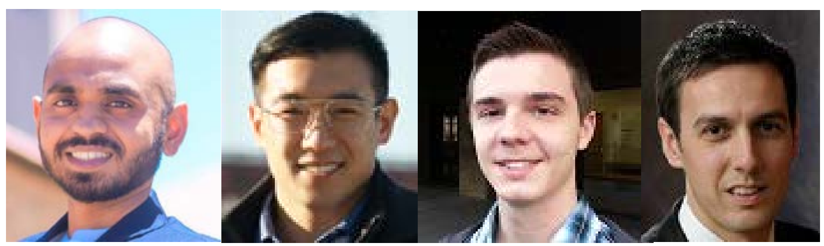
NEEDS Workshop at Stanford: June 21, 2017

2D Materials and Graphene: Science to Nanofunctions

Saurabh Suryavanshi & Eric Pop
Stanford University



Experimental collaborators: Ning Wang, Kirby Smithe (Pop group)
Industry collaboration: ARM, Lam, Northrop Grumman + CEA LETI

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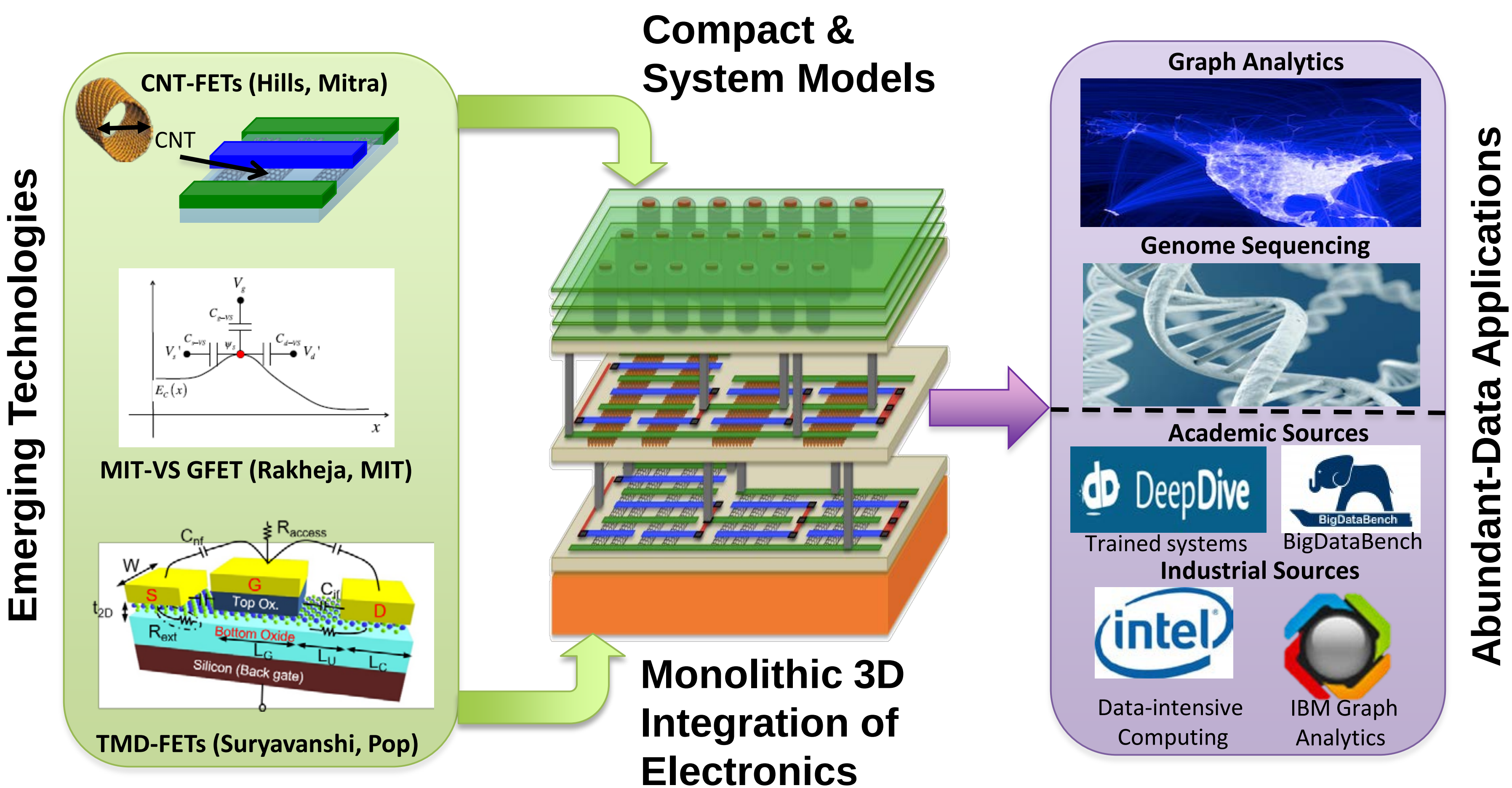
Introduction

Compact device models do not exist by themselves but as part of a system



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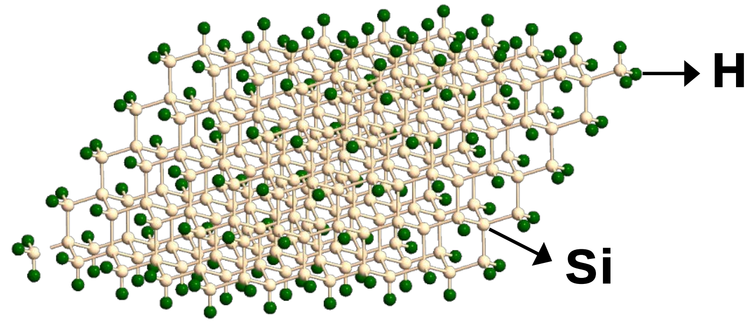
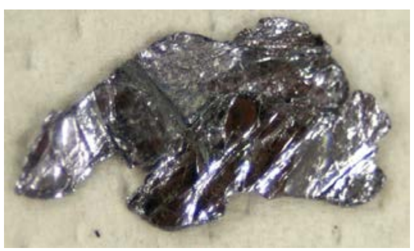
2D materials or Layered materials

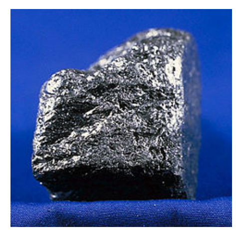
Crystal images taken from Wikipedia.org

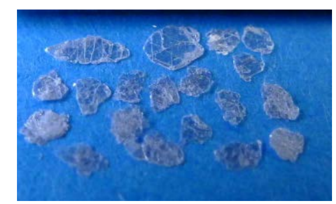
Silicon

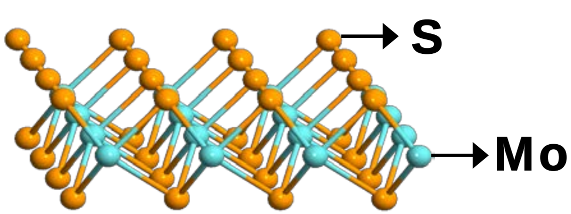


- Atomically thin, no surface dangling bond

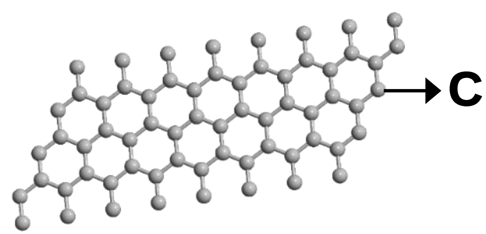




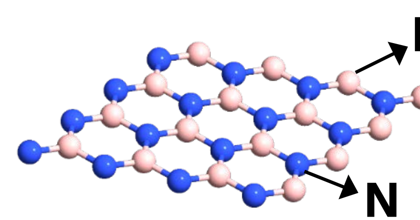




MoS_2



Graphene



h-BN

- Semiconducting(MoS_2), Semimetallic (graphene), Insulating(BN)$_3$

2D Materials to Systems (Today)

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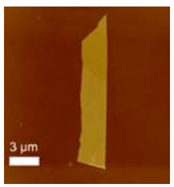

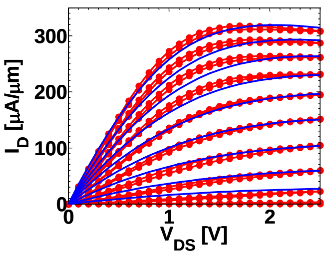

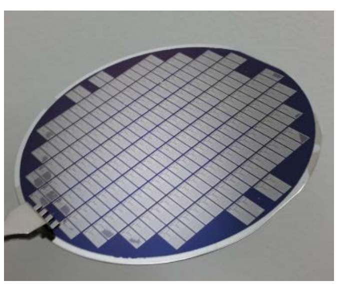

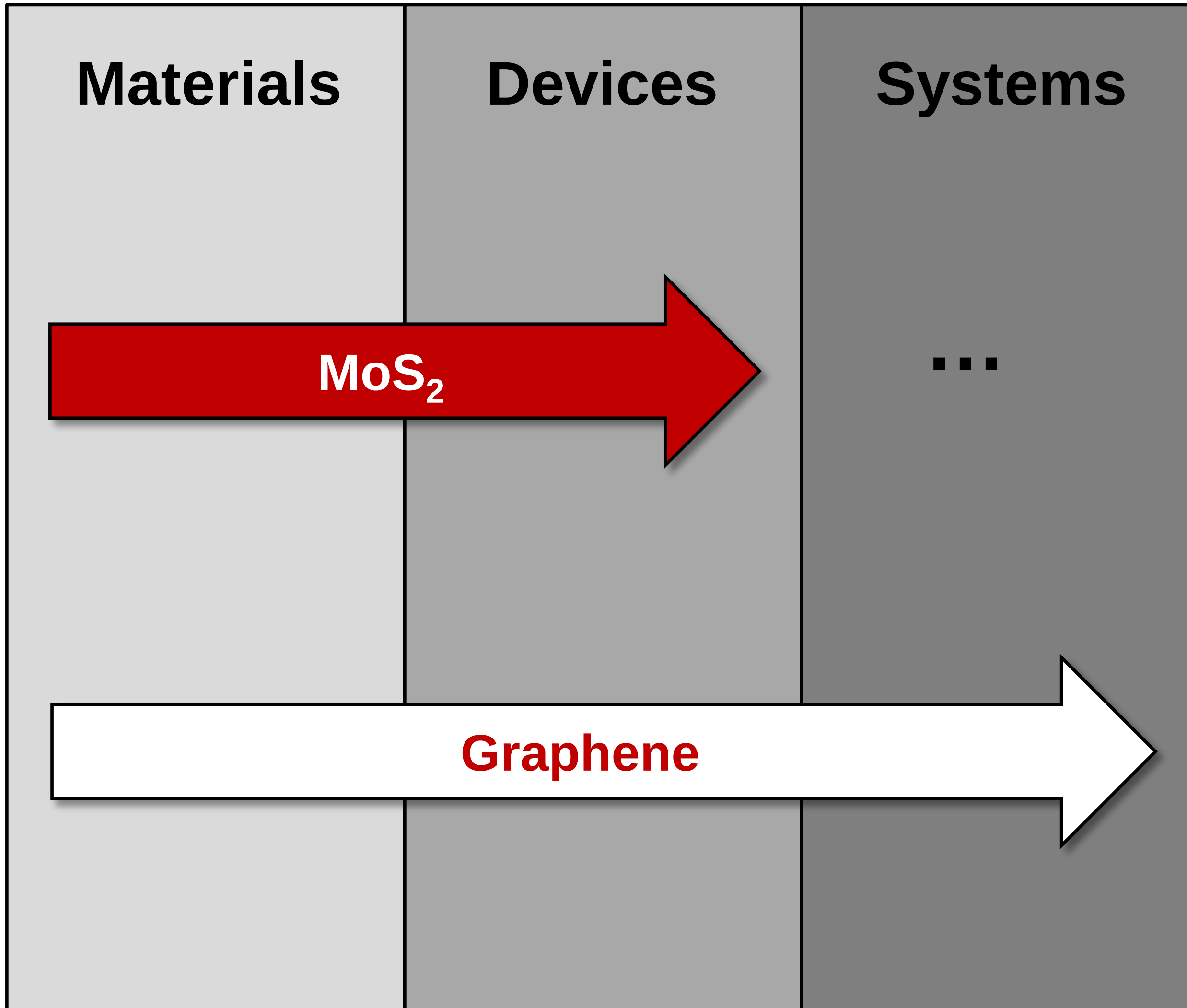

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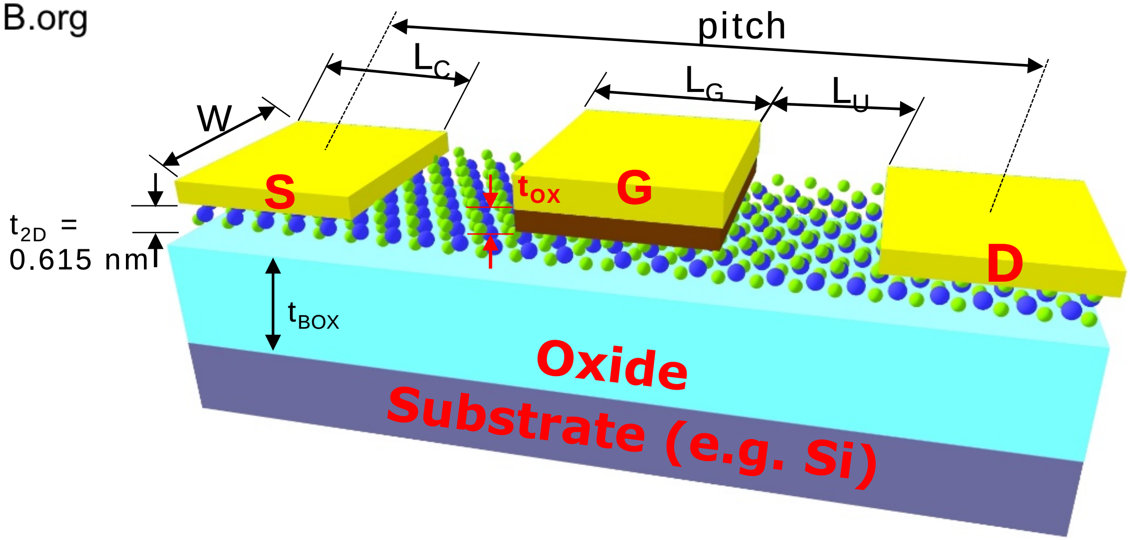
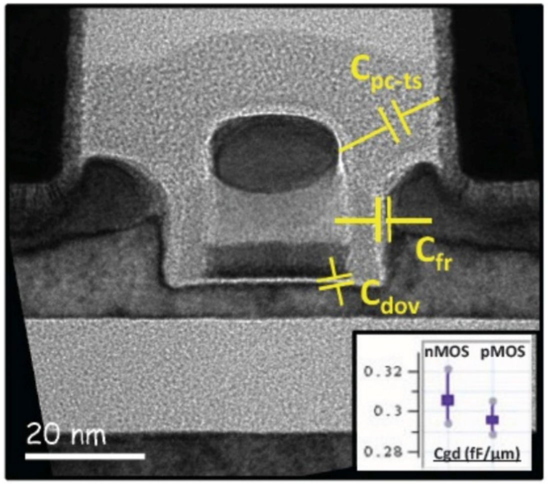
2D Field Effect Transistors

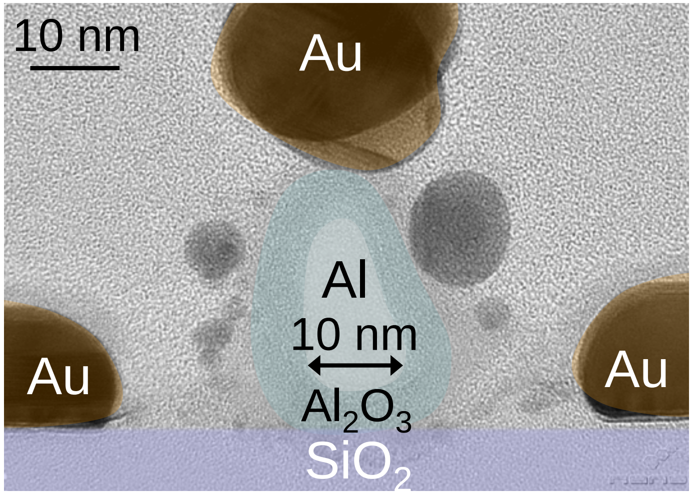


“14 nm” FD SOIFET



(O. Weber et al., VLSI Technology, 2014)[LETI, IBM]

“14 nm” MoS_2 on oxide FET



(C. D. English; E. Pop et. al, IEDM, 2016) [Stanford]

S2DS: Physics-Based Compact Model

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S. V. Suryavanshi and E. Pop, *J. Applied Phys.* **120**, 224503 (2016)

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Stanford 2D Semiconductor (S2DS) Transistor Model 1.1.0

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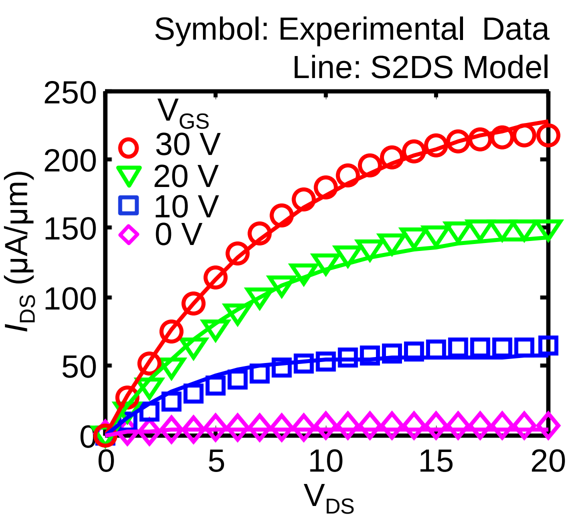
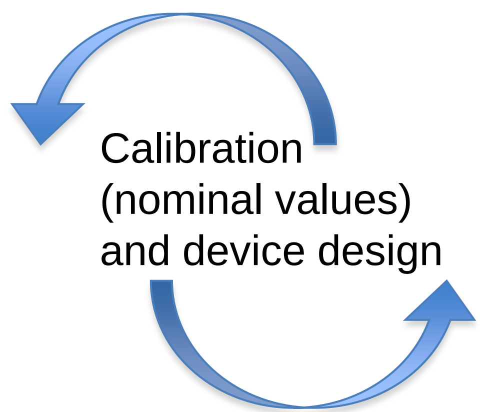
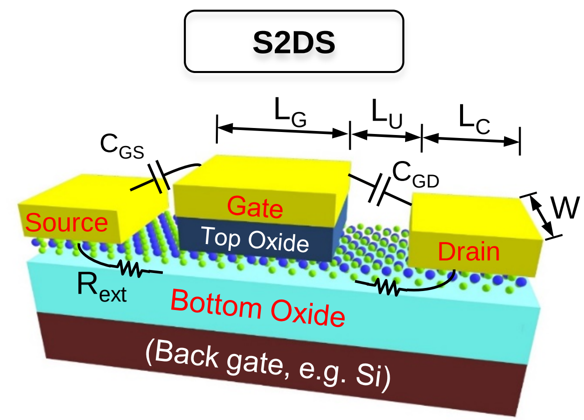
Additional materials available

Version 1.1.0 - published on 04 Apr 2016

doi:10.4231/D3ZC7RV9X - cite this







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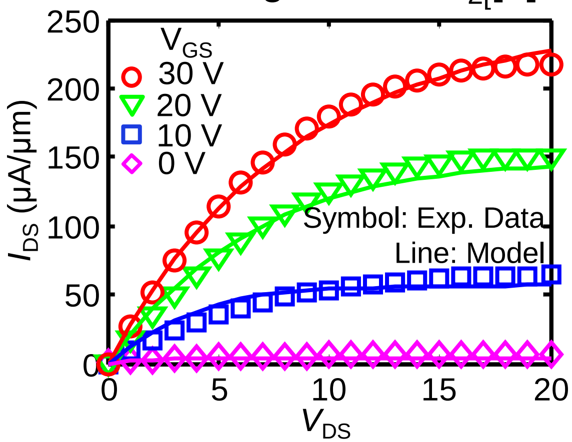
S2DS: Physics-Based Compact Model

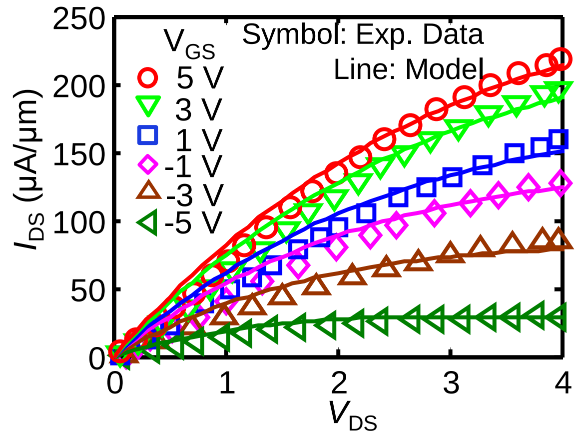
S. V. Suryavanshi and E. Pop, *J. Applied Phys.* **120**, 224503 (2016)

- S2DS, key highlights:
  a) Emphasis on agreement with experimental data
  b) Simulate sub-100 nm channel lengths
  c) 2D channel and quantum capacitance
  d) Mobility: temperature, field, traps and doping
  e) Self-heating considering anisotropy

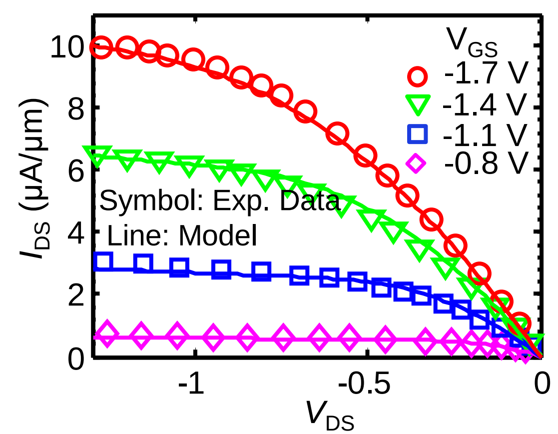
Back gated MoS_2[1]



Top gated MoS_2 [2]



Top gated WSe_2 [3]



[1] Kirby Smithe and Eric Pop, unpublished
[2] A. Sanne et al., Nano Letters, 15, 5038-5045 (2015)
[3] H. Fang et al., Nano Letters, 12, 3788-3792 (2012)

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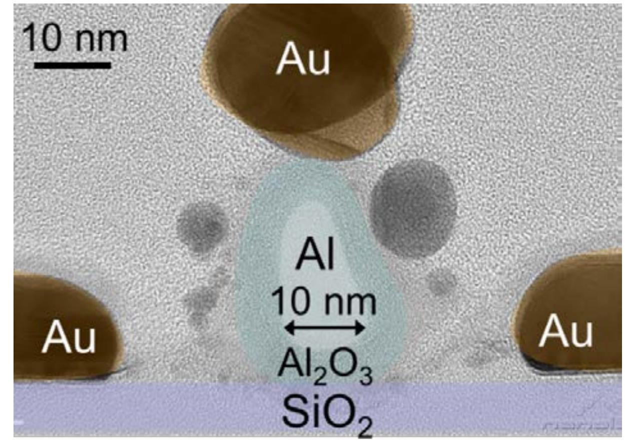
2D for Sub-10 nm: Challenges

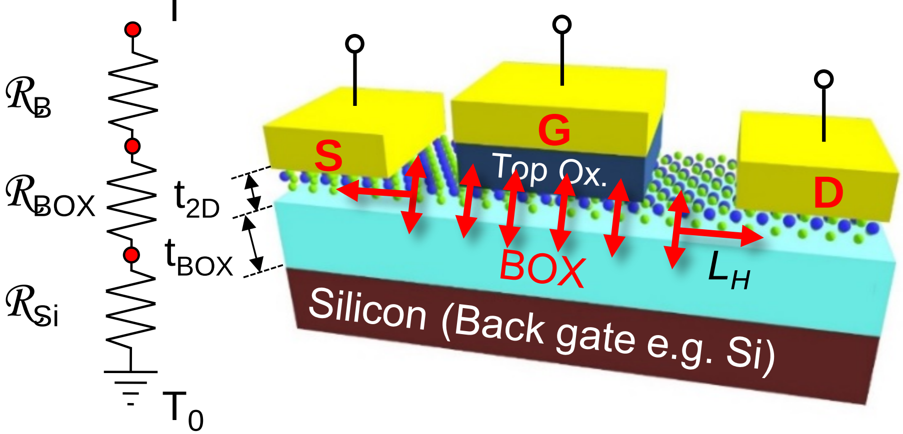
S. V. Suryavanshi and E. Pop *(in preparation)*

C. English, E. Pop, *et al*. IEDM (2016)

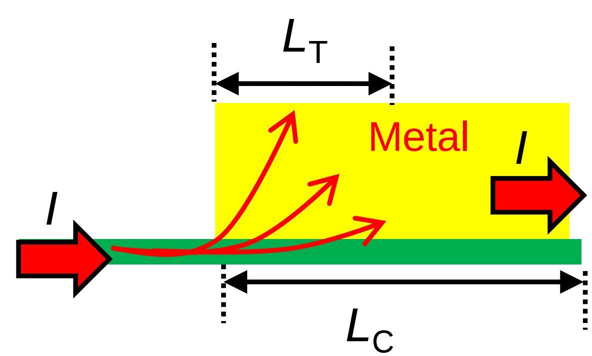


- Importance of scaled devices
- Physical understanding helps to develop better models and guide experimental efforts

Thermal Resistance (R_{TH})



Contact Resistance (R_C)



Self-Heating – Experiment & Models

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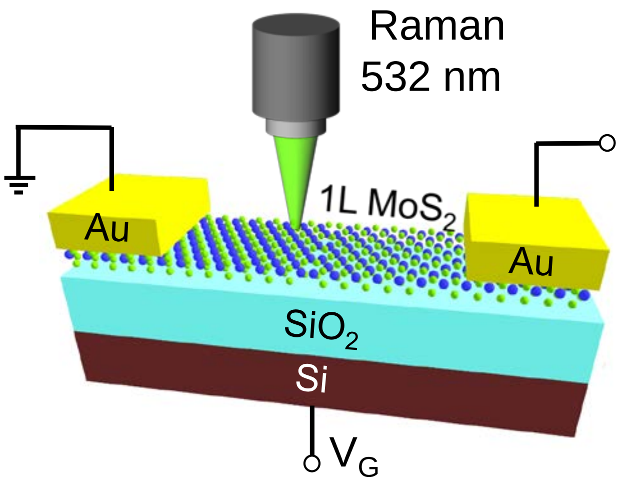
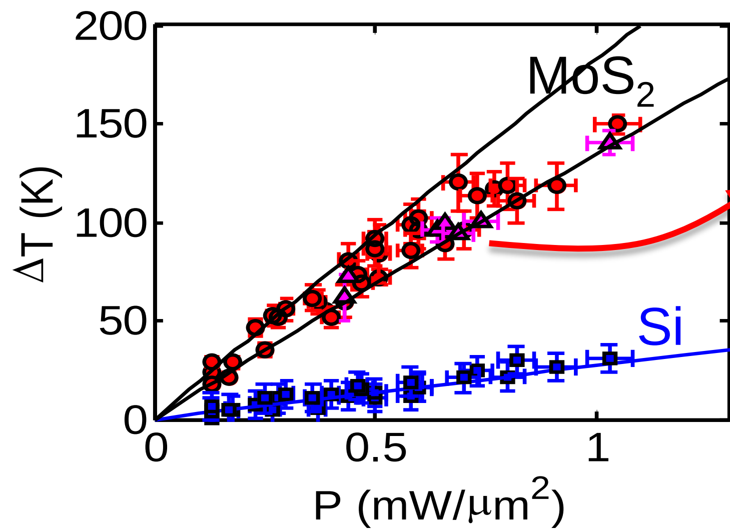
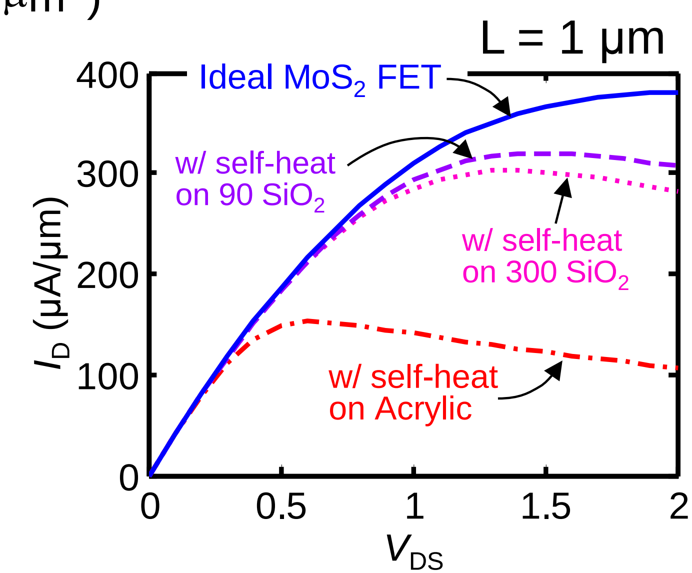
S. V. Suryavanshi and E. Pop, *J. Appl. Phys.* 120, 224503 (2016)
E. Yalon, …, S.V. Suryavanshi, E. Pop et al., *Nano. Lett.*, 2017





slope gives TBR ~ 6 to 10 x 10^{-8} Km^2/W

(50x higher than Si-SiO_2 TBR)



- Raman thermometry **verifies our thermal models**
- MoS_2-SiO_2 thermal boundary resistance (TBR) accounts for 30% of R_{TH}
- Perfect heat sinking could boost I_D > 20%

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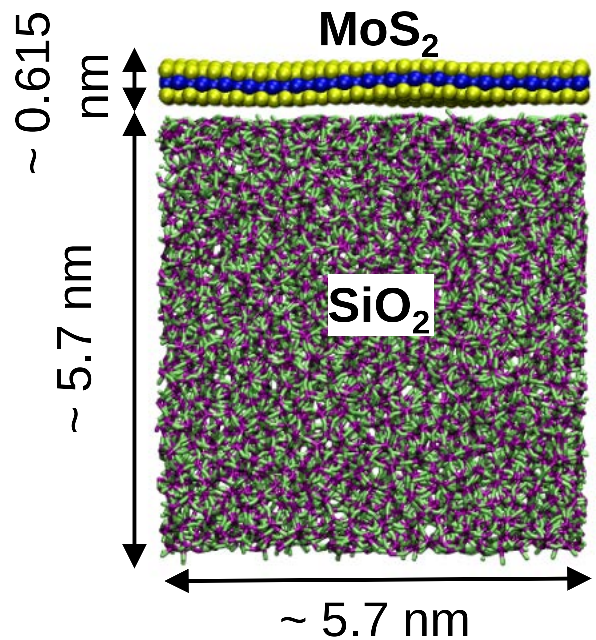
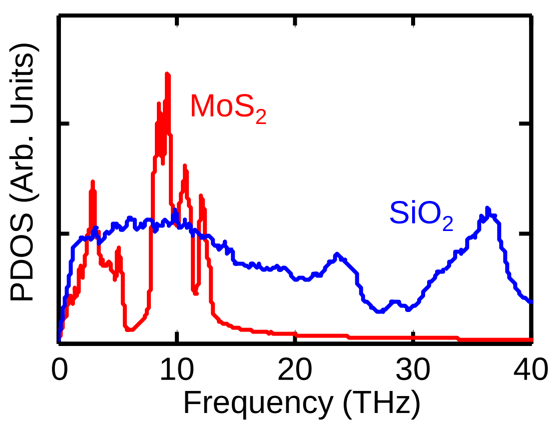
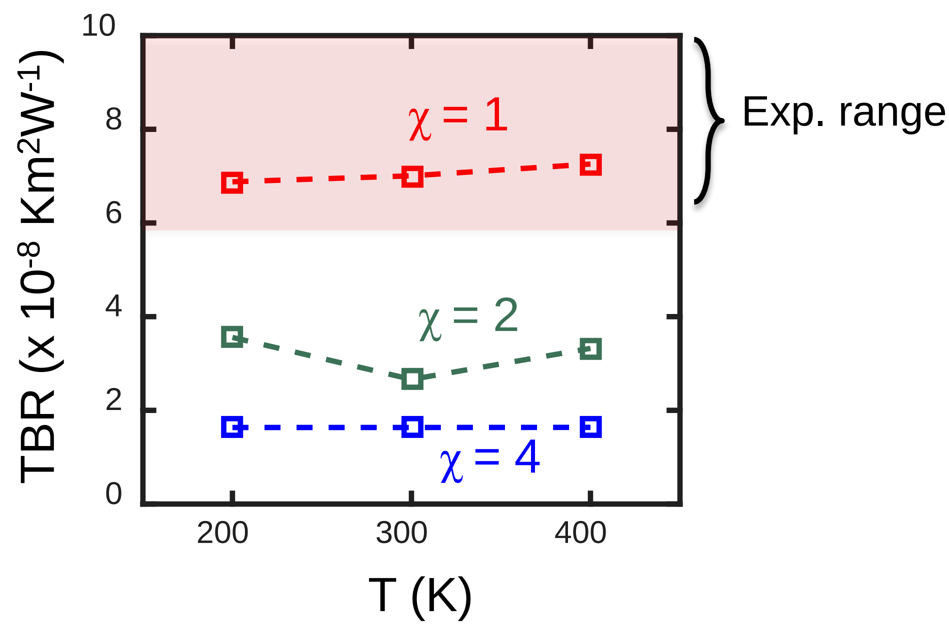
Self-Heating – Reducing TBR

S. V. Suryavanshi, E. Pop et al., *IEEE Nano*, 2017





Molecular Dynamic (MD) Simulations



- χ is the interaction strength between MoS_2 and SiO_2
- Increasing χ or making the interface cleaner could decrease the TBR

Contact Resistance – Crowding

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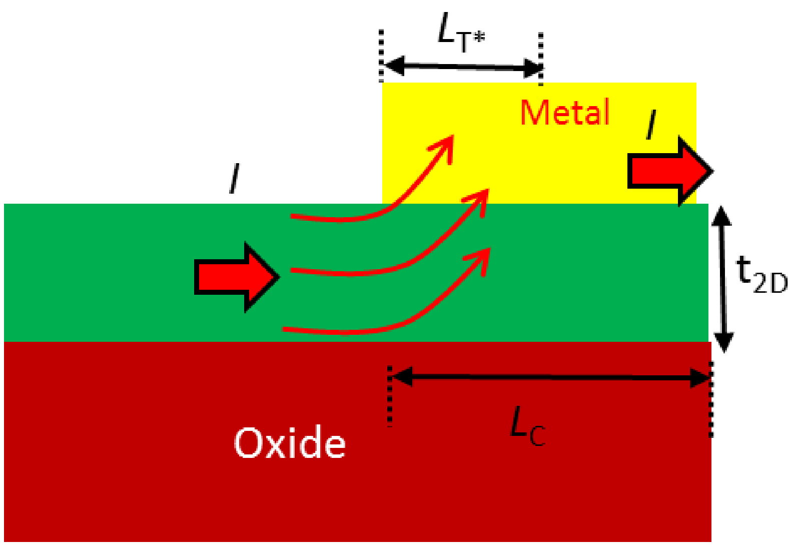
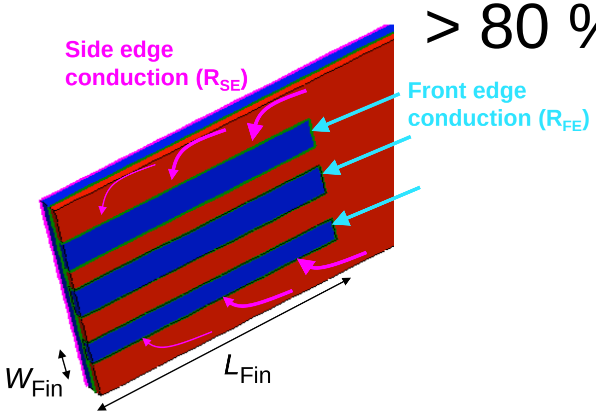
S. V. Suryavanshi and E. Pop (in preparation)

Significant current crowding…

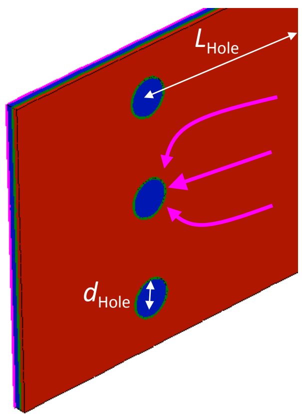
- Material property ($\propto \mu_{in}/\mu_{out}$)
- Contact geometry ($\propto t_{2D}/L_T$)
- Contact depletion ($\propto \exp(\varphi_B)/t_{2D}$)
- Intrinsic contact resistivity



✓ Current crowding can be reduced by contact patterning



> 80 % reduction



> 30 % reduction

Contact Resistance – Intrinsic Limit

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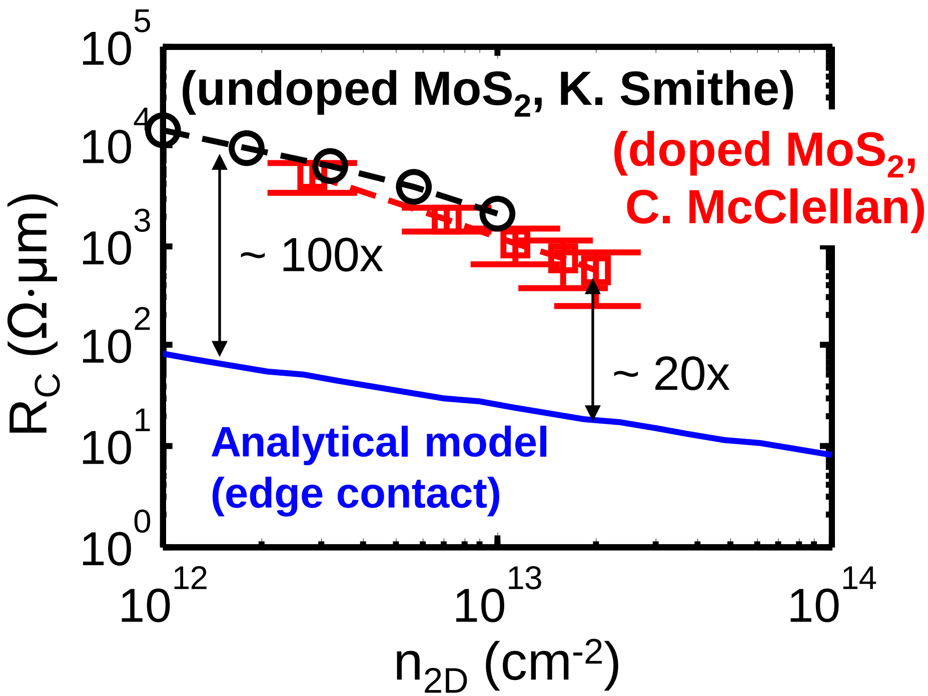
S. V. Suryavanshi and E. Pop (in preparation)
C. McClellan, …, S.V. Suryavanshi, E. Pop, DRC, 2017



- Landauer model (J. Maassen et al., APL, 2013)
- Assumptions:
  - Single parabolic band structure
  - T = 0 K

$$\frac{1}{\rho_C^{LL}} = \frac{4q^2}{h}\int_{-\infty}^{\infty} M(\varepsilon)T(\varepsilon)\left[-\frac{df}{d\varepsilon}\right]d\varepsilon$$

✓ Large carrier density increases the number of modes

✓ Doping reduces the transmission

✓ Making cleaner interface (C. English, E. Pop et al., *Nano Lett.*, 2016)

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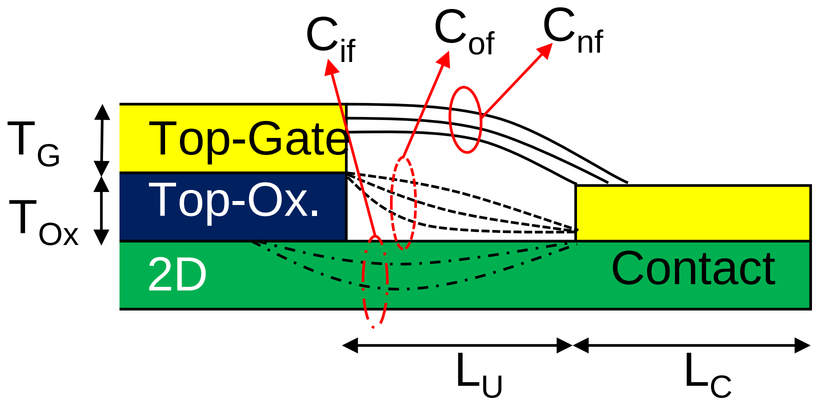
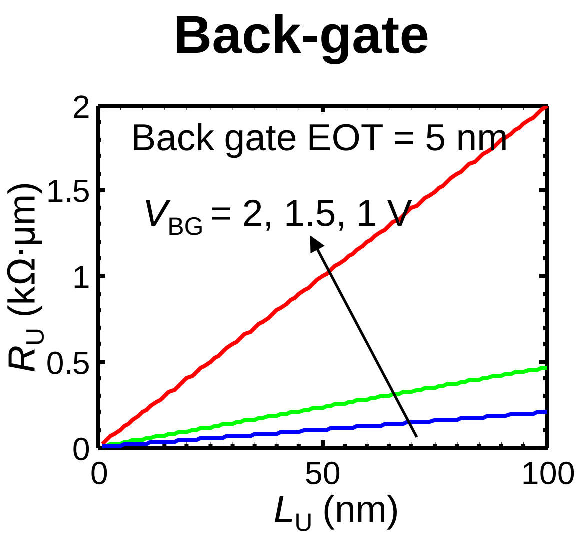
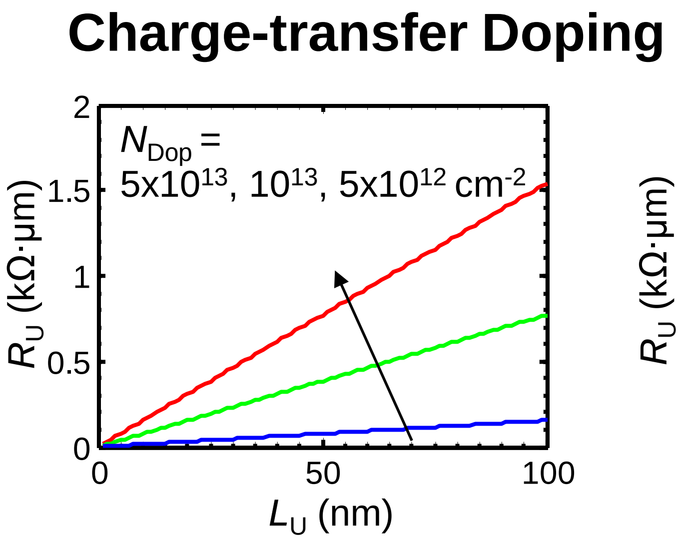
Device Optimization, Design and Benchmarking

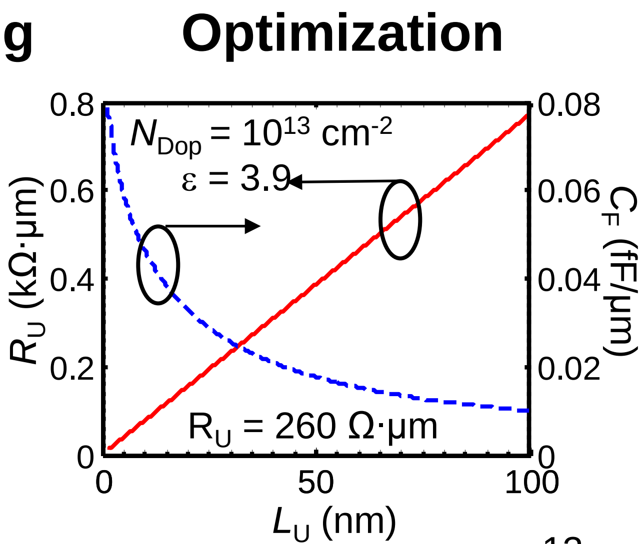
S. V. Suryavanshi and E. Pop, *J. Applied Phys.* **120**, 224503 (2016)



S2DS includes analytical forms for fringe capacitances and external resistances







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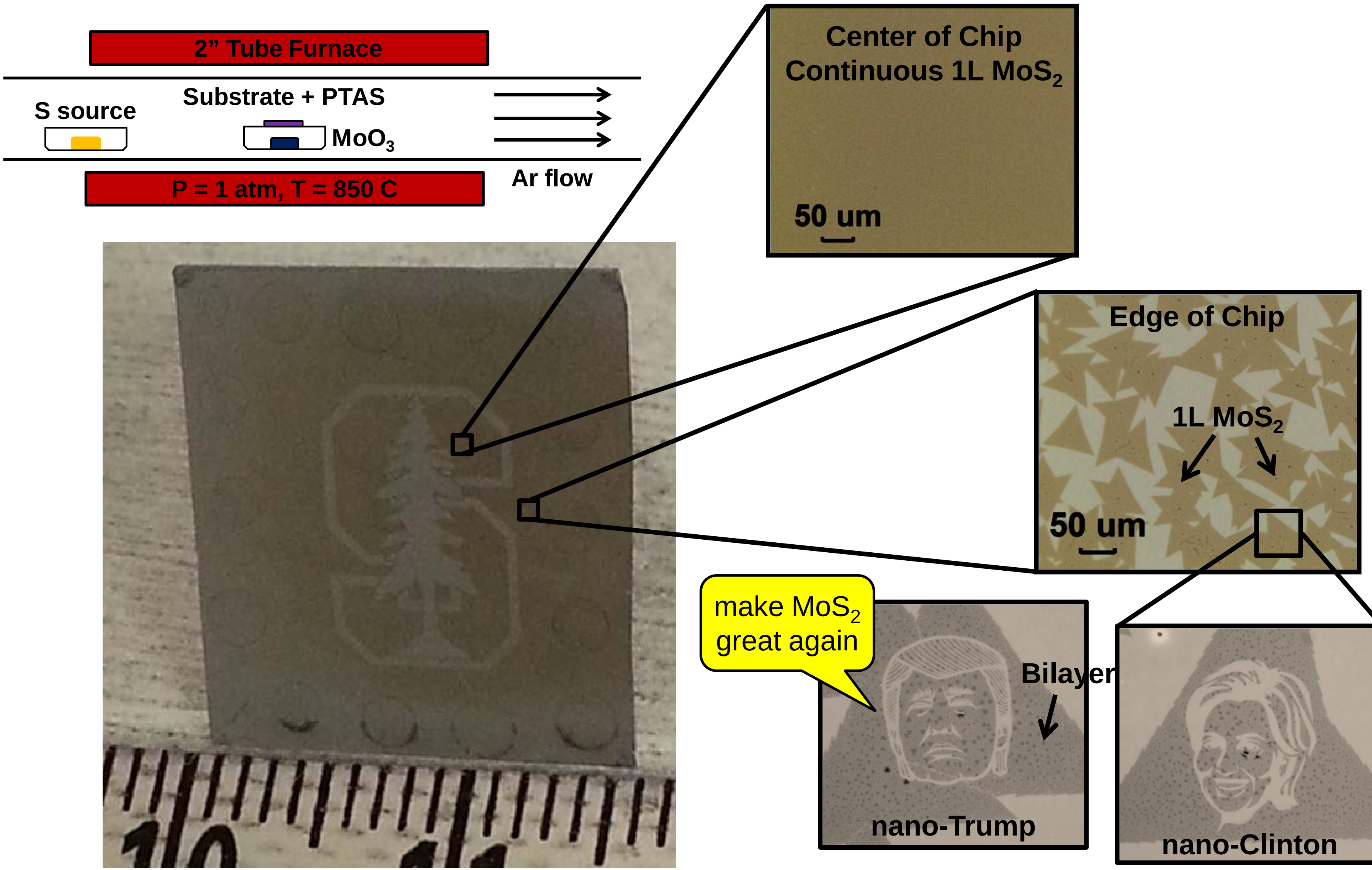
Large-Area MoS_2 Grown by CVD

K.K.H. Smithe, C. D. English, S. V. Suryavanshi, and E. Pop, *2D Mater.* **4** 0110009 (2017).



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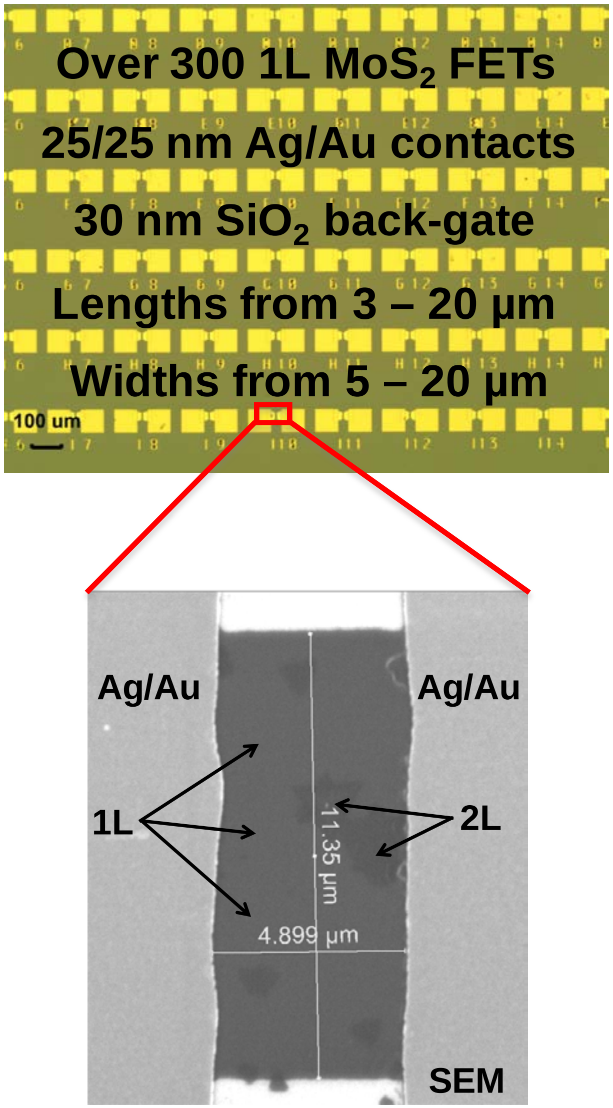
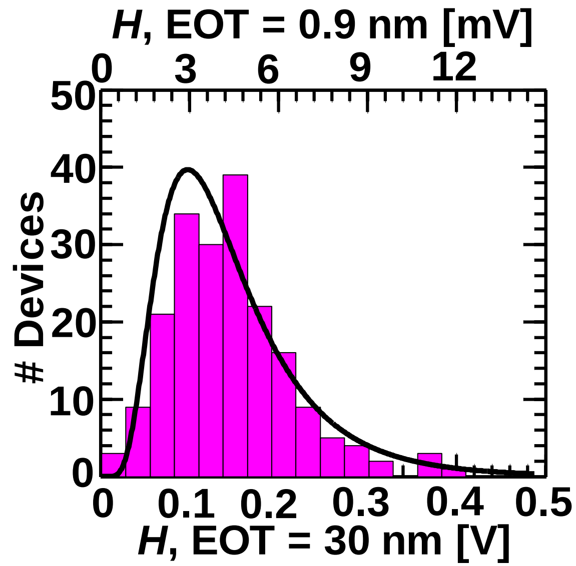
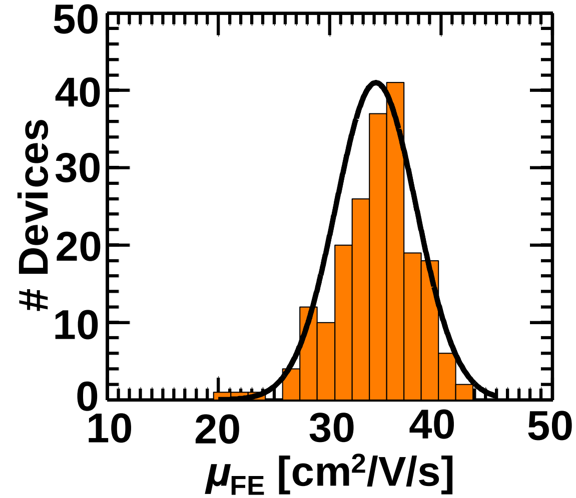
Scaling Up MoS_2 - 100s of devices

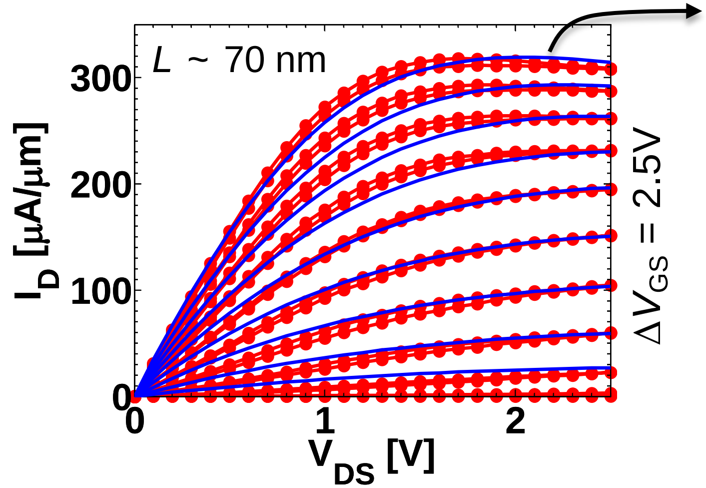
K.K.H. Smithe, S. V. Suryavanshi, E. Pop et al., in review, 2017

Over 300 1L MoS_2 FETs
25/25 nm Ag/Au contacts
30 nm SiO_2 back-gate
Lengths from 3 – 20 µm
Widths from 5 – 20 µm









S2DS model simulations

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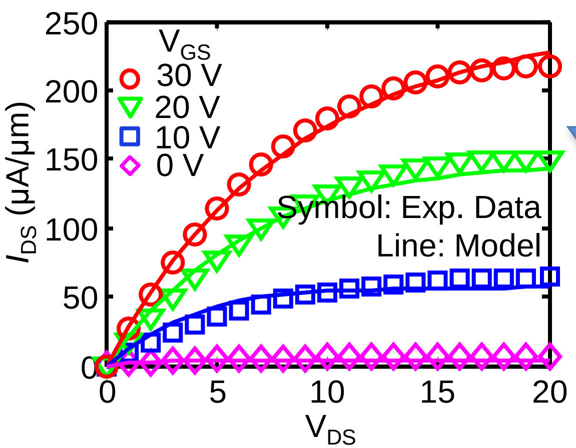
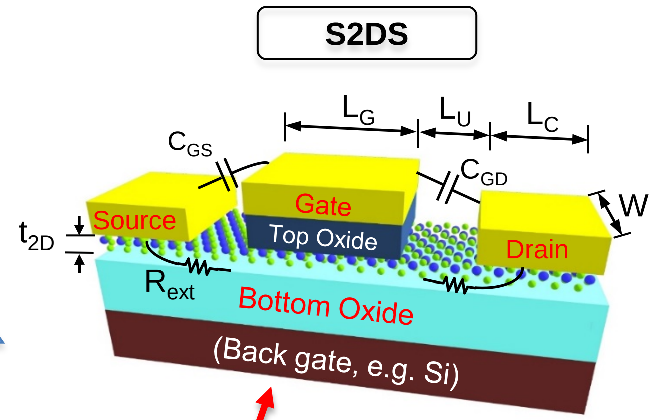
Modeling Variability in 2D Nanofabrics

S. V. Suryavanshi and E. Pop, *J. Applied Phys.* **120**, 224503 (2016)
K.K.H. Smithe, S. V. Suryavanshi, E. Pop et al., in review, 2017

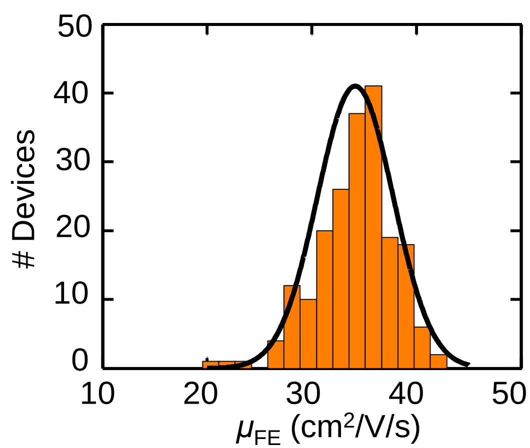
Device data



Calibration
(nominal values)
and device design



Variability



Variation model (***New***)
(Coefficient of variation, CV)

$$\begin{bmatrix} R_C \\ v_{sat} \\ \mu_{eff} \\ n_{IMP}, V_T \\ (x_i, y_i, z_i) \\ \vdots \end{bmatrix}$$

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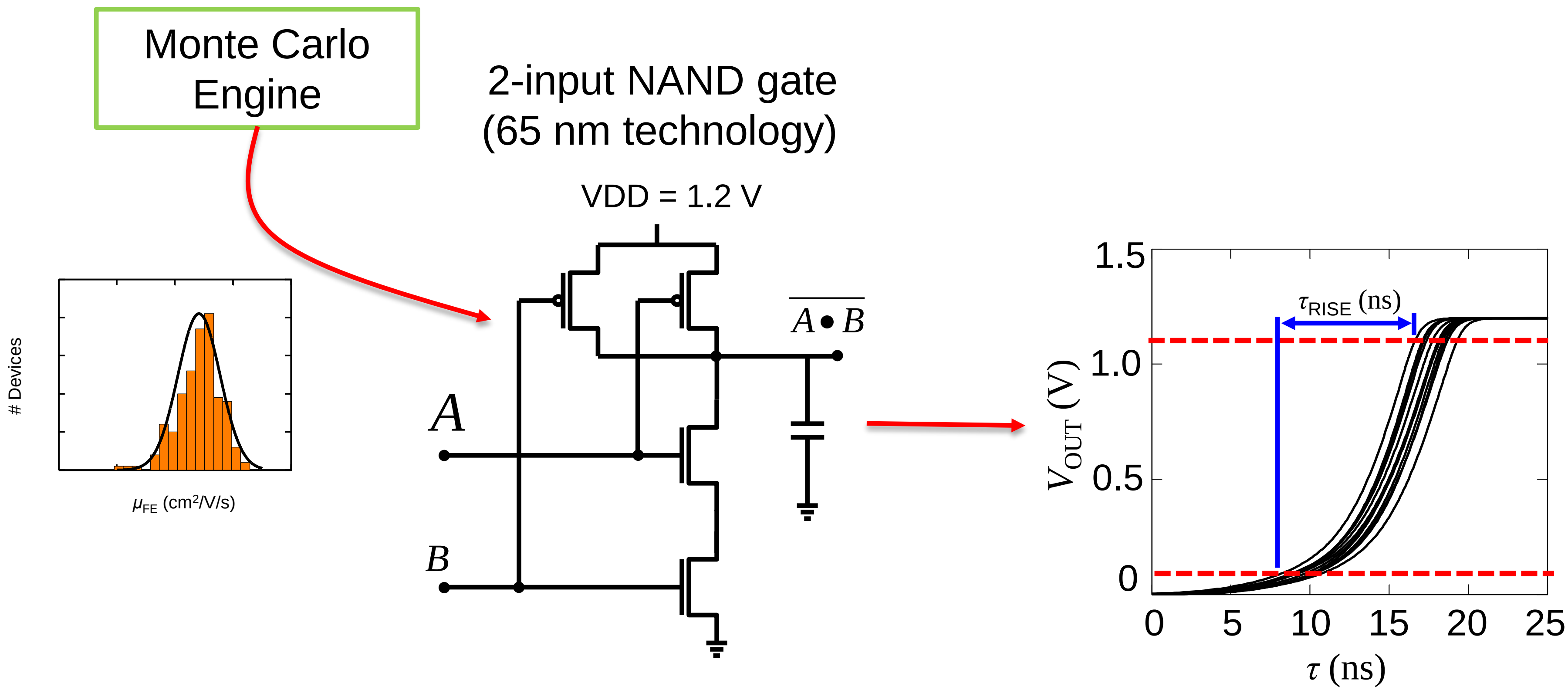
Variability in 2D *Nanofunctions*

K.K.H. Smithe, S. V. Suryavanshi, E. Pop et al., in review, 2017



- Monte Carlo simulations to assess the effective variability in nanofunctions
- Can be extended to any circuits and systems

Variability in 2D *Nanofunctions*

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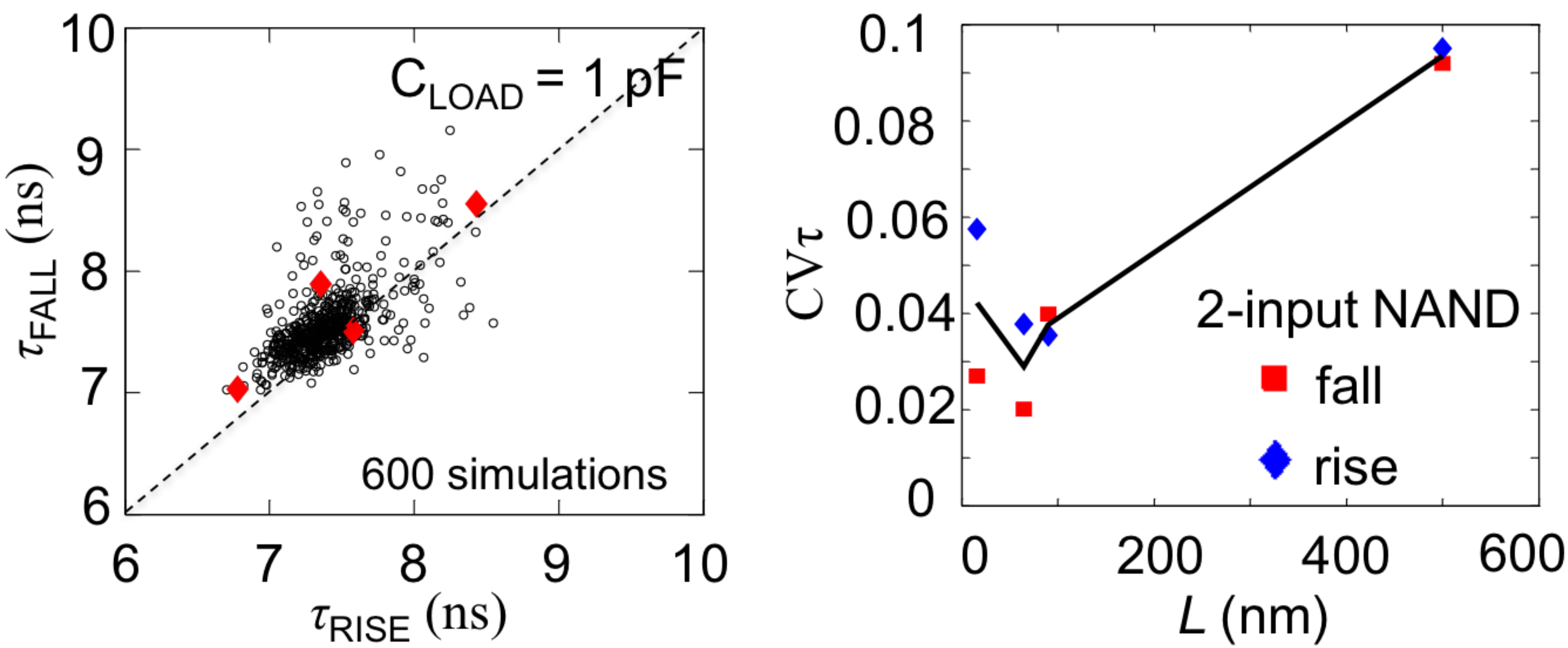
K.K.H. Smithe, S. V. Suryavanshi, E. Pop et al., in review, 2017



- Bi-layer islands do not cause significant variation for n-type devices
- We can do similar Monte Carlo calculations for nanofunction *energy*
- **Future work:** how does variation affect the EDP in large circuits?

Variability in 2D Nanofabrics

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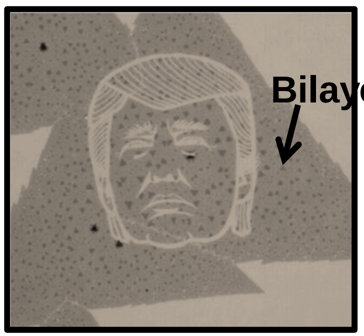
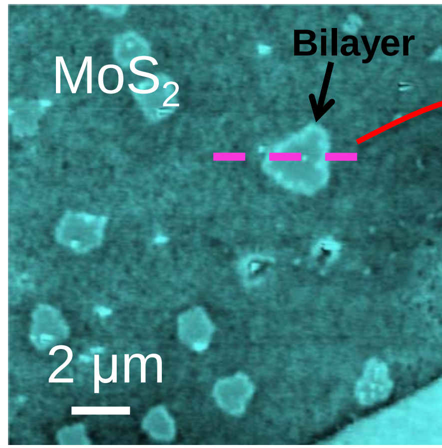
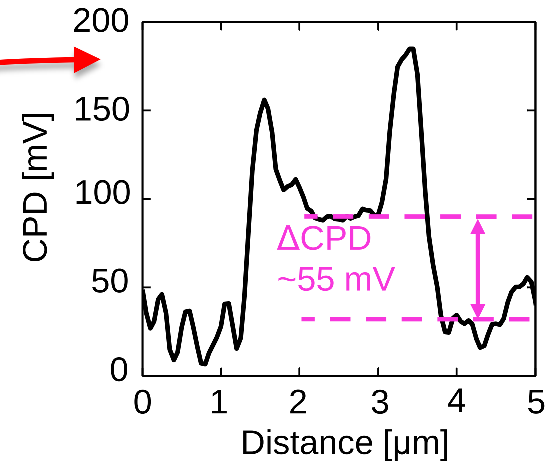
K.K.H. Smithe, S. V. Suryavanshi, E. Pop et al., in review, 2017

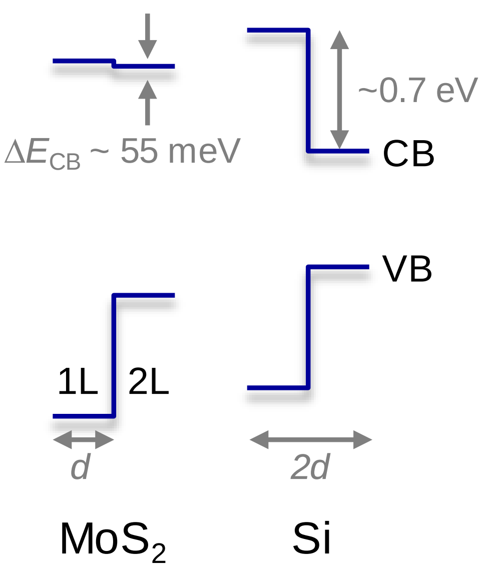


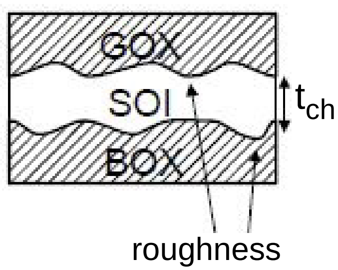


(SKPM: Miguel Minoz)



(*CPD – contact potential difference)





- Less variation in V_T due to smaller band offset in conduction band (CB)
- Silicon, for similar thickness variation, will have >10x larger CB variation

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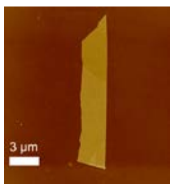
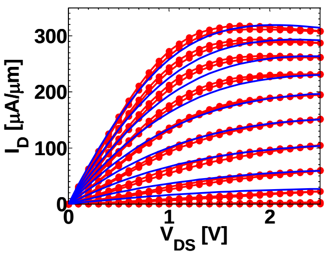
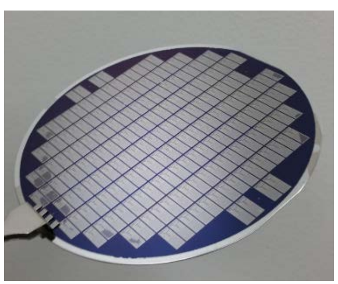
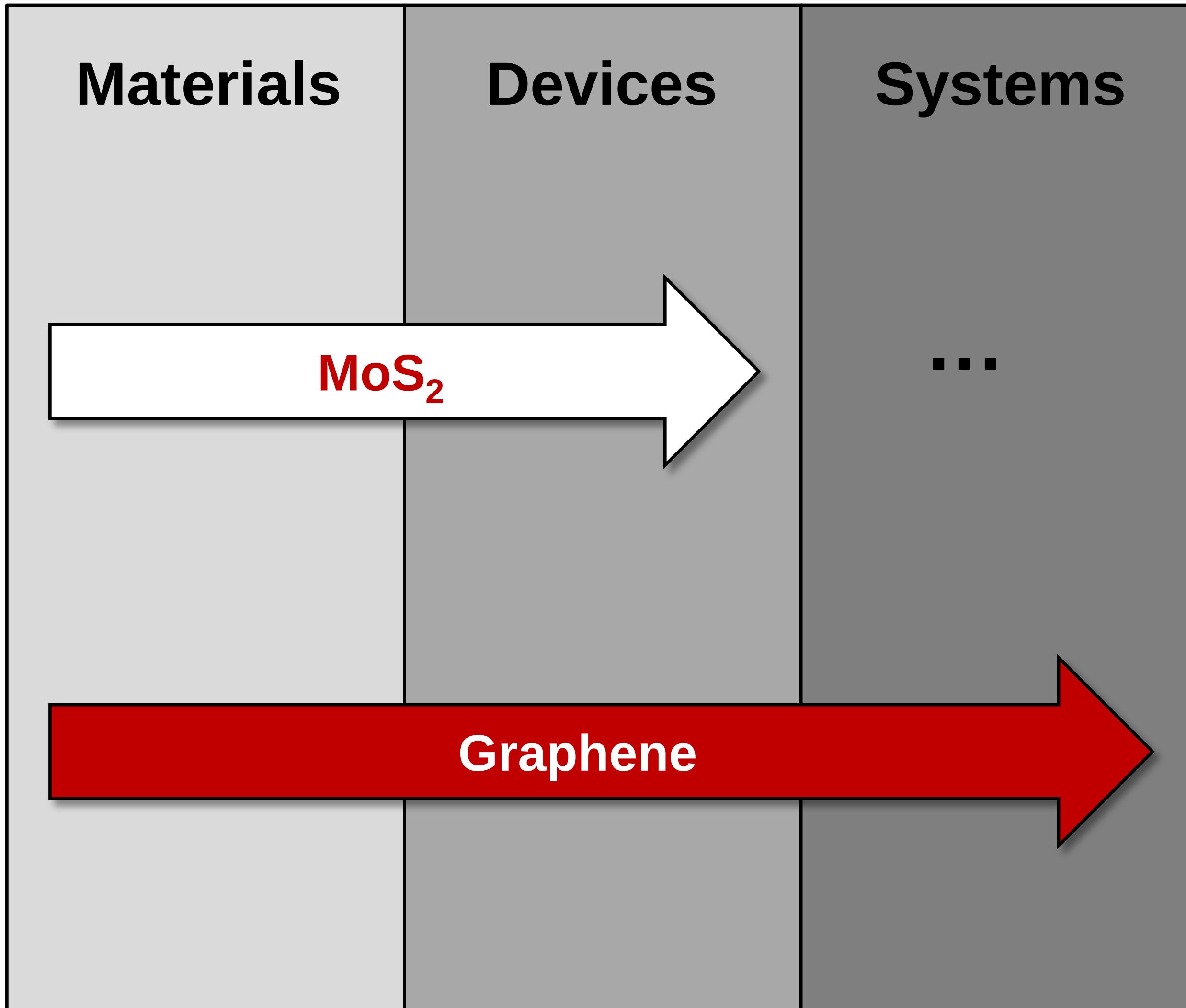
2D Materials to Systems (Today)

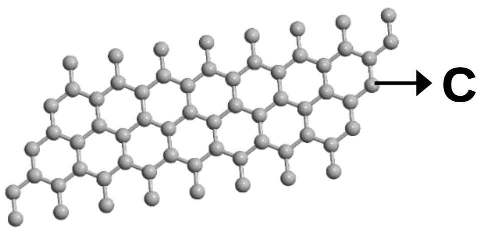




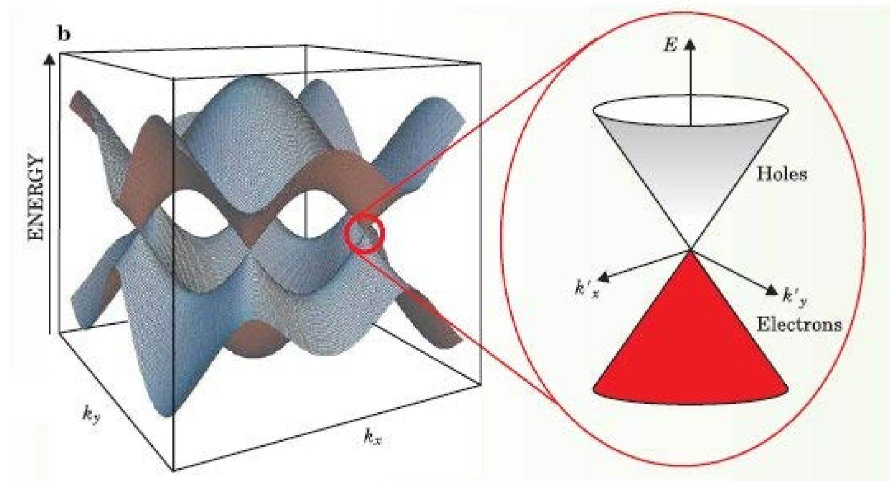




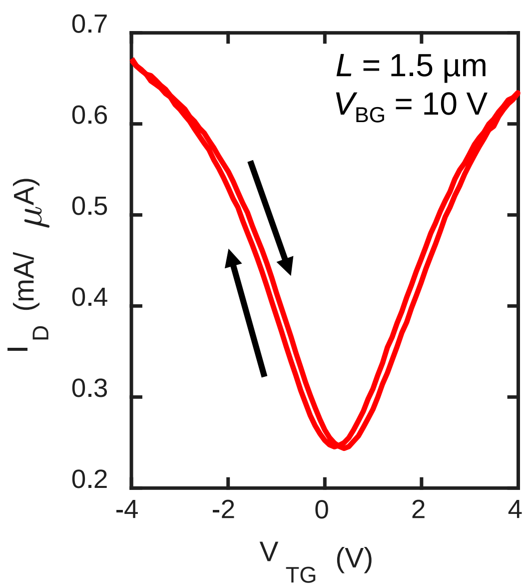
Graphene - Introduction

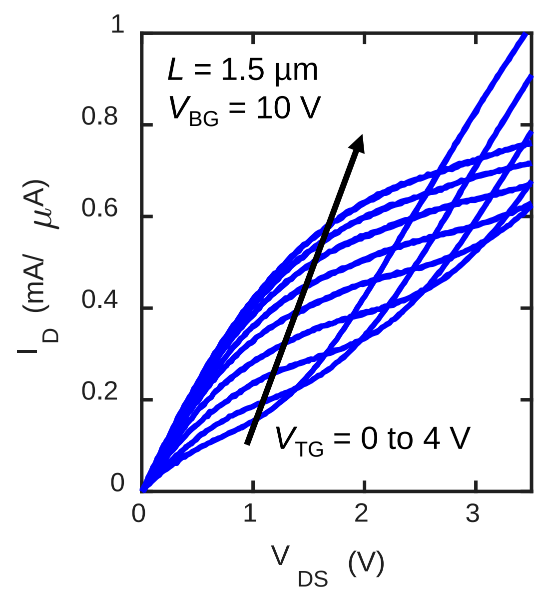


Graphene



- Low on-off ratio
- Poor current saturation





Graphene Dot Product Nanofunction

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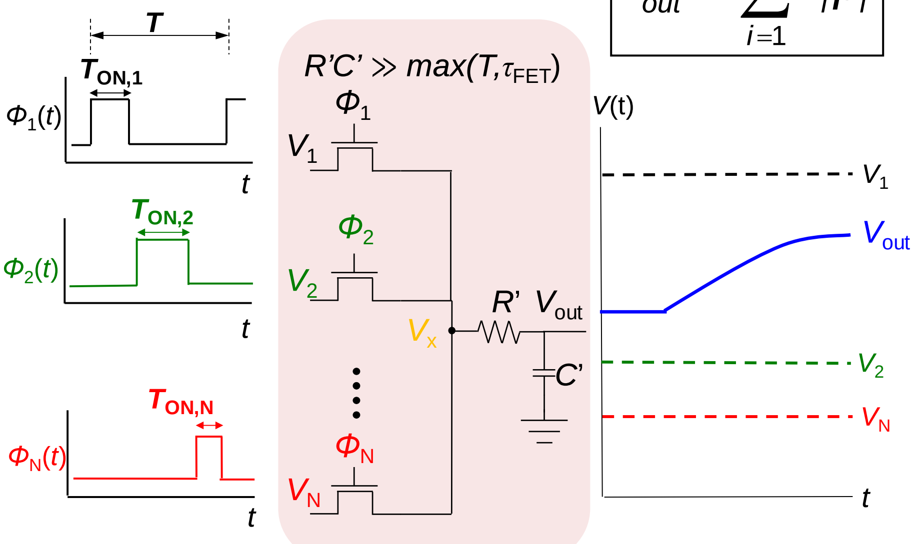
N. Wang, S. Gonugondla, I. Nahlus, N. Shanbhag, E. Pop, *VLSI Symp.* (2016)

- **Dot product** nanofunction used for image processing, neural networks…
- Takes advantage of native graphene properties (**high μ**, flexible…)
- Tolerates graphene drawbacks (low I_{ON}/I_{OFF} ratio)

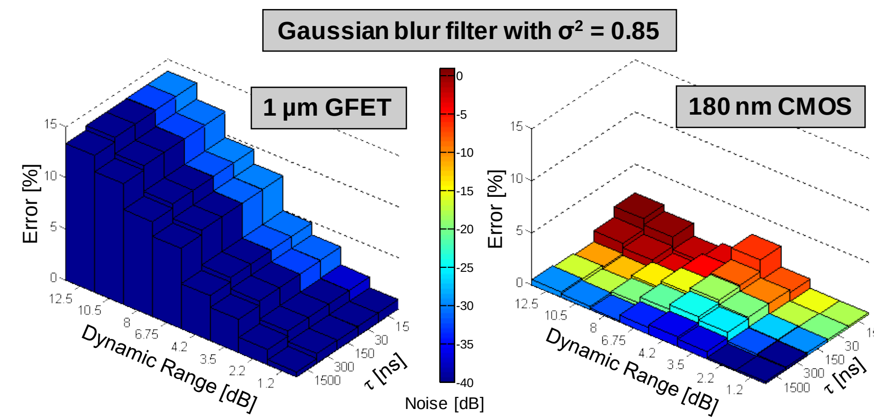
Idea:

$$V_{out} \approx \sum_{i=1}^{N} V_i p_i$$



weights encoded by pulse widths $p_i T$

Simulation with MIT-VS



+ Fast
+ Smaller area
+ Low noise
- Narrow input range (due to low I_{ON}/I_{OFF})

+ High accuracy
+ Wide input range
- Slow and noisy
- Larger area

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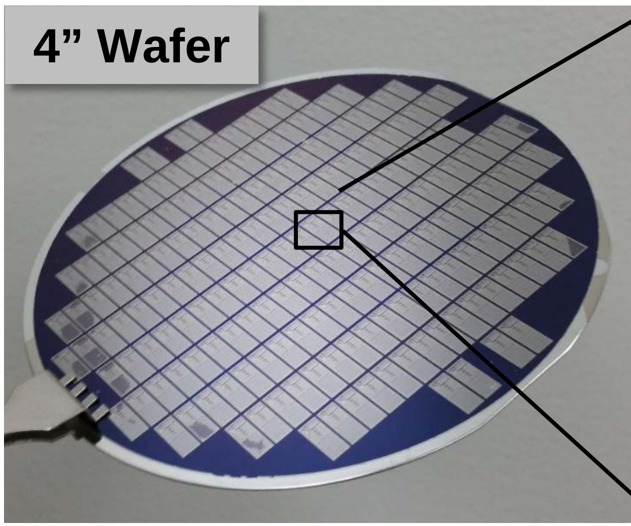
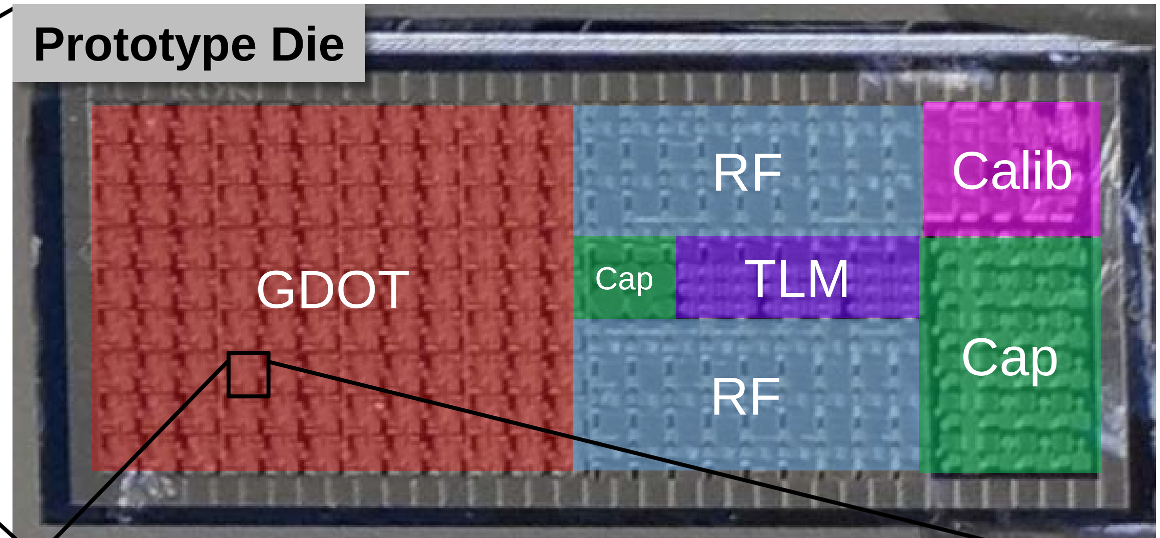
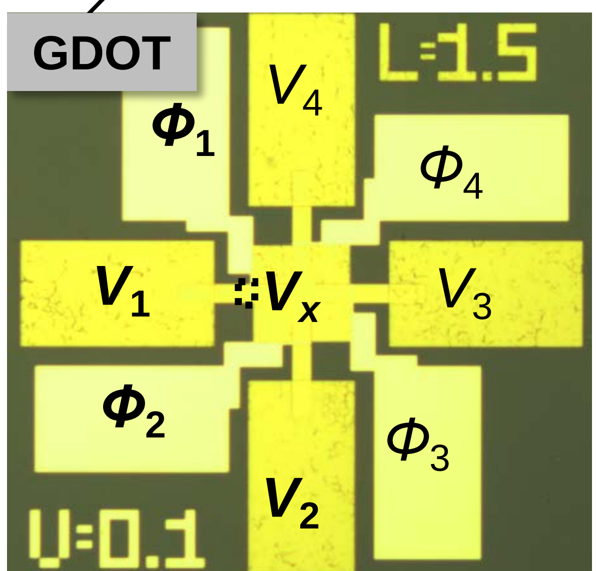
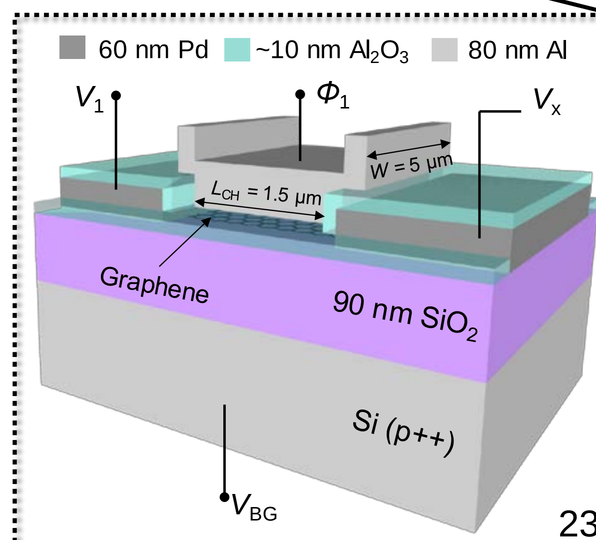
GDOT Implementation





- Wafer-scale graphene growth
- Advances in heterogeneous integration
- “Average” devices but unique function





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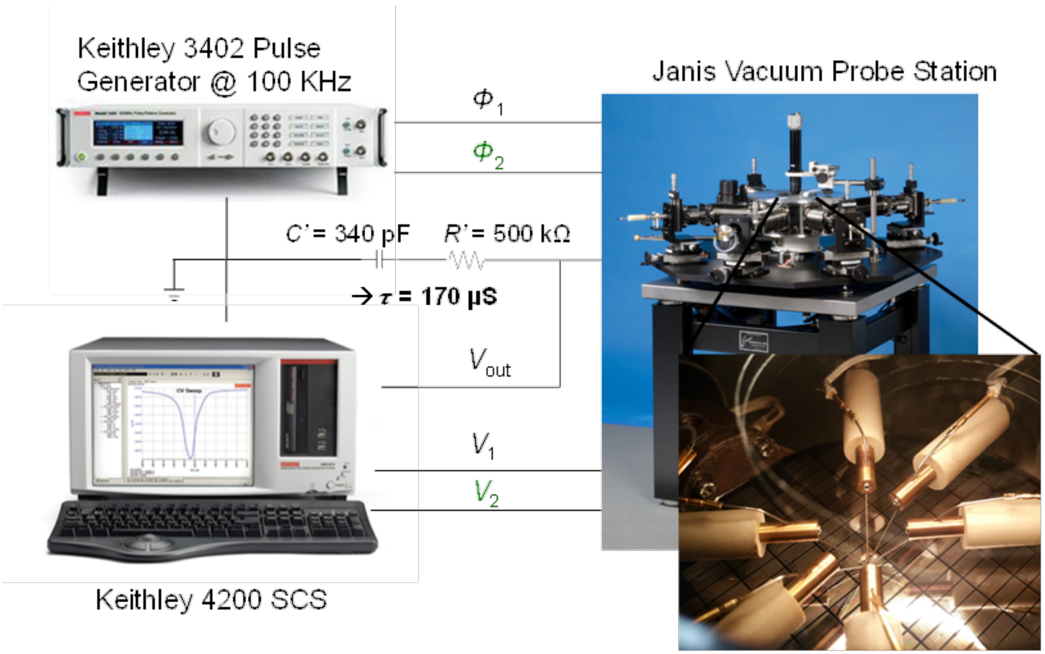
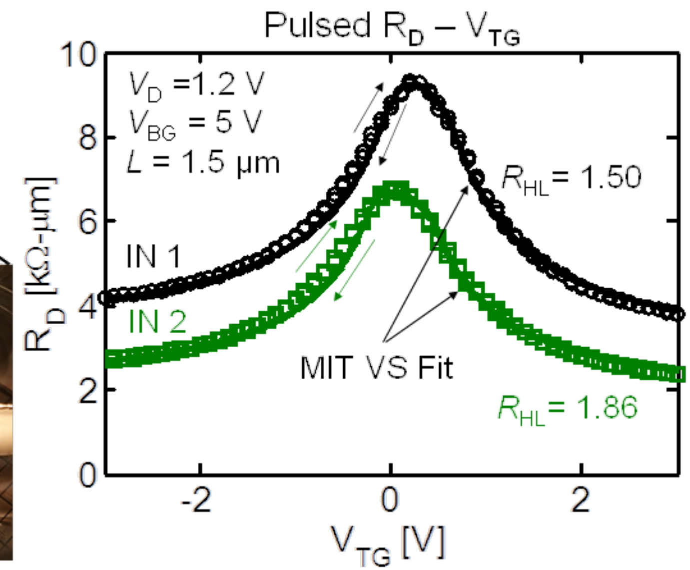
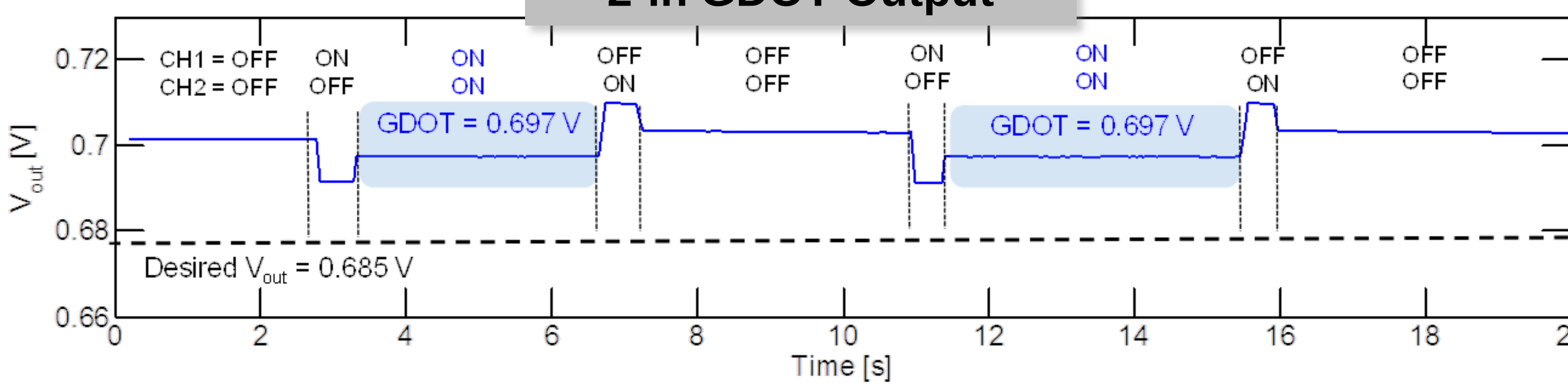
GDOT Prototype

N. Wang, S. Gonugondla, I. Nahlus, N. Shanbhag, E. Pop, *VLSI Symp.* (2016)

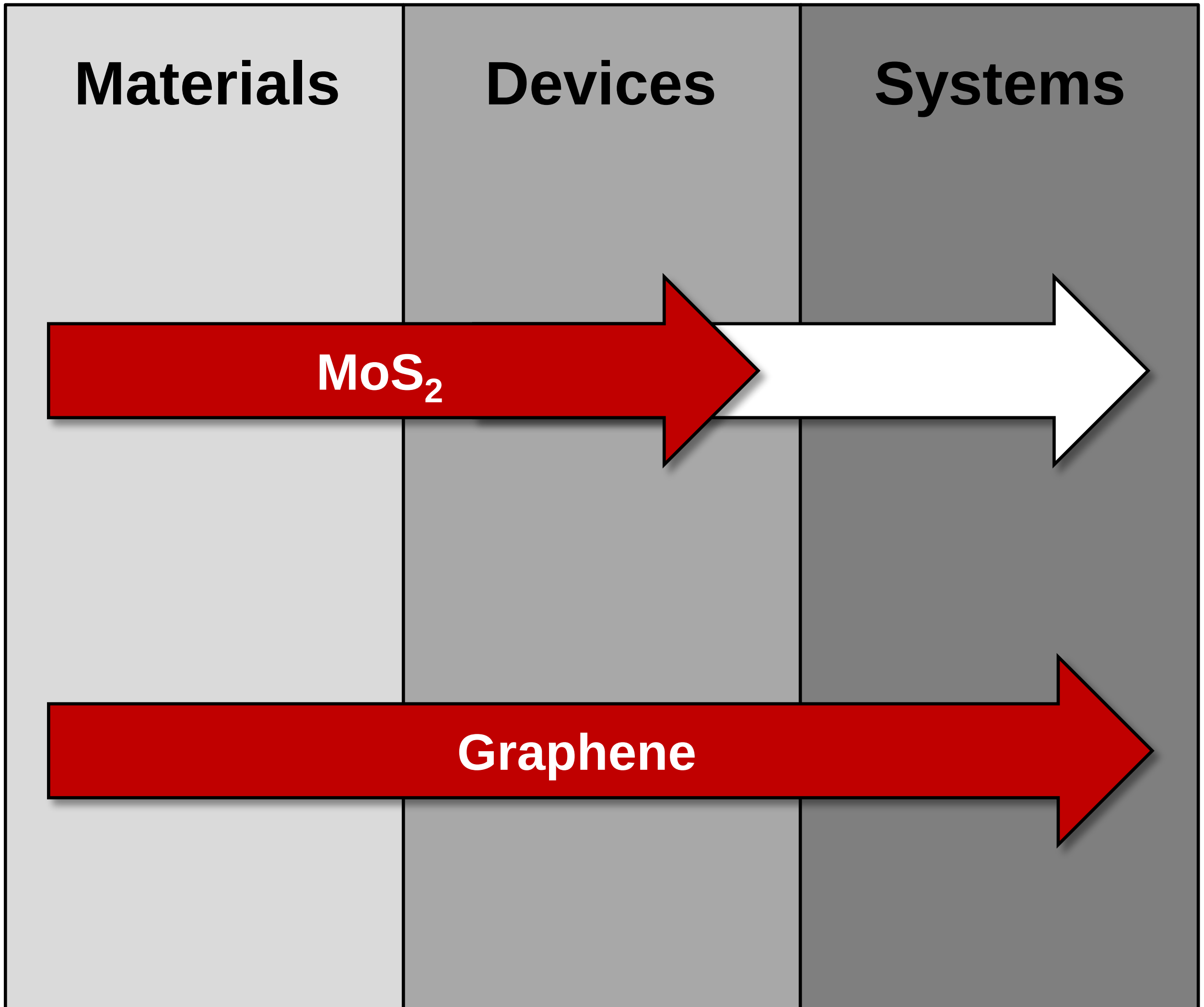


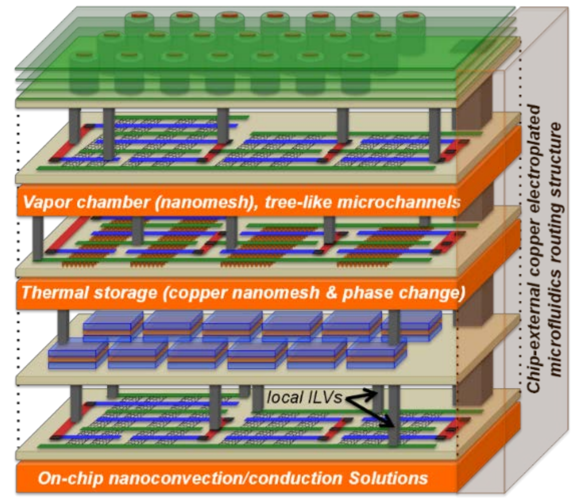


2-in GDOT Output



2D Materials to Systems (Today)





M. Aly et al., "Energy-Efficient Abundant-Data Computing: The N3XT 1,000X," *IEEE Computer* 48, 24 (2015)

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Conclusion

- Developed S2DS containing accurate models for
  - Carrier transport (v_{sat}, μ, C_q) and contacts
  - Thermal resistance
  - Non-idealities including traps, doping etc.
  - Analytical model of all possible fringe capacitances in a 2D FET
- Used compact models to identify the technology challenges
- Used compact models to design and optimize nanofunctions
- Showcased capability to design and fabricate large-scale systems from 2D materials (graphene and MoS_2)

Thank You!

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