WG	High-speed DLG-EAM [1]		High-speed DLG-EAM [2]
Peak-to-peak Voltage	V	7		12	16	~9
IL @highV	dB	0.88	14.4	20	14.3	~20
Modulation efficiency	dB/V/um	0.0213	0.039	0.0367	0.0295	-
Modulation depth	dB/mm	117	168	75	128	25
Transmission Penalty	dB	5.69	>20	25	18	26
3dB bandwidth	GHz	12.5	15.9	39	-	29

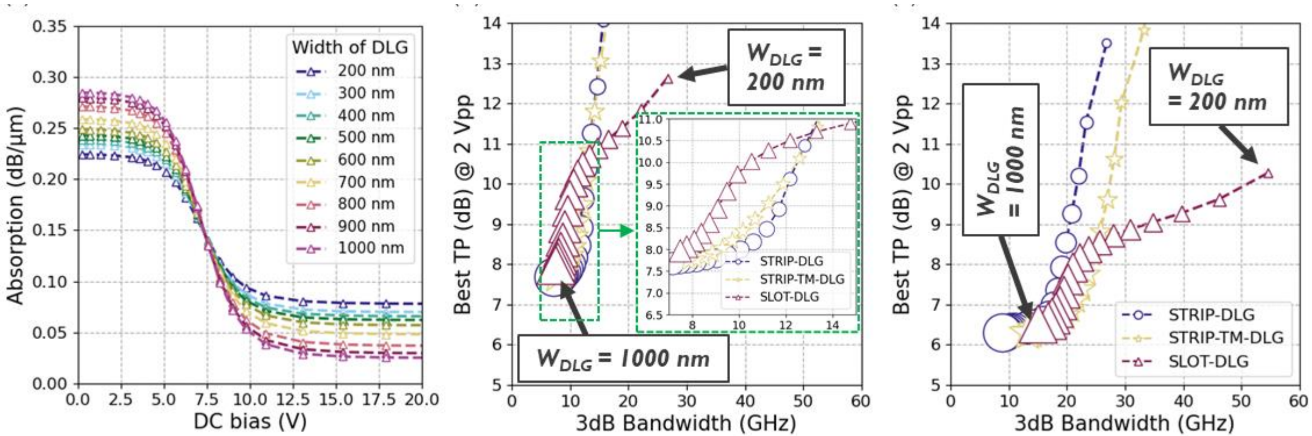
[1] Agarwal, Hitesh, et al. "2D-3D integration of hexagonal boron nitride and a high-κ dielectric for ultrafast graphene-based electro-absorption modulators." Nature communications 12.1 (2021): 1-6.
[2] Giambra, Marco A., et al. "High-speed double layer graphene electro-absorption modulator on SOI waveguide." Optics express 27.15 (2019): 20145-20155.

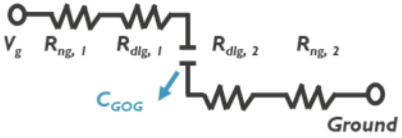
EAMs with different materials		DLGEAM Strip WG	DLGEAM Slot WG	Ge FK EAM [3]	III-V EAM [4]
Peak-to-peak Voltage	V	2		2	2.2
IL @highV	dB	1.71	15	4.9	4.8
Modulation depth	dB/mm	52.2	71.5	115	>100
Transmission Penalty	dB	8.90	>20	9.76	~8.26
3dB bandwidth	GHz	12.5	15.9	>50	>67
Optical bandwidth	nm	>80 Expected		~30	>30
Temperature Tolerance	ºC	>100 Expected		<30	-

[3] Srinivasan, Srinivasan Ashwyn, et al. "56 Gb/s germanium waveguide electro-absorption modulator." Journal of Lightwave Technology 34.2 (2015): 419-424.
[4] Tang, Yongbo, Jonathan D. Peters, and John E. Bowers. "Over 67 GHz bandwidth hybrid silicon electroabsorption modulator with asymmetric segmented electrode for 1.3 μm transmission." Optics Express 20.10 (2012): 11529-11535.

ROADMAP







- Safe metal offset is required to prevent extra losses caused by metal contacts.
- Balanced EOT for tradeoff between efficiency and bandwidth.
- A narrower DLG width leads to enhanced performance in slot-based devices.

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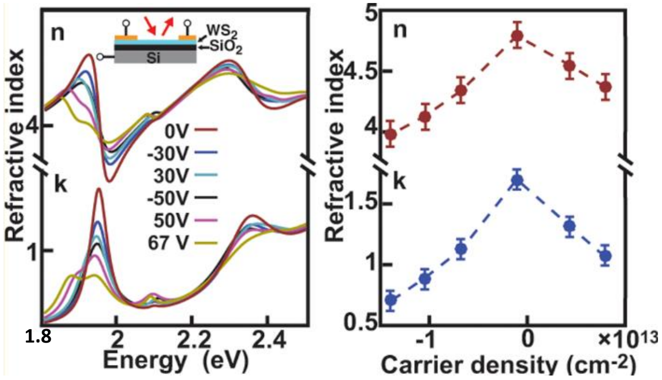
EXPLORATORY!

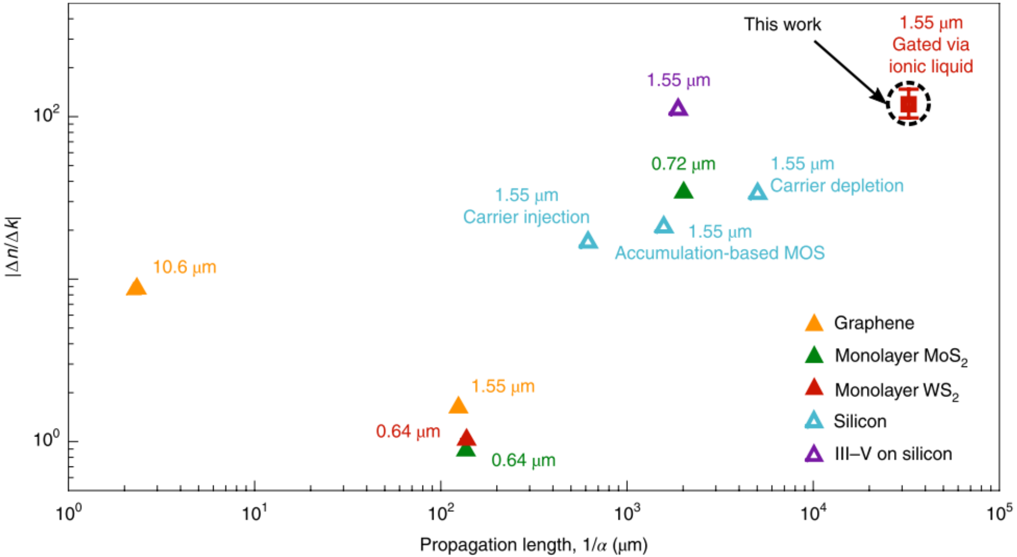
OTHER 2D-MATERIALS (MoS_2) FOR LOW LOSS INTEGRATED PHOTONICS PHASE SHIFTERS

Motivation



- TMDC (MX_2) exhibit strong index modulation at the excitonic peak.
- Also, it has strong index modulation within the C-band with low loss!

WS$_2$: |Δn/Δk|~125



[1] Yu, Yiling, et al. "Giant gating tunability of optical refractive index in transition metal dichalcogenide monolayers." *Nano letters* 17.6 (2017): 3613-3618.
[2] Datta, Ipshita, et al. "Low-loss composite photonic platform based on 2D semiconductor monolayers." *Nature Photonics* 14.4 (2020): 256-262.

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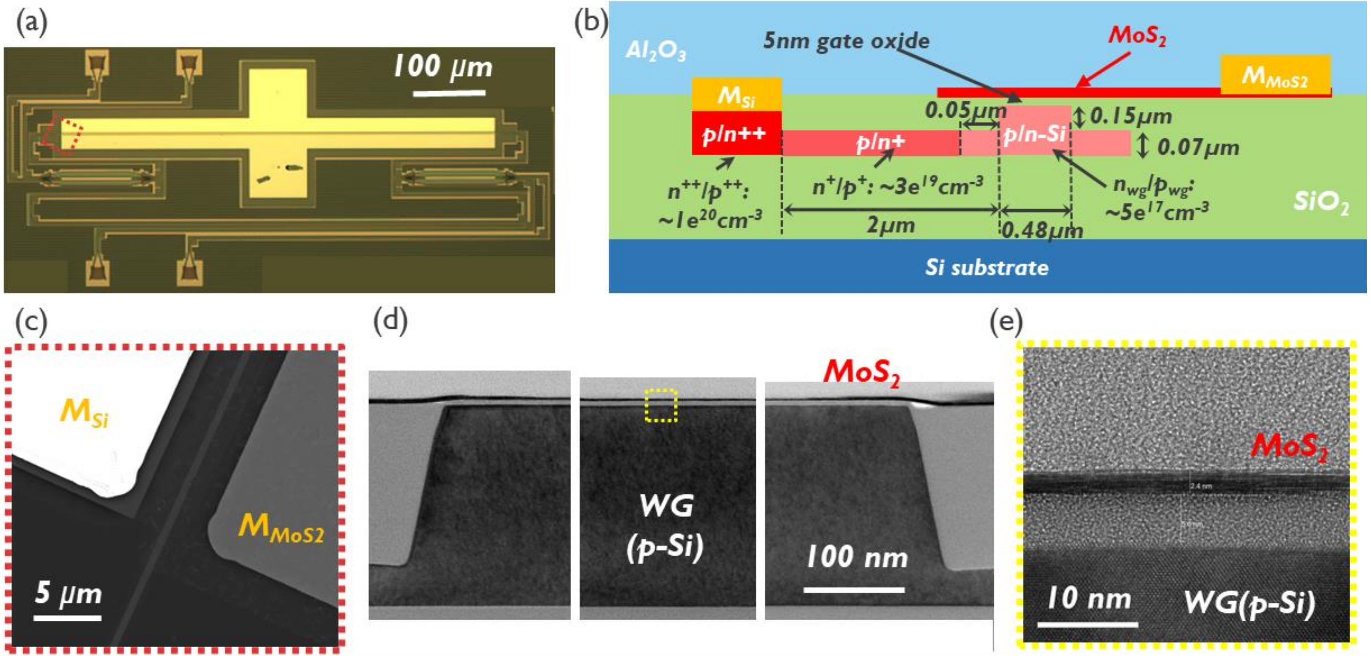
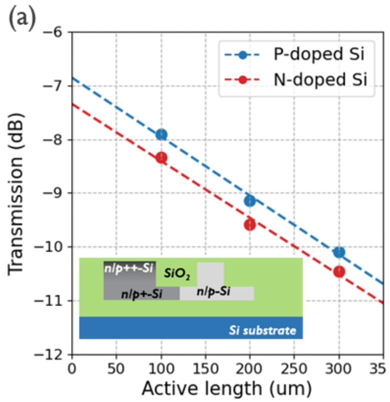
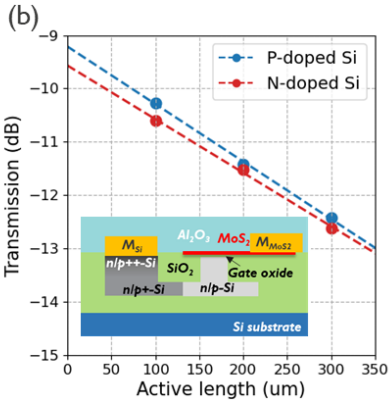
SINGLE-LAYER MOS2 (SL-MOS2)

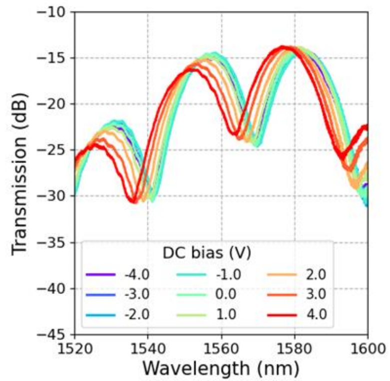


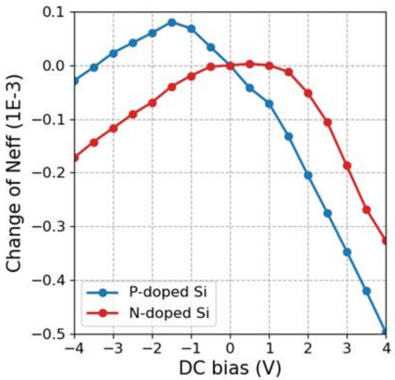
SL-MoS2 EXPERIMENTAL PERFORMANCE

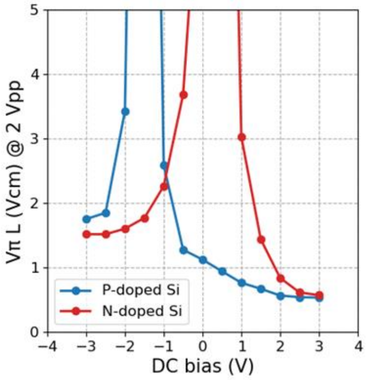




Propagation loss [dB/cm]	P-type	N-type
Before MoS_2	109	106
After MoS_2	108	100







$$\Delta\phi = \frac{wavelengthshift}{FSR} 2\pi$$

$$V_\pi L = \frac{\Delta V}{\Delta \phi} \pi L \;\; ; \;\; \Delta V = V_{pp}$$

p-type: $V_\pi L = 0.53$ Vcm

n-type: $V_\pi L = 0.57$ Vcm

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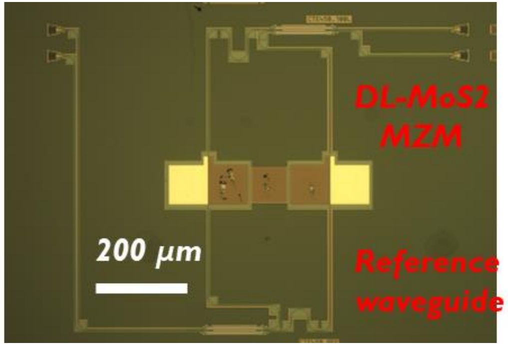
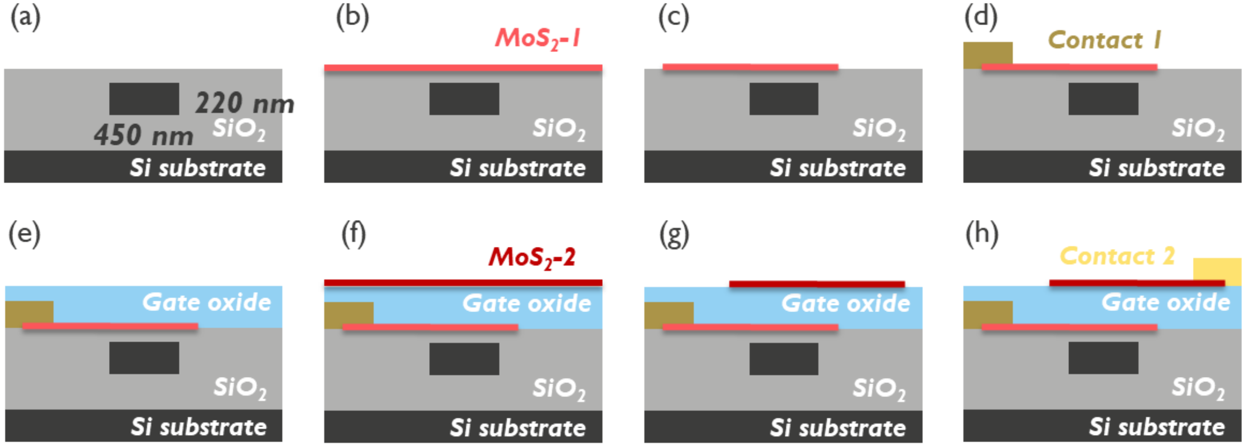
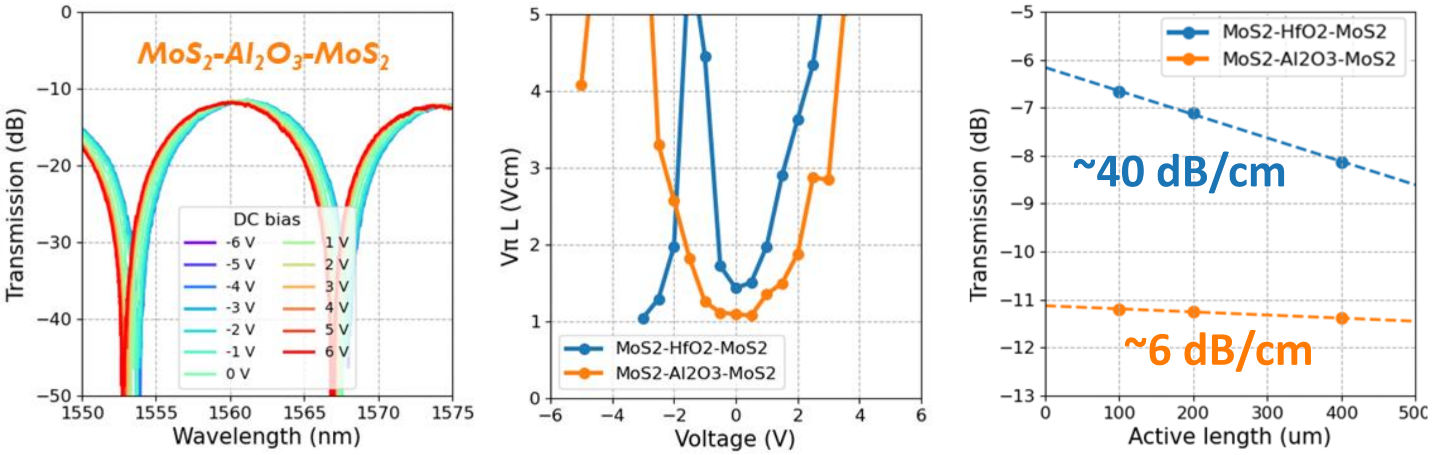
Dual-layer MoS2 (DL-MoS2)





DL-MoS2 EXPERIMENTAL PERFORMANCE



- DL-MoS_2 have lowest loss reported in this thesis.
  - 50 and 6.4 dB/cm for HfO_2 and Al_2O_3 device, respectively.
- FOM_{PM} outperform Si-based and 2D-materials based modulators.

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BENCHMARKING TABLE

MZMs		EOT	Loss	$V_\pi L$	FOM_{pm}	3dB bandwidth
		nm	dB/cm	Vcm	dBV	GHz
Si-oxide-Si	[1]	5 & 10	60 & 54	0.25 & 0.4	15 & 22	5.6 & 11.2
SLG	[2]	10	~236	0.28	66.1	5
DLG	[3]	11	746	0.3	223	24
WS_2-ITO	[4]	-	135	0.8	108	0.33
SL-MoS_2	This Work	5	100	0.57	57	0.91
DL-MoS_2	This Work	9.5	6.4	0.97	6	0.3

[1] Abraham, A., et al. "Evaluation of the performances of a silicon optical modulator based on a silicon-oxide-silicon capacitor." 11th International Conference on Group IV Photonics (GFP). IEEE, 2014.
[2] Sorianello, V., et al. "Graphene–silicon phase modulators with gigahertz bandwidth." Nature Photonics 12.1 (2018): 40-44.
[3] Watson, Hannah. Graphene Modulators for Silicon Photonic Optical Links. Diss. University of Cambridge, 2021.
[4] Datta, Ipshita, et al. "Low-loss composite photonic platform based on 2D semiconductor monolayers." Nature Photonics 14.4 (2020): 256-262.

CONCLUSION

Conclusion

SCALABILITY

- The CMOS integration of graphene based photonics devices is established.
- The knowledge can be extended to other sophisticated building blocks.

PERFORMANCE

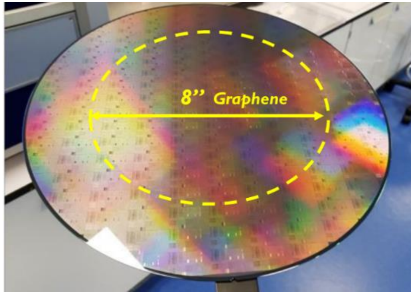
- The Figure of merits outperform state-of-the-art graphene-based modulators.
- Slot waveguide offers a new platform with greater design trade-off flexibility.

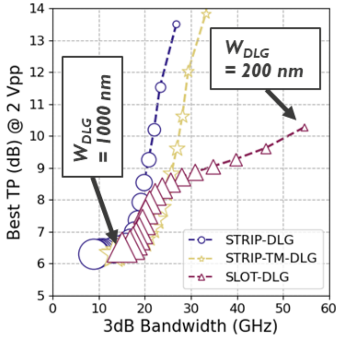
EXPLORATORY

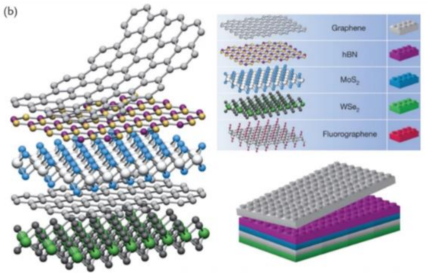
- MoS_2 emerges as a promising material option for low-loss phase shifters.
- The exploration of other 2D materials remains an exciting subject for investigation .

Can 2D material based photonic devices be adopted in industry for the next generation of data communication and telecommunications applications?

YES! THEY CAN!







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