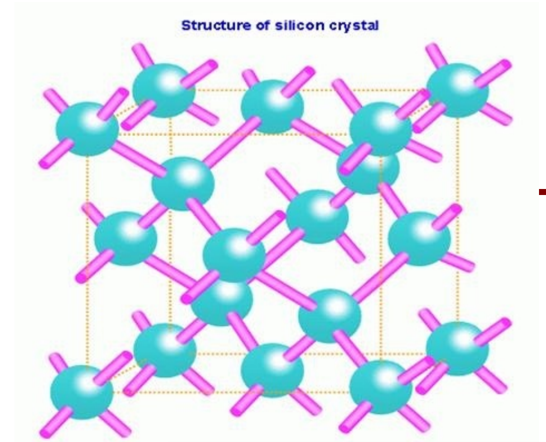
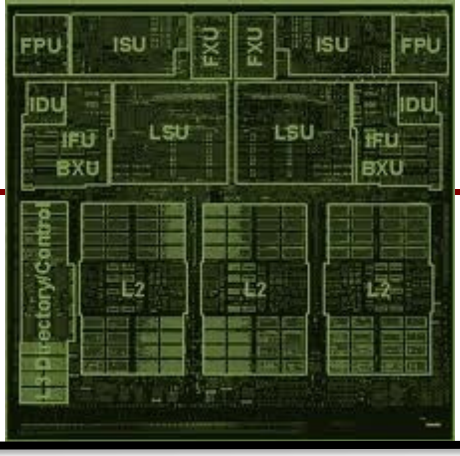
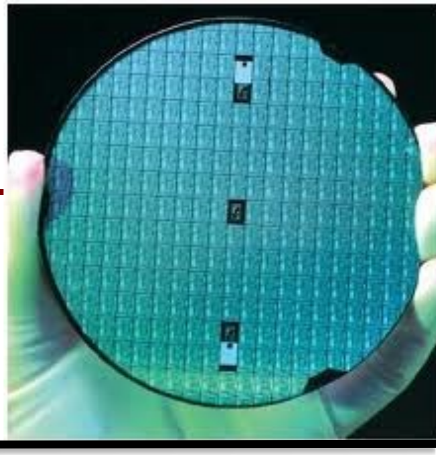






ECE 225

Lecture 16

Cryogenic 2D-CMOS Enabled Next-Generation High-Performance Large-Scale Quantum Computing

by Kunjesh Agashiwala (PhD Candidate, NRL)

Prof. Kaustav Banerjee

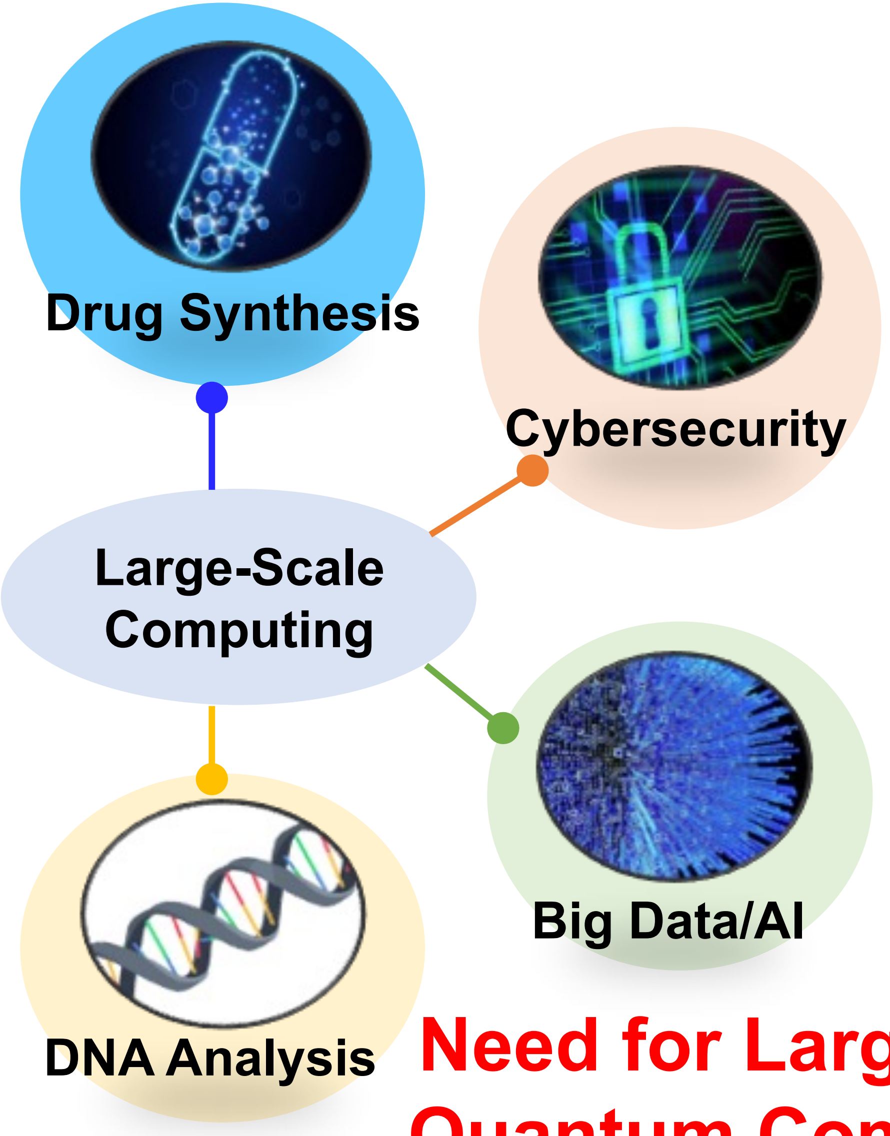
Electrical and Computer Engineering

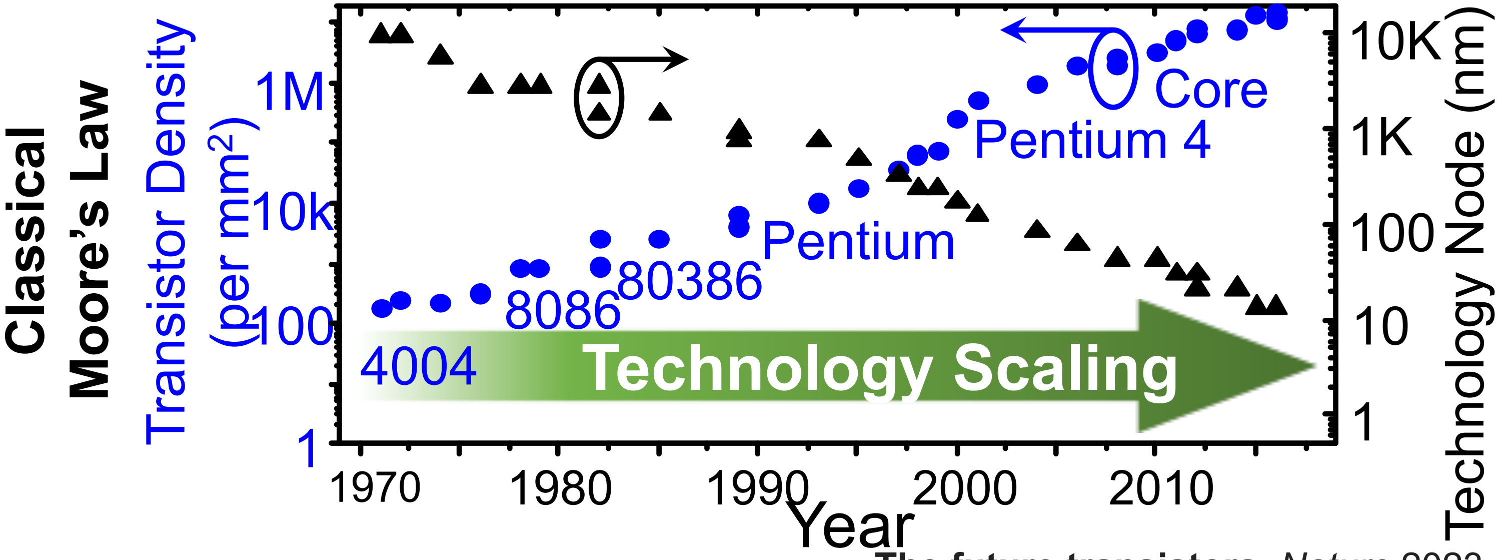
University of California, Santa Barbara

Outline

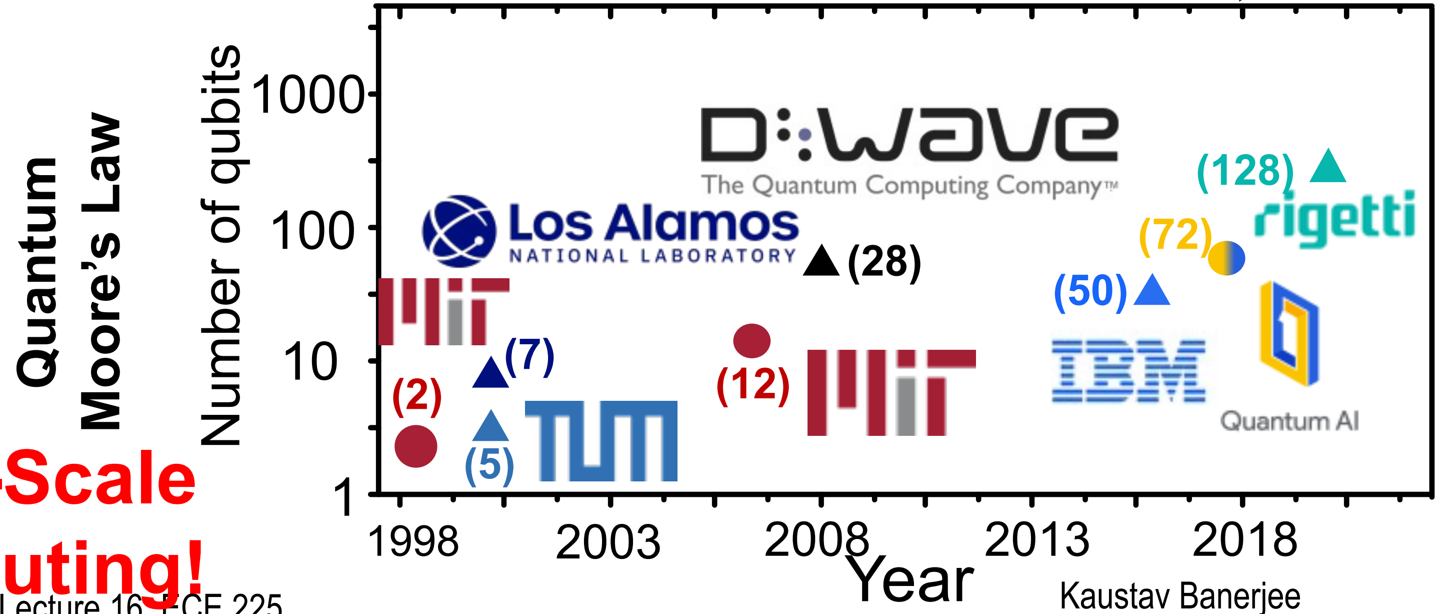
- Quantum Computing: Basics and Overview
- Interface Electronics in Quantum Computing
- 2D-Materials enabled Interface Electronics
- Benefits using 2D-Materials
- Summary

Quantum Computing





The future transistors, *Nature* 2023



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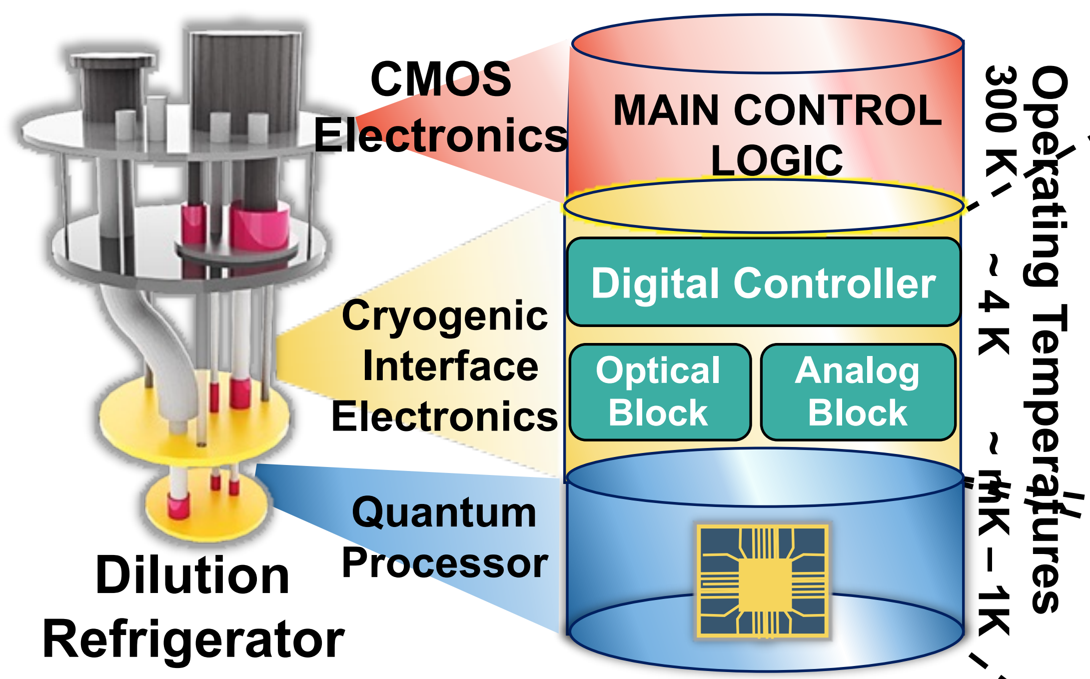
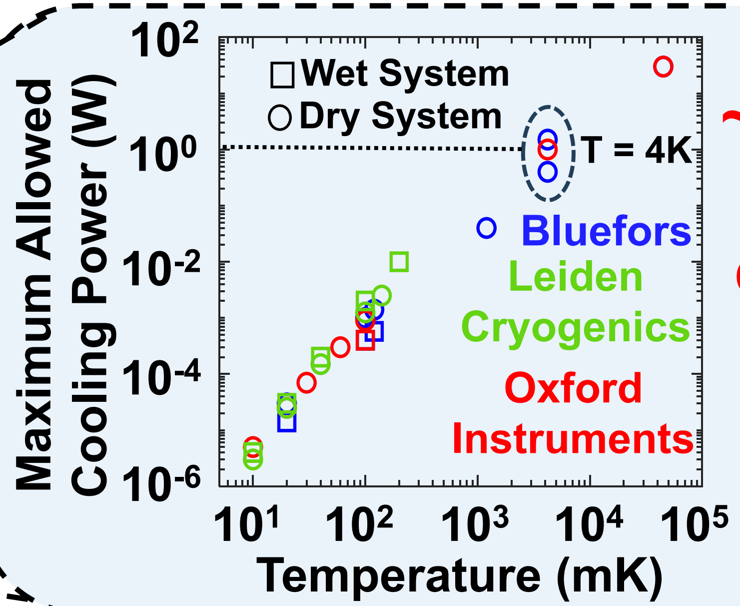
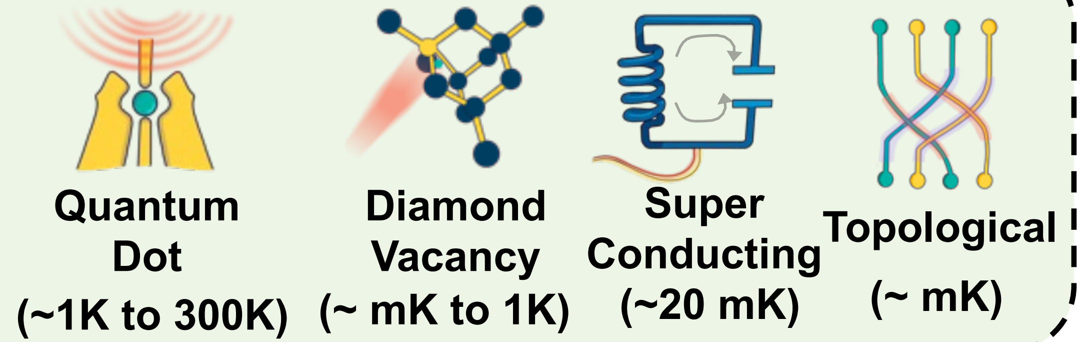
Need for Large-Scale Quantum Computing!

Challenges of Cryogenic Interface Electronics (CIE) in Large-Scale QM





~1mW/qubit power dissipation for a 1000-qubit system!

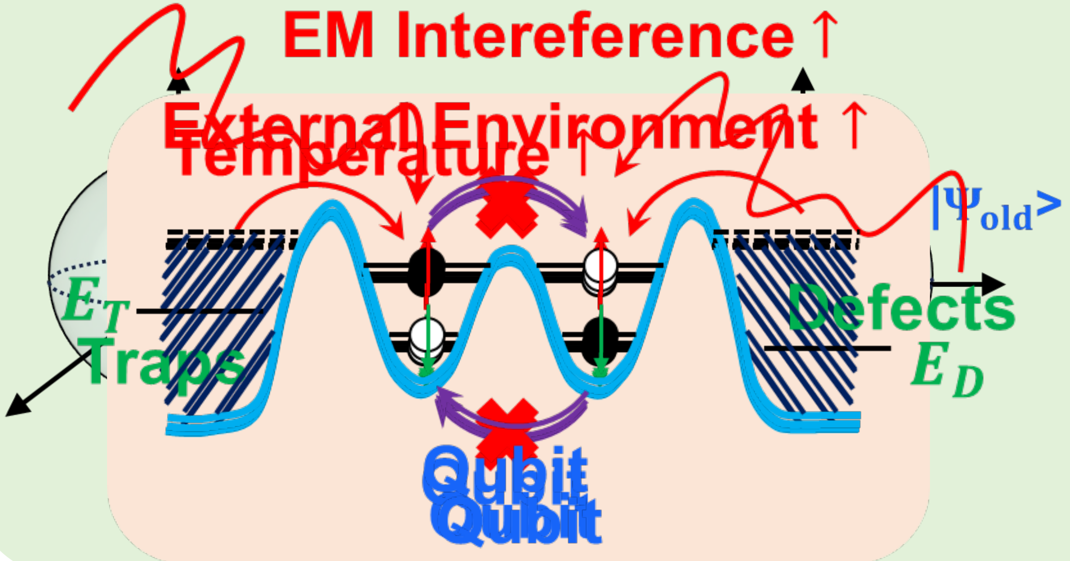


Need low power and energy-efficient CIEs for large-scale Quantum Computing!! ..major motivation of this work!

Challenges of Cryogenic Interface Electronics (CIE) in Large-Scale QM

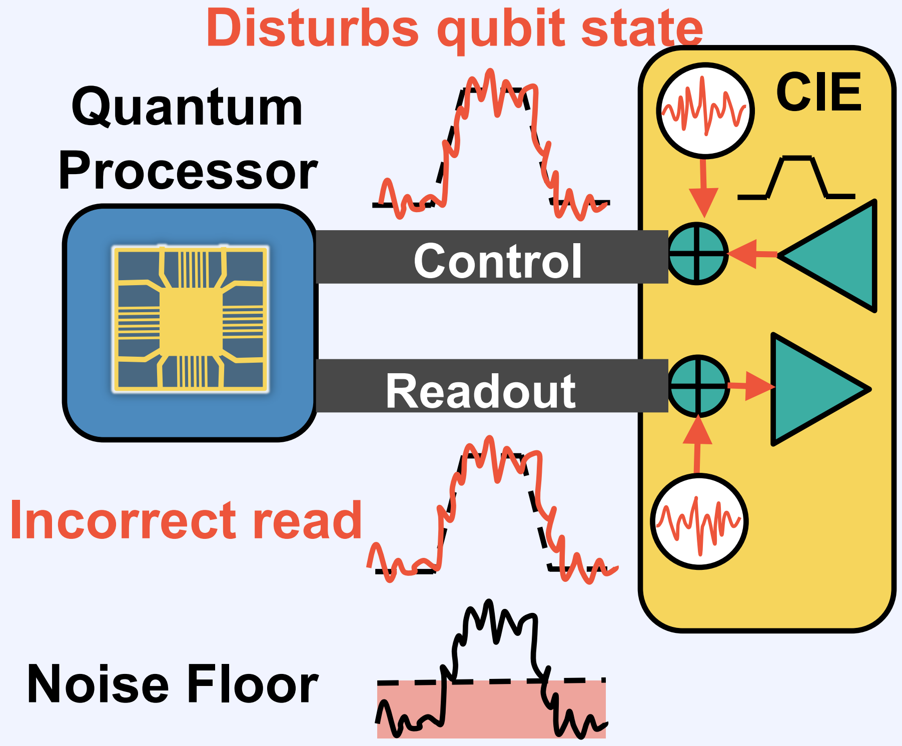
Noise- Qubits are Fragile!

- Major source of qubit decoherence
- Internal and external sources of noise
  - External environments (Defects/Traps)
    - Thermal fluctuations
      - EM interference

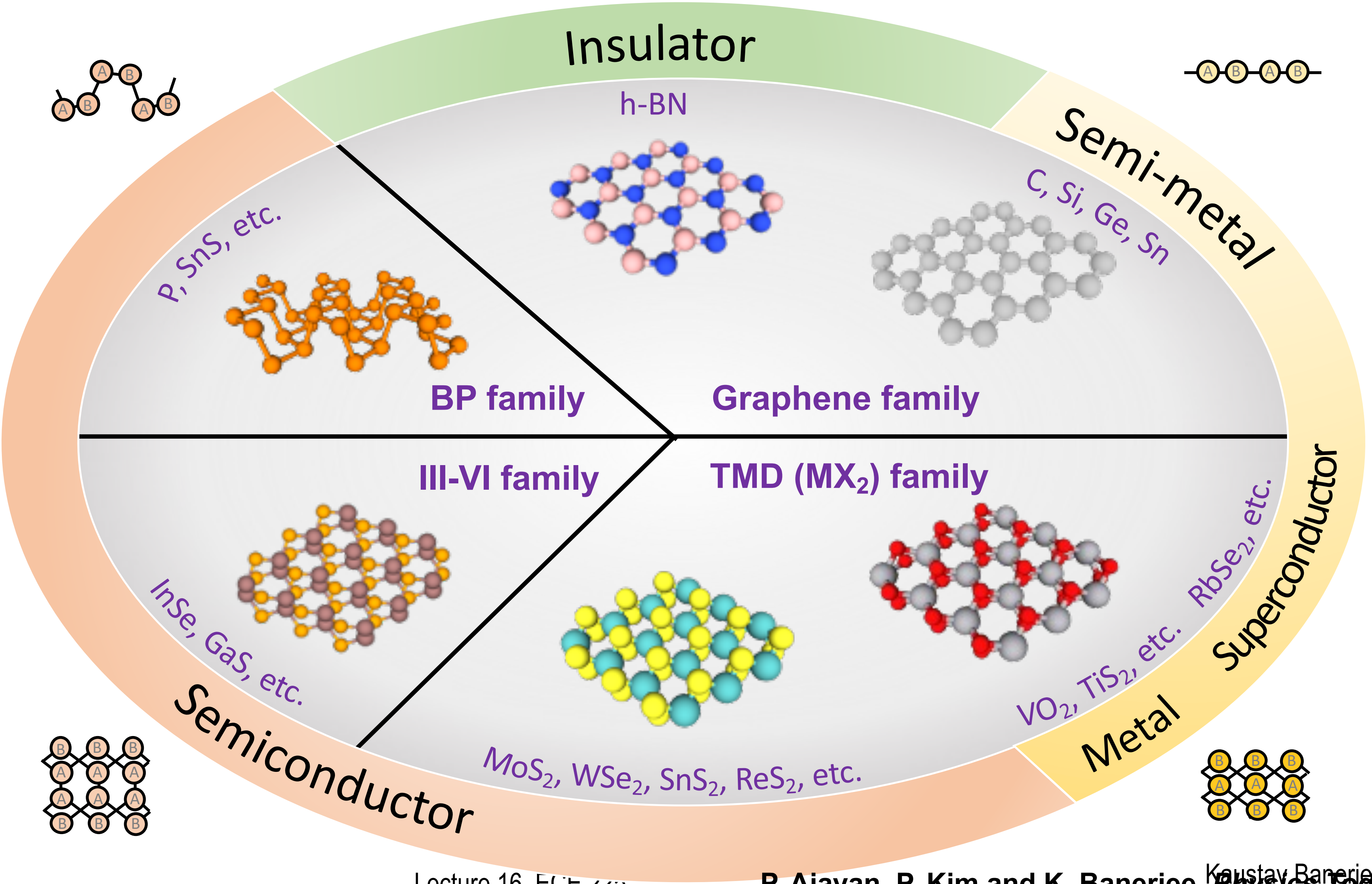


Noise in CIE

- Incorrect control read/write
  - Affects qubit fidelity



Two-Dimensional van der Waals Materials



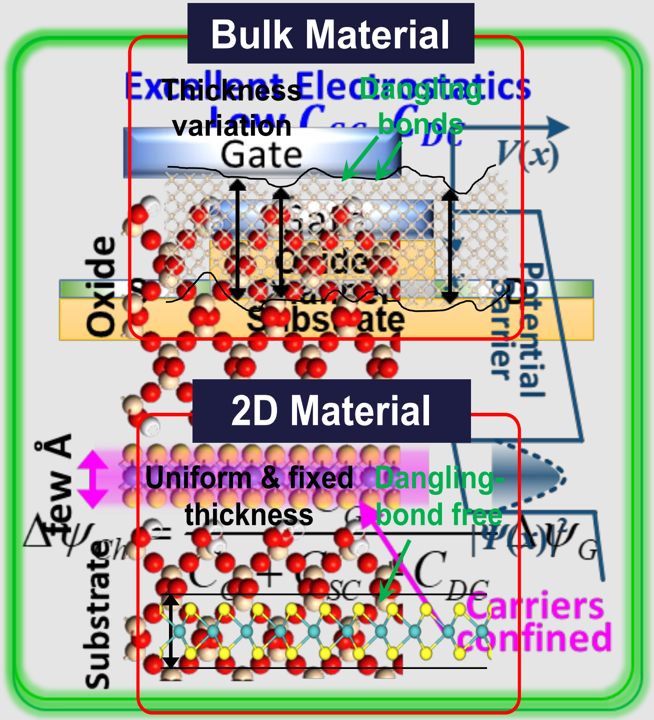
Kaustav Banerjee

P. Ajayan, P. Kim and K. Banerjee, *Physics Today*, Sept 2016

Why 2D Materials for CIE?

Layered/pristine nature

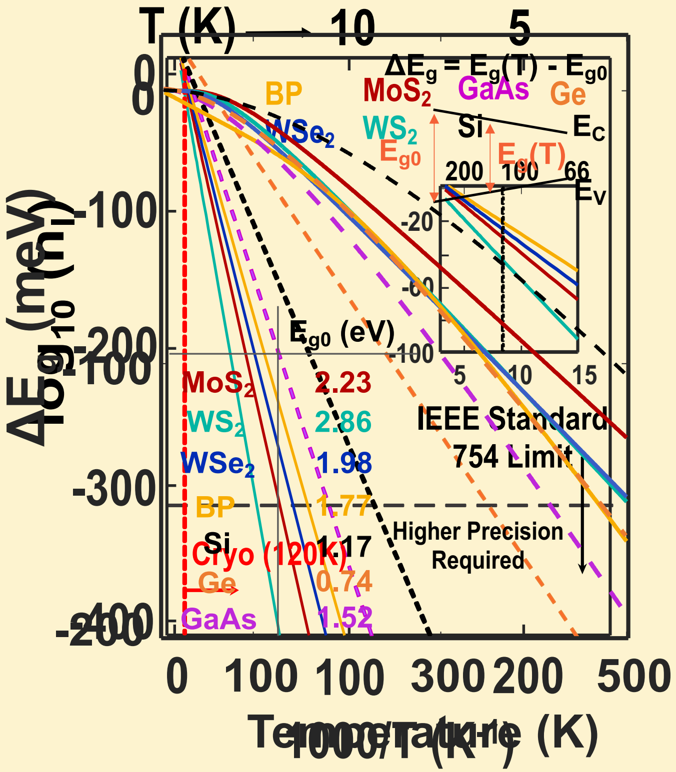
- Excellent Electrostatics[1]
- Low Device Parasitics



[1] J. Kang/K. Banerjee, *Physical Review X*, 2014.

Lower Leakage w.r.t Si

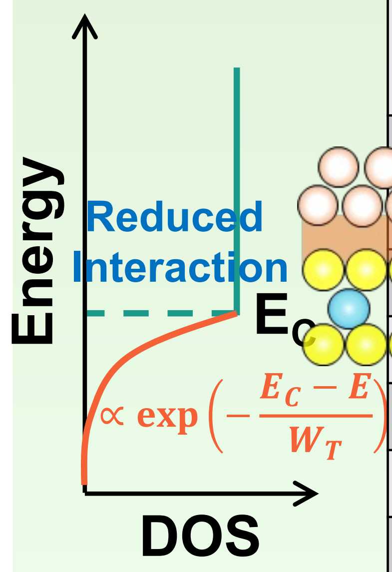
- Larger bandgap of 2DMs
- Lower intrinsic conc. n_i



Shorter Band-tails[2] w.r.t Si

- SS reduction with temperature
- Better immunity against noise

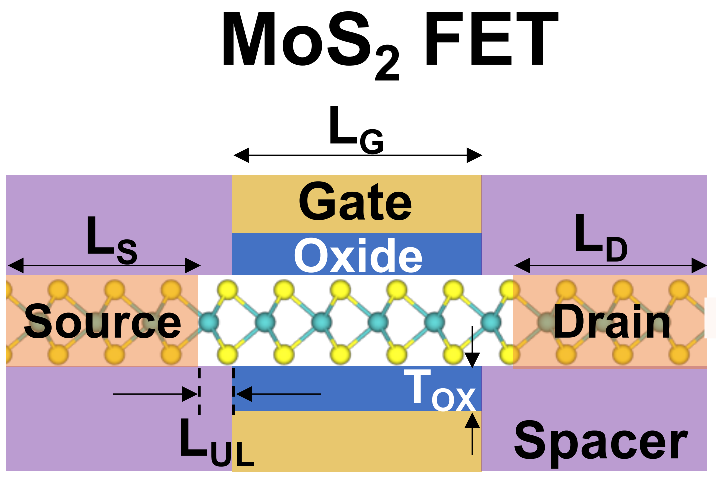
..this work



Material	Urbach Energy (W_T) (@RT) (meV)
Si	23.18
Ge	[illegible]
GaAs	4.20
MoS_2	2.77
WSe_2	2.40
WS_2	1.82
BP	1.80

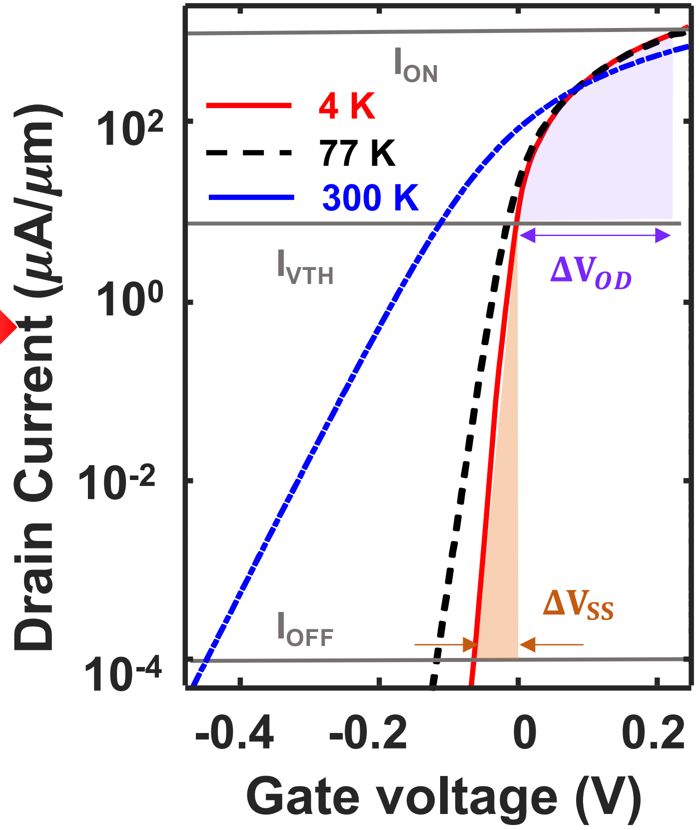
[2] H. Zhang/K. Banerjee, *IEDM*, 2016.

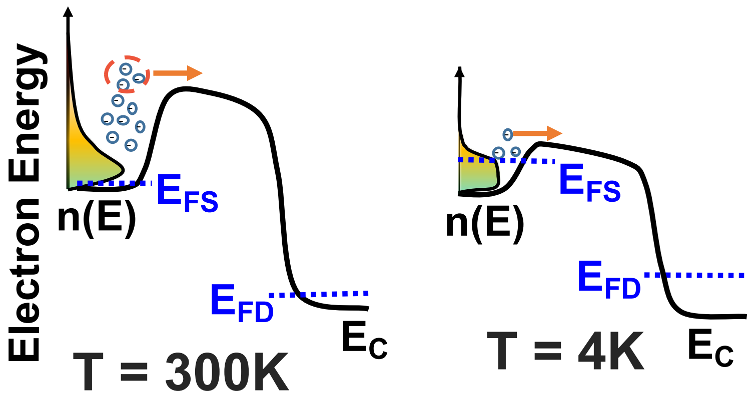
Device Characteristics at CT



Channel length = 20 nm

EOT = 1 nm



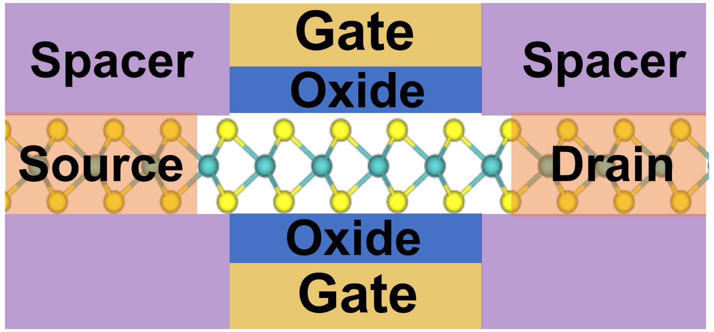


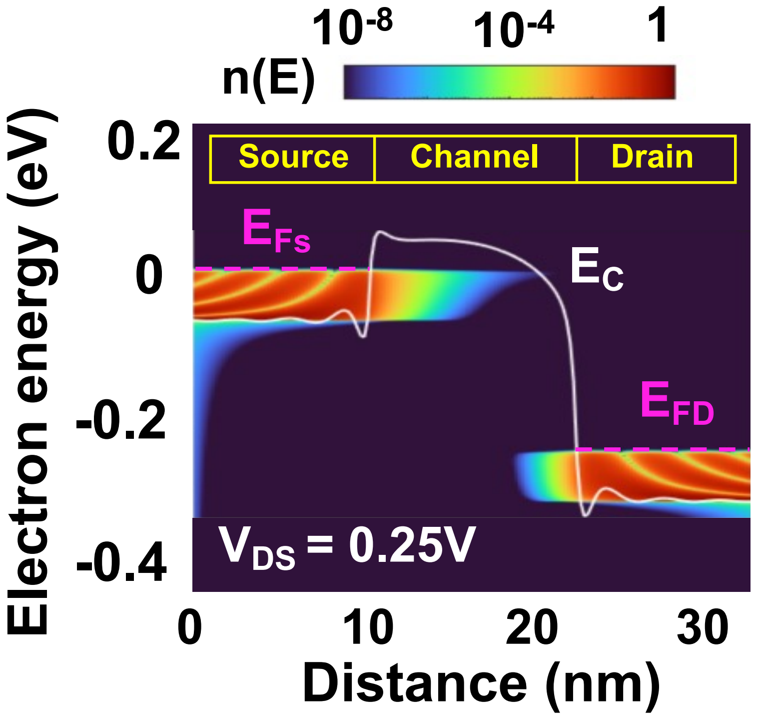
T (K)	SS (mV/dec)	ΔV_{SS} (mV)	ΔV_{OD} (mV)
300	68	320	375
77	21	102	188
4	13	62	148

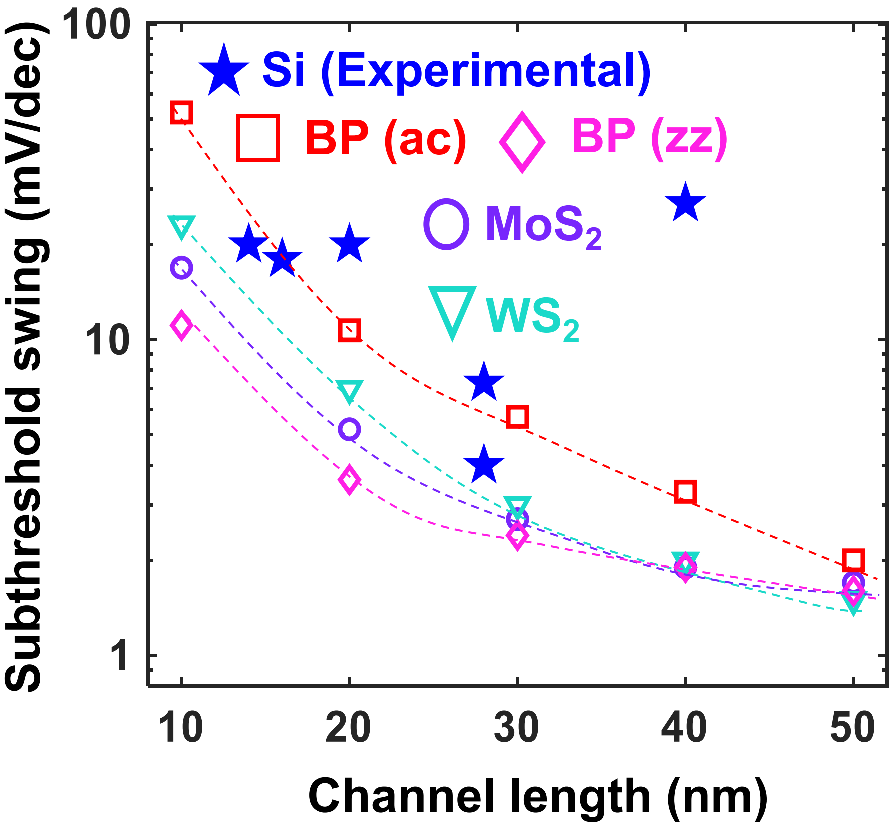
Higher V_T and lower SS at CT as compared to RT!

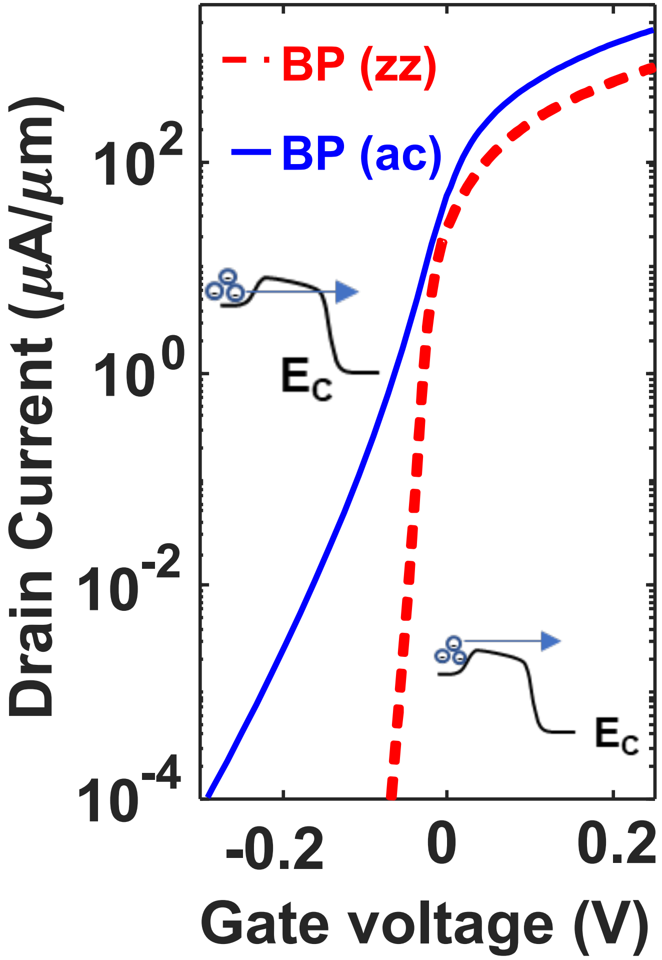
**RT = Room Temperature*

Impact of Source Drain Tunneling at CT



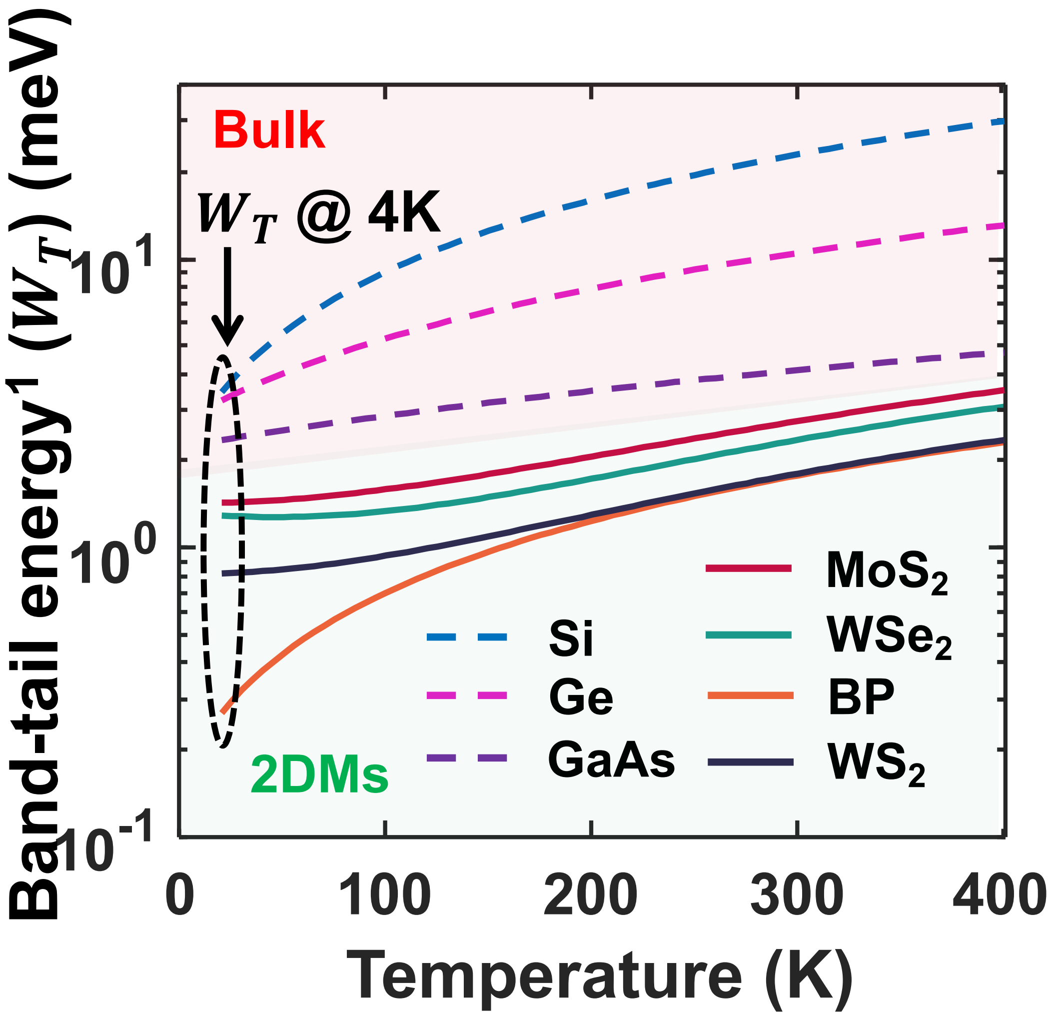




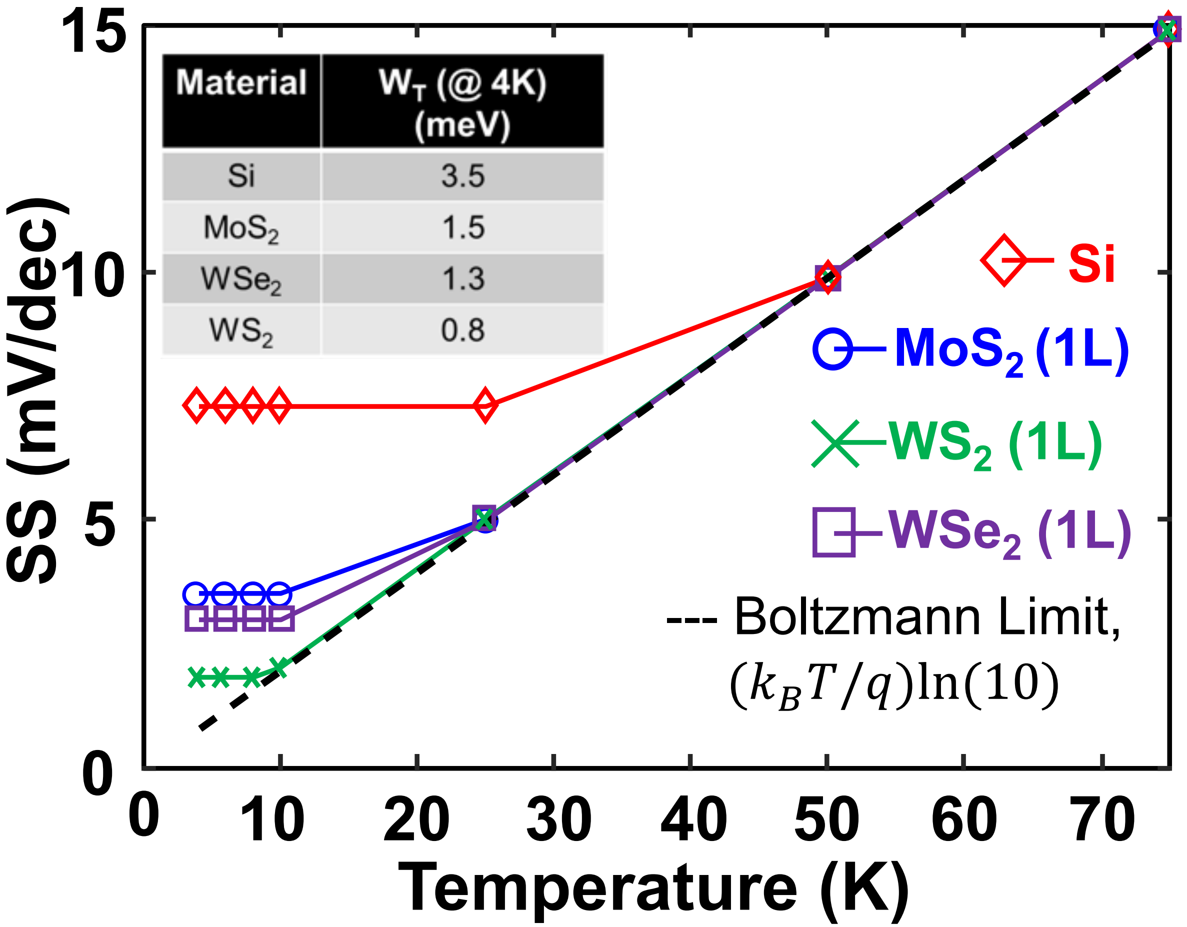


SDT significantly affects transport at CT!

SS Saturation at CT



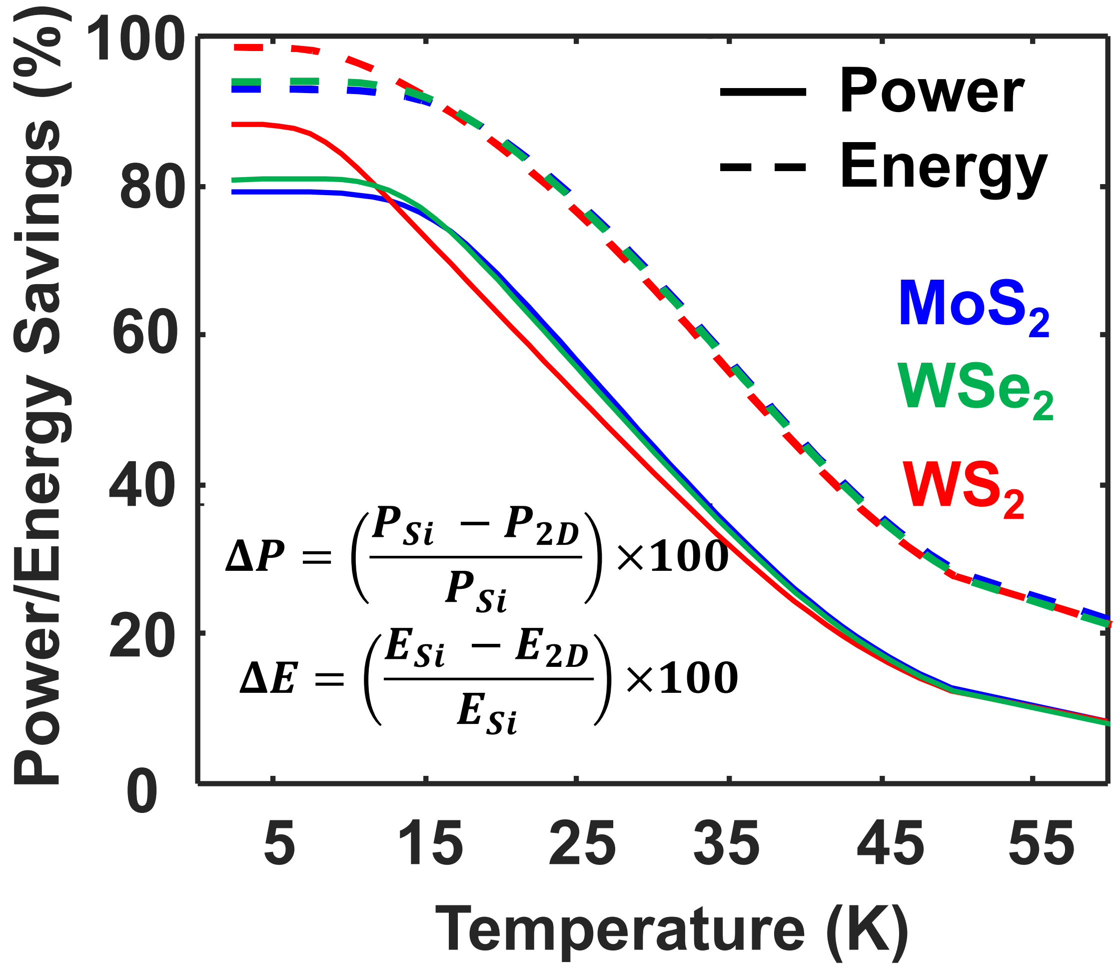
[1] H. Zhang/K. Banerjee, *IEDM* 2016.

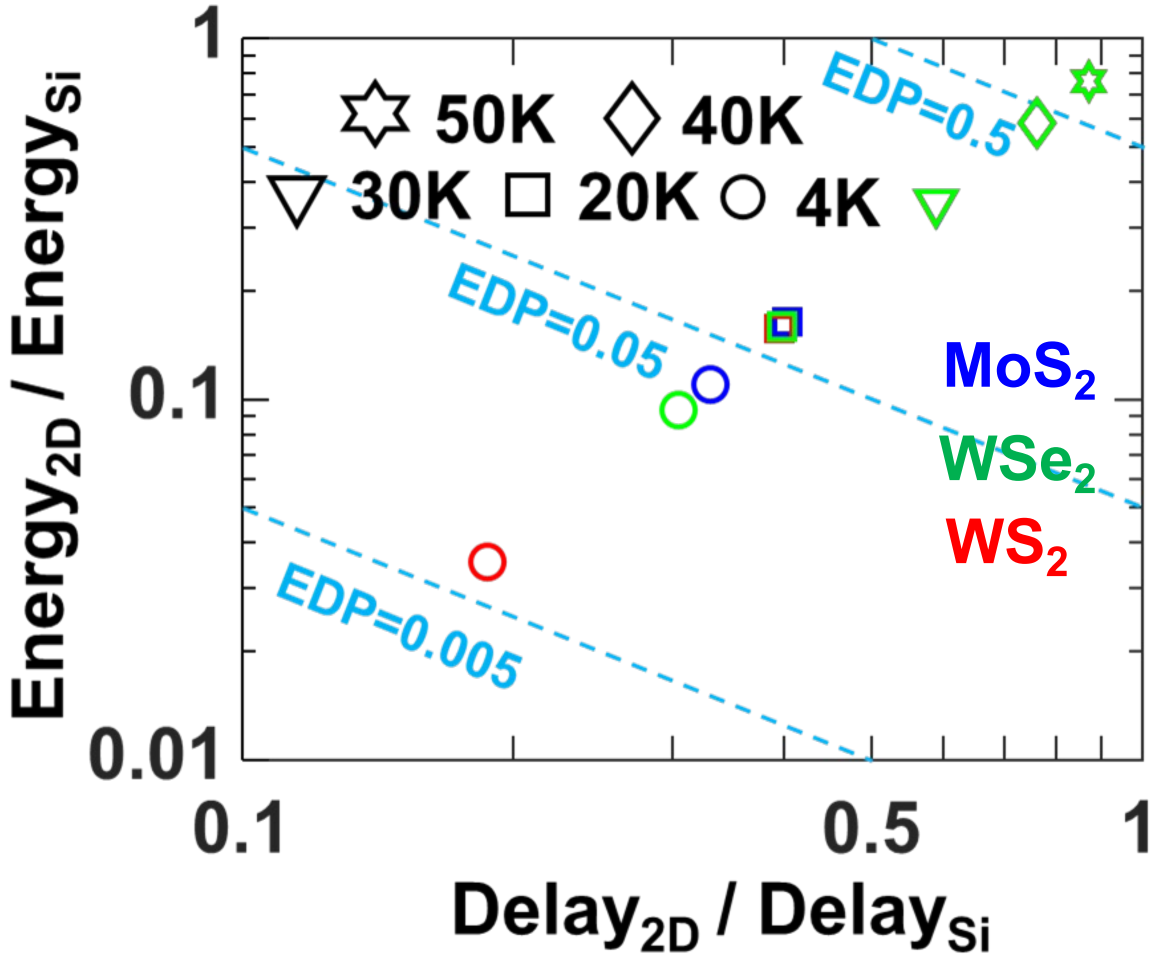


Material	W_T (@ 4K) (meV)
Si	3.5
MoS_2	1.5
WSe_2	1.3
WS_2	0.8

Lower W_T of 2D-Materials enable lower SS saturation!!

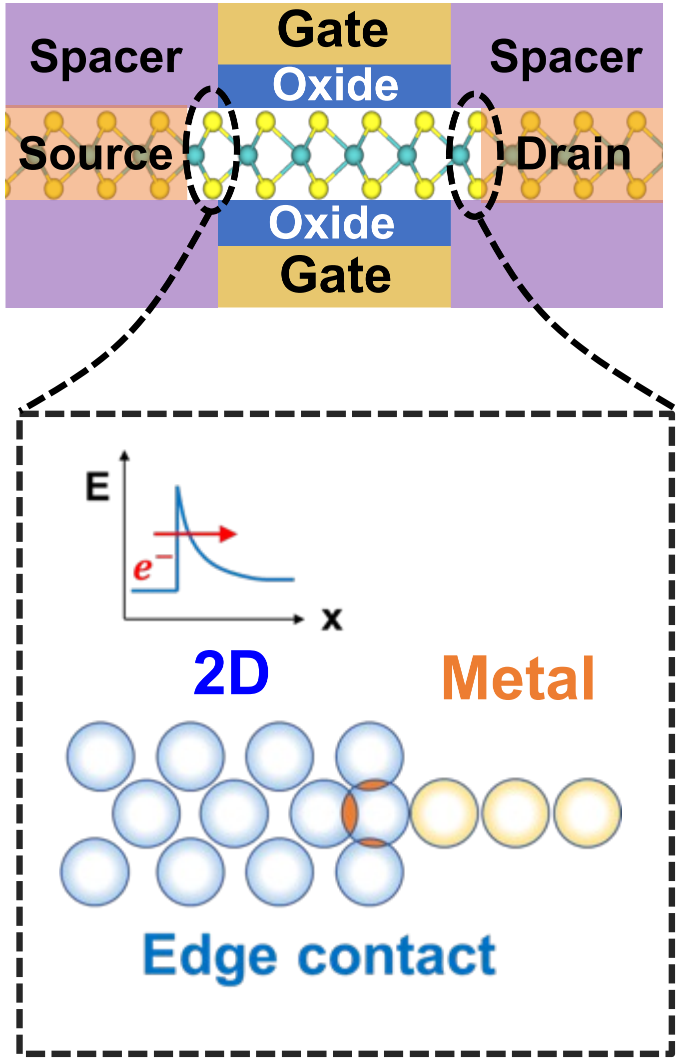
Energy and Power Benefits at CT

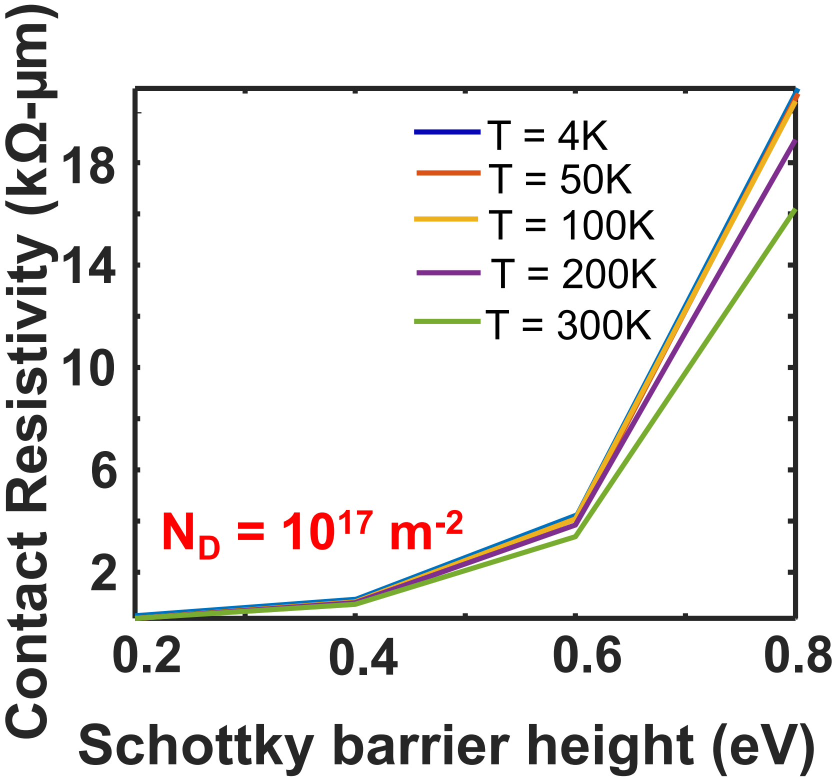


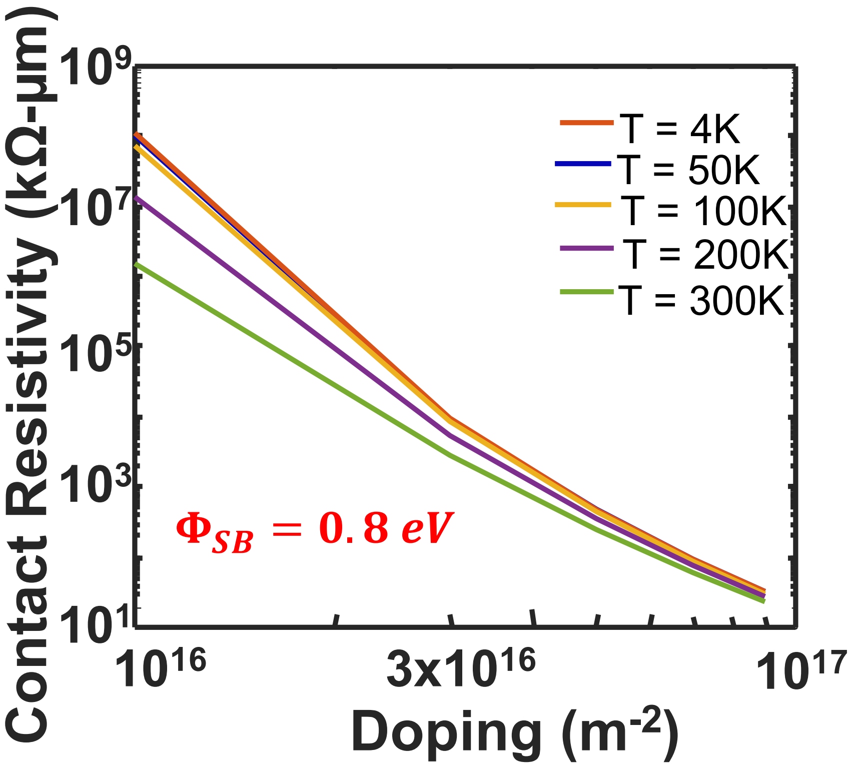


Significant power/energy benefits enabled by the lower W_T of 2DMs!

Contacts at CT



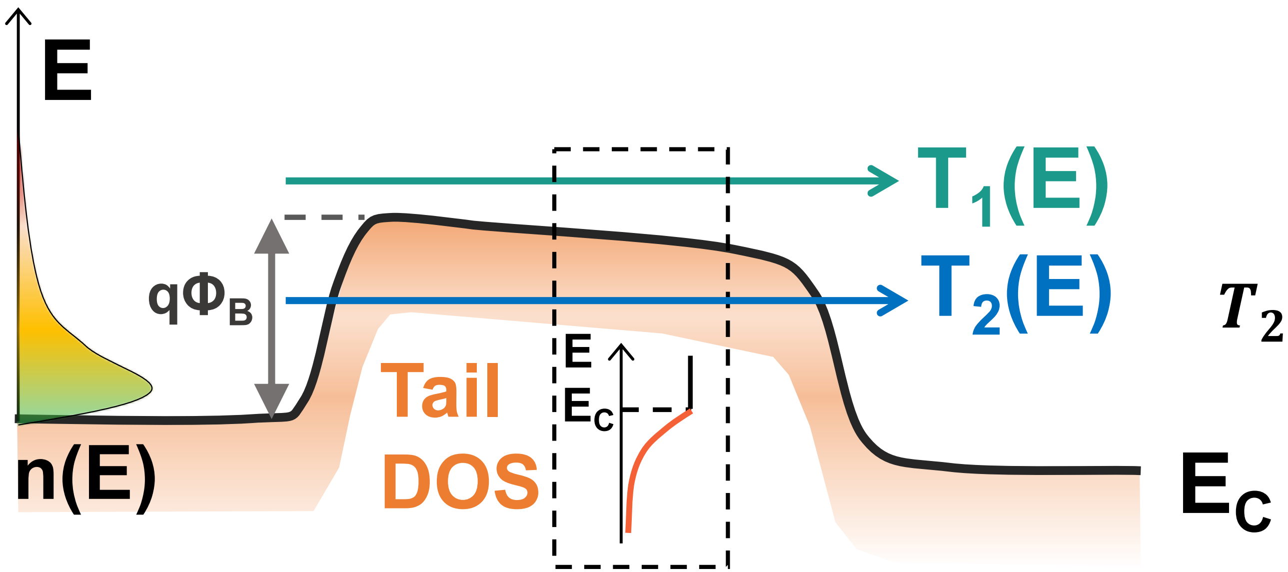




Model adopted from A. Pal/K. Banerjee *et. al.*, *IEDM* 2022.

Significantly higher contact resistance at CT!

Compact Model Incorporating Band-Tails



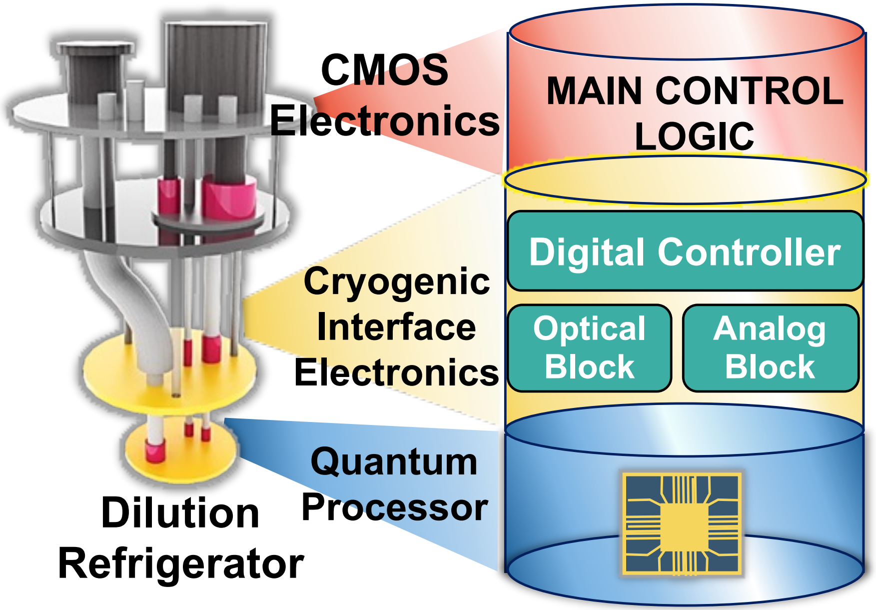
$$T_1(E) = \frac{\lambda}{\lambda + L}$$

$$T_2(E) = \frac{\lambda}{\lambda + L} exp\left(\frac{E - q\phi_B}{W_T}\right)$$

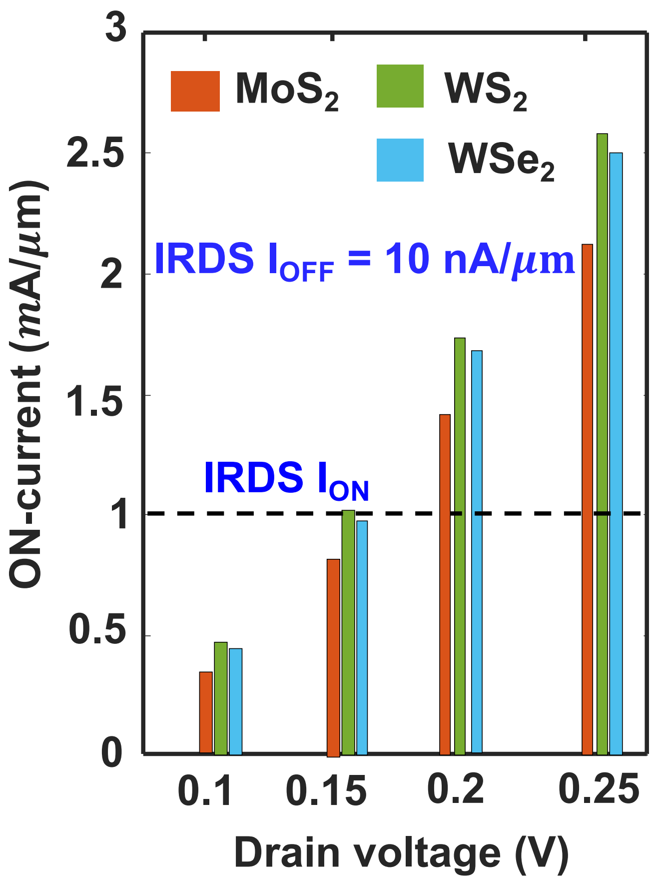
$$I_D = \frac{2q}{\hbar}\int_{-\infty}^{\infty} M(E)T(E)\big(f_S(E) - f_D(E)\big)dE$$

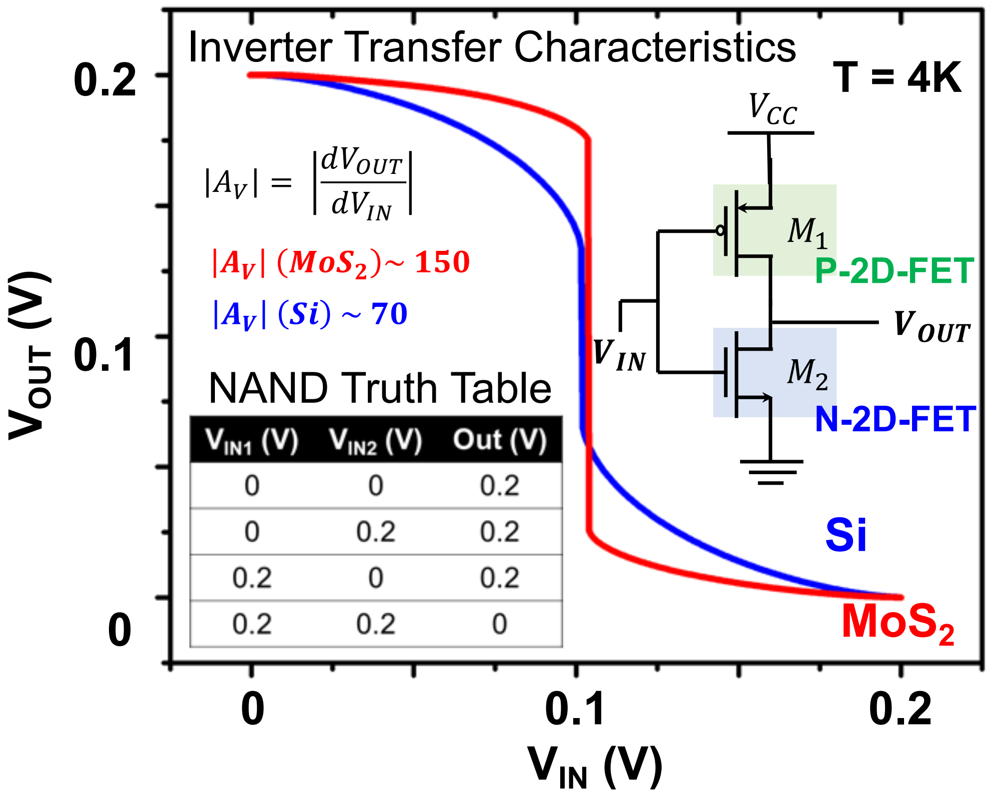
Compact model which incorporates the effect of band-tails!

Digital Circuit Performance at CT



Better digital performance of 2DMs as compared to Si!

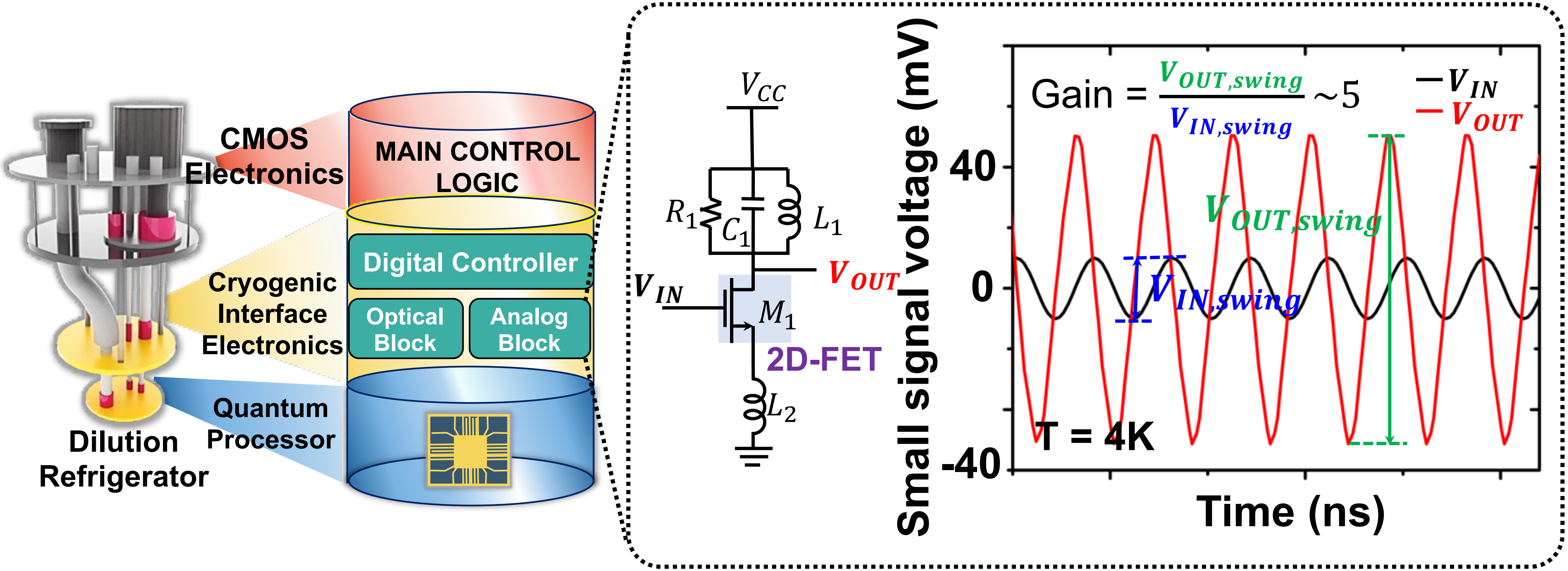




NAND Truth Table

V_{IN1} (V)	V_{IN2} (V)	Out (V)
0	0	0.2
0	0.2	0.2
0.2	0	0.2
0.2	0.2	0

Analog Circuit Performance at CT

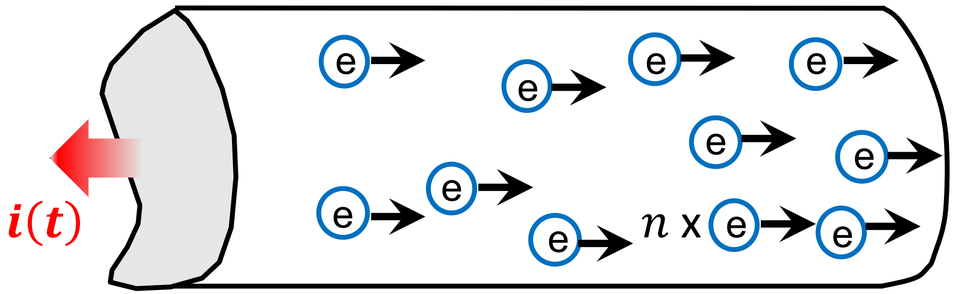


- LNA- building block of analog controllers

Better analog performance as compared to Si (Gain: ~5 for MoS_2 vs ~3.5 for Si)

Noise at CT (1)

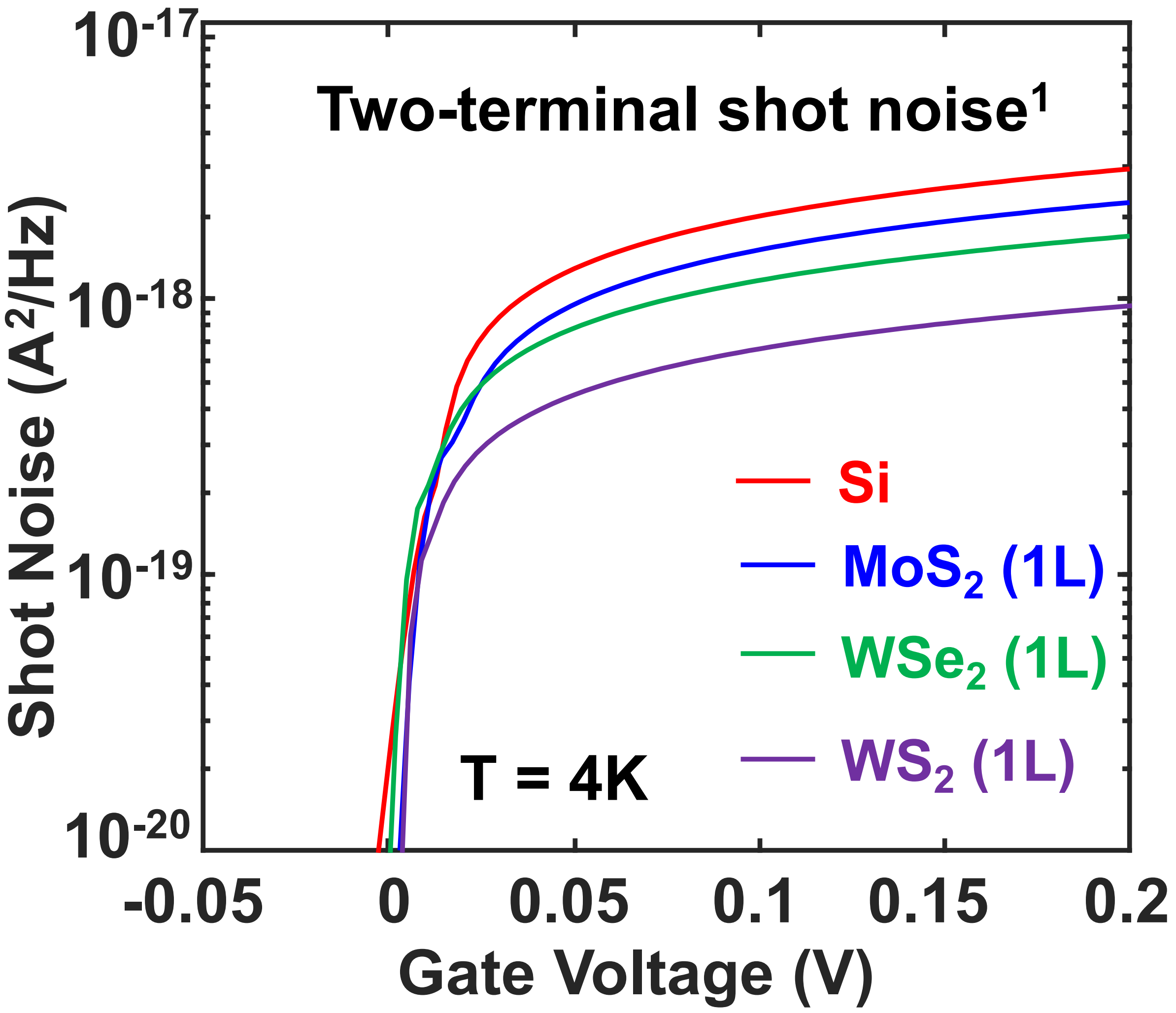
Shot Noise



- Shot noise → Quantum nature of charge

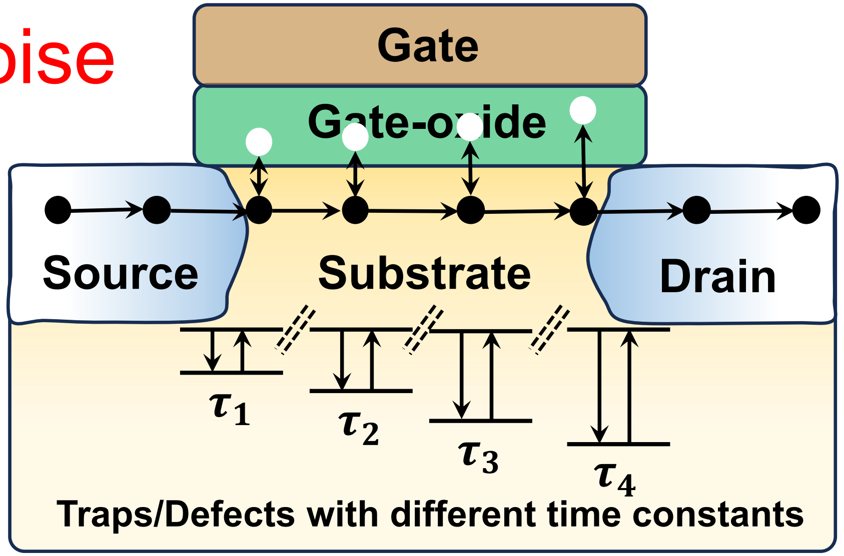
- Determines the level of white (background) noise at CTs

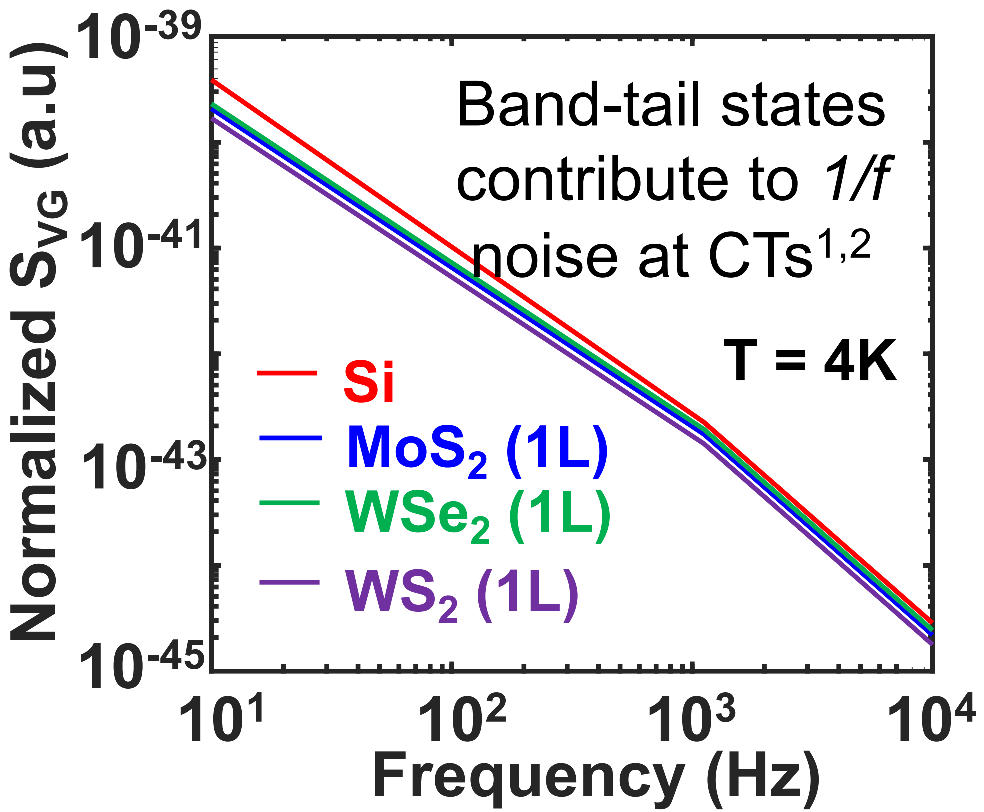
2DMs posses lower shot noise as compared to bulk Si!



Noise at CT (2)

$1/f$ Noise





- Contributed by traps/defects/scattering
- $I \propto nq\mu \Rightarrow \delta I \propto \underbrace{(\delta n)q\mu}_{\text{Carrier number fluctuation}} + \underbrace{nq(\delta\mu)}_{\text{Mobility fluctuation}}$

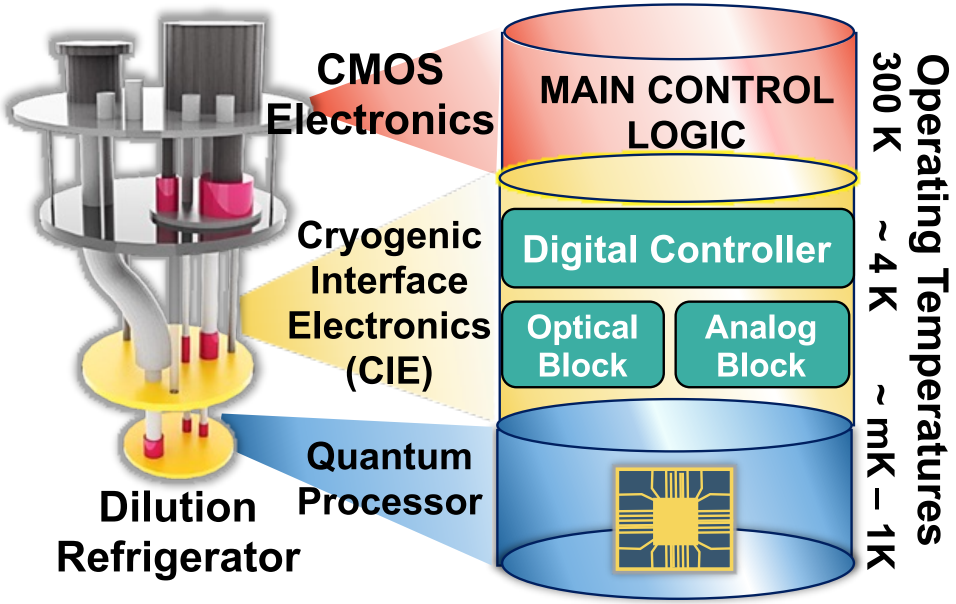
Lower band-tail states in 2DMs (w.r.t Si) enable lower $1/f$ noise!

[1] R. Asanovski, *et. al.*, *IEDM, 2022*. [2] X. Xie/K. Banerjee, *ACS Nano*, 2014.

Summary

- **First comprehensive study of 2D materials-based CIE**
- **Significant energy and performance benefits w.r.t bulk materials (Si)**
- **Better immunity against $1/f$ and shot noise at CTs w.r.t bulk materials (Si)**
- **Unique 2D-cryo-CMOS compact model incorporating band-tails**
- **2D-materials make ideal digital/analog CIE components**

2D-materials enable large-scale quantum computing!!



Device Metric (w.r.t Si) (T= 4K)	MoS_2	WSe_2	WS_2
Energy ↓	67%	69%	61%
Power ↓	89%	96%	91%
EDP ↓	96%	97%	99%
Shot Noise ↓	15%	30%	58%
Flicker Noise (1/f) ↓	46%	41%	58%