

Neuromorphic Devices and Systems Enabled by Wafer-Scale CVD Growth of 2D Transition Metal Dichalcogenides

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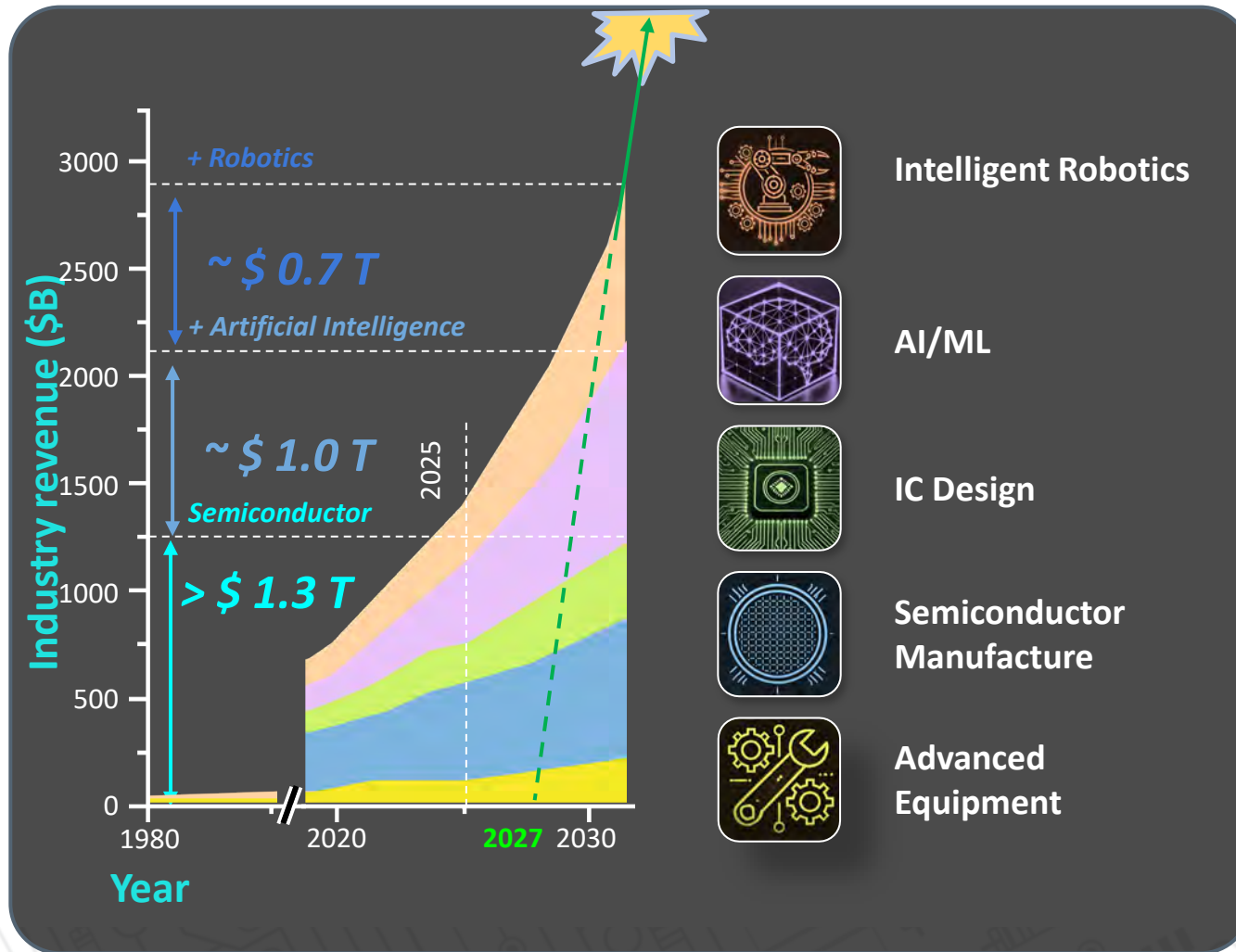


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AI Hardware



- Data Center
- Edge Intelligence
- Consumer Electronics
- Automotive Vehicles
- Intelligent robotics

Performance Boost

Better Energy Efficiency

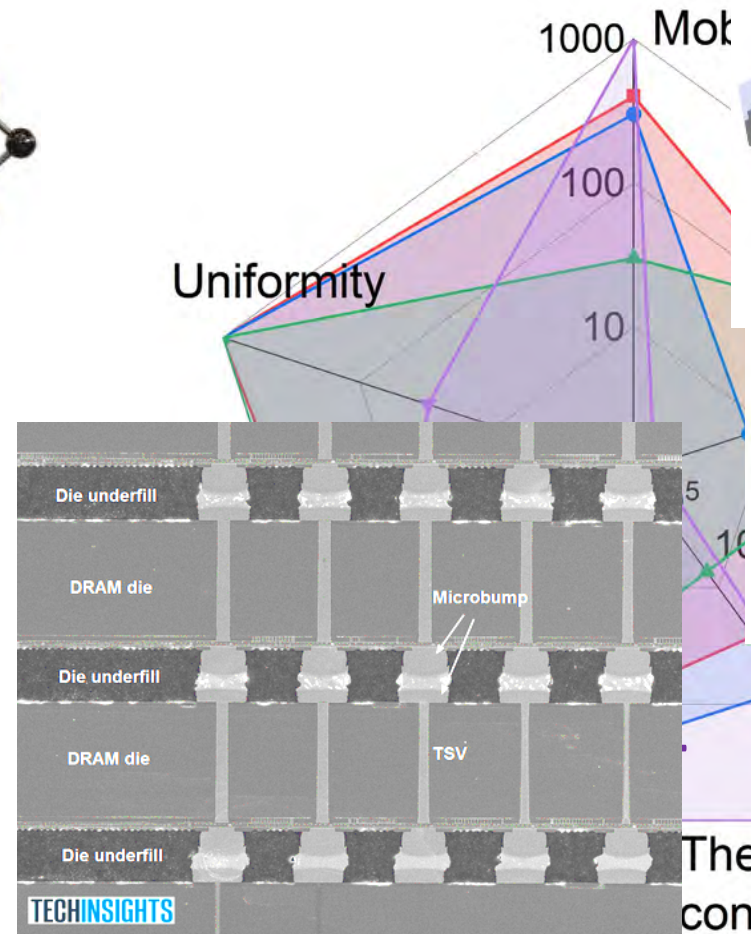
Solution: Heterogeneous integration & 2D materials

- Molybdenum disulfide (MoS_2)

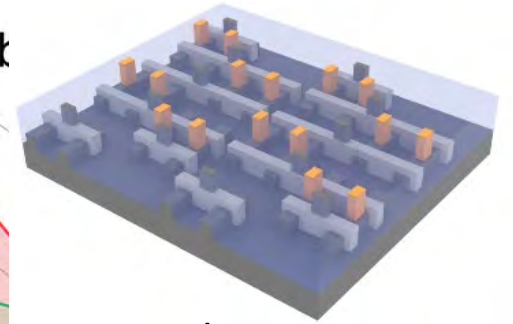


- Layered structure
- Atomic thickness ($\sim 0.67\text{nm}/\text{layer}$)
- Excellent material properties
- Varieties of application
- A typical transition metal dichalcogenides (TMDs)

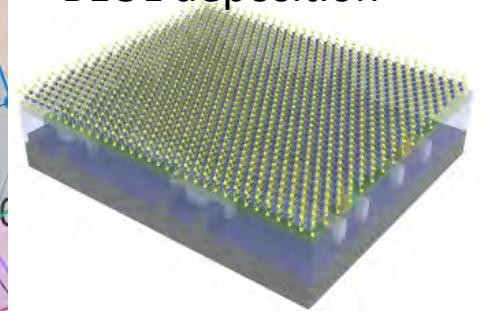
Conventional Chiplet packaging



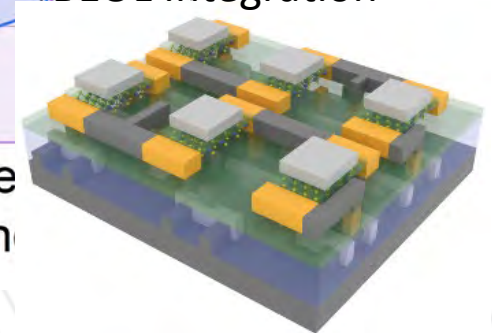
FEOL Si circuits



BEOL deposition



BEOL Integration

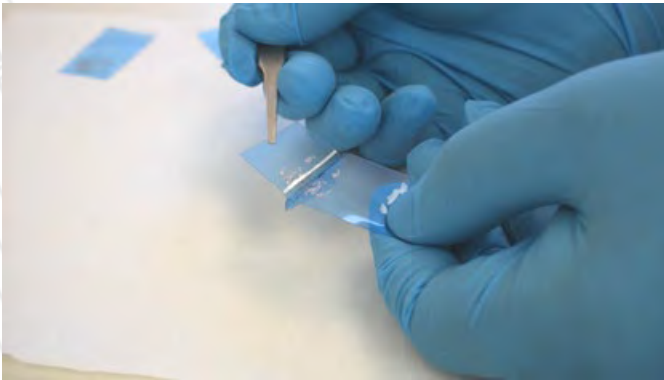


Key Technology: low-temperature MOCVD synthesis

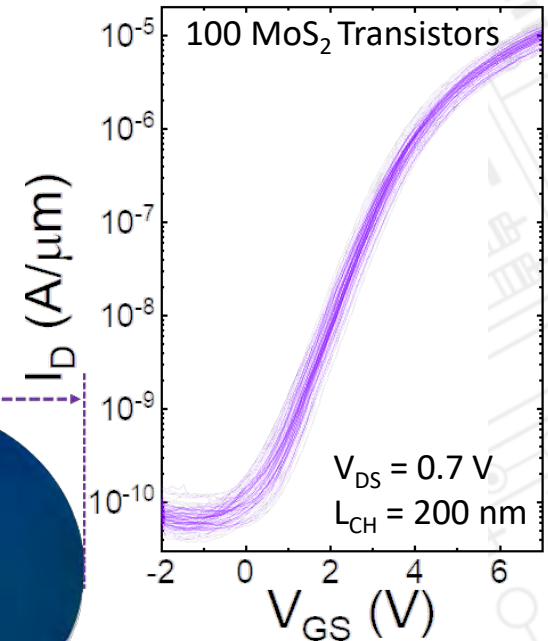
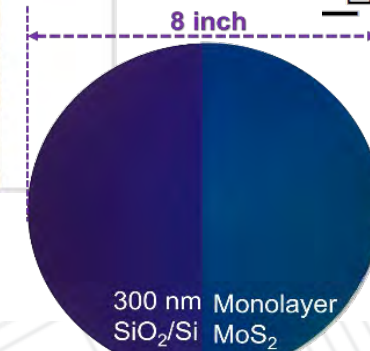
Chemical Vapor Deposition (CVD)



Mechanical exfoliation



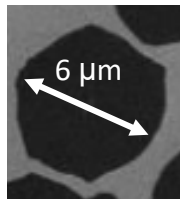
- 8-inch metal-organic chemical vapor deposition system
- MoS₂ growth (from mm-scale to 8-inch wafers)
- Good material uniformity



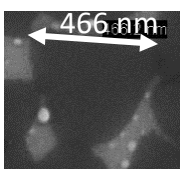
Key-technology: Silicon compatible Wafer-scale synthesis

- Explored the dependence of NaCl promoter concentration on lateral growth rate at different synthesis temperature
- Applied this understanding to non-sodium promoters

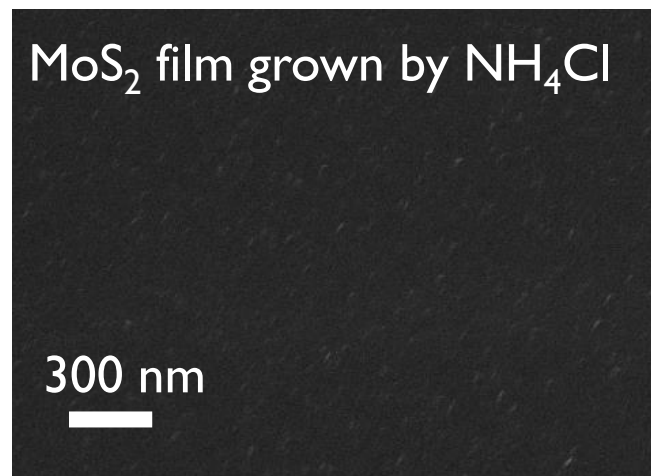
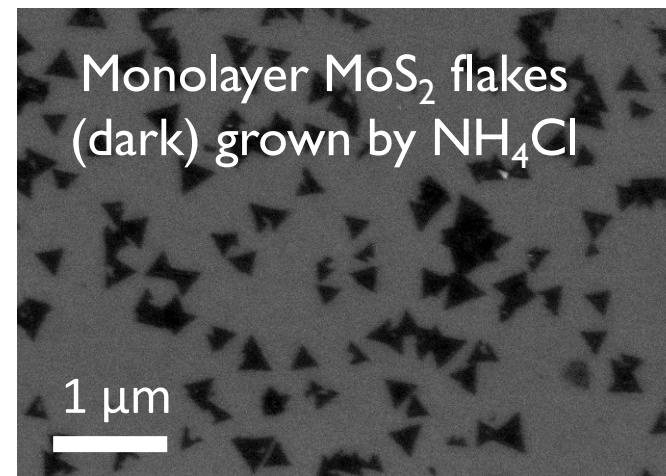
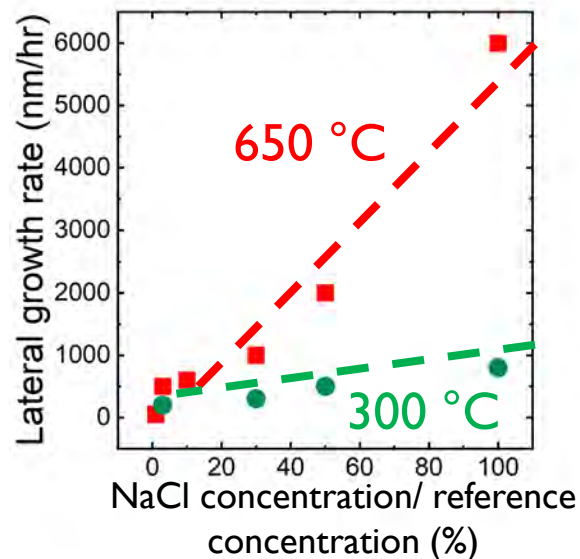
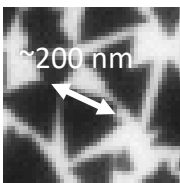
High conc. (100%) 650 °C



Low conc. (3%) 650 °C

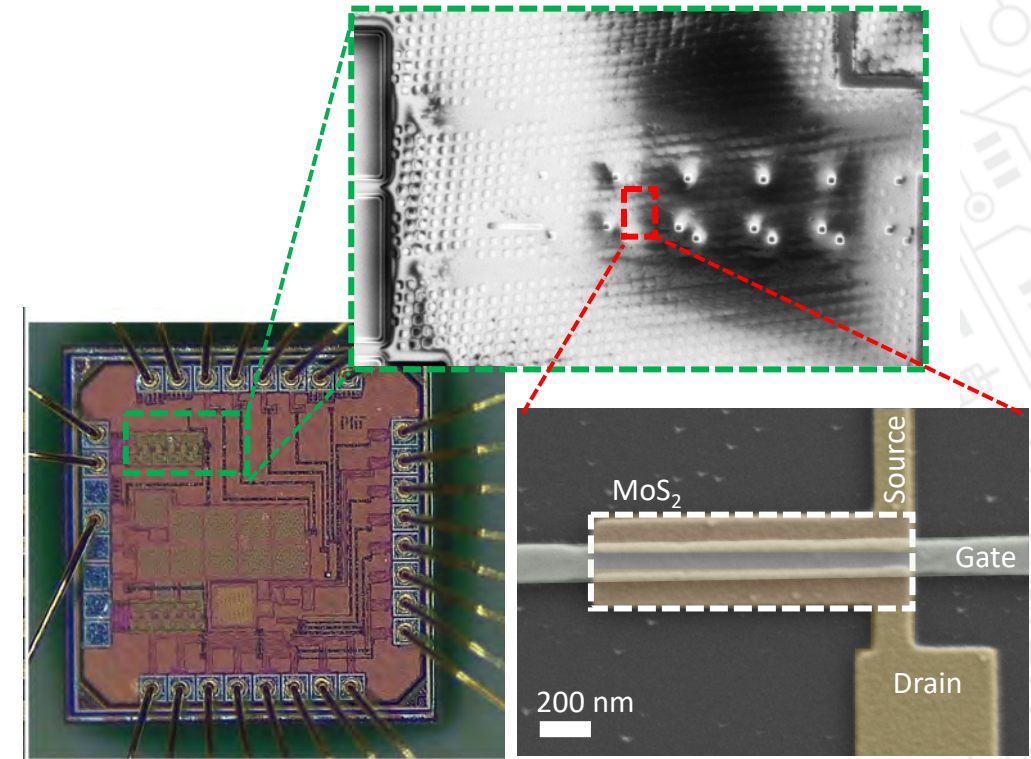
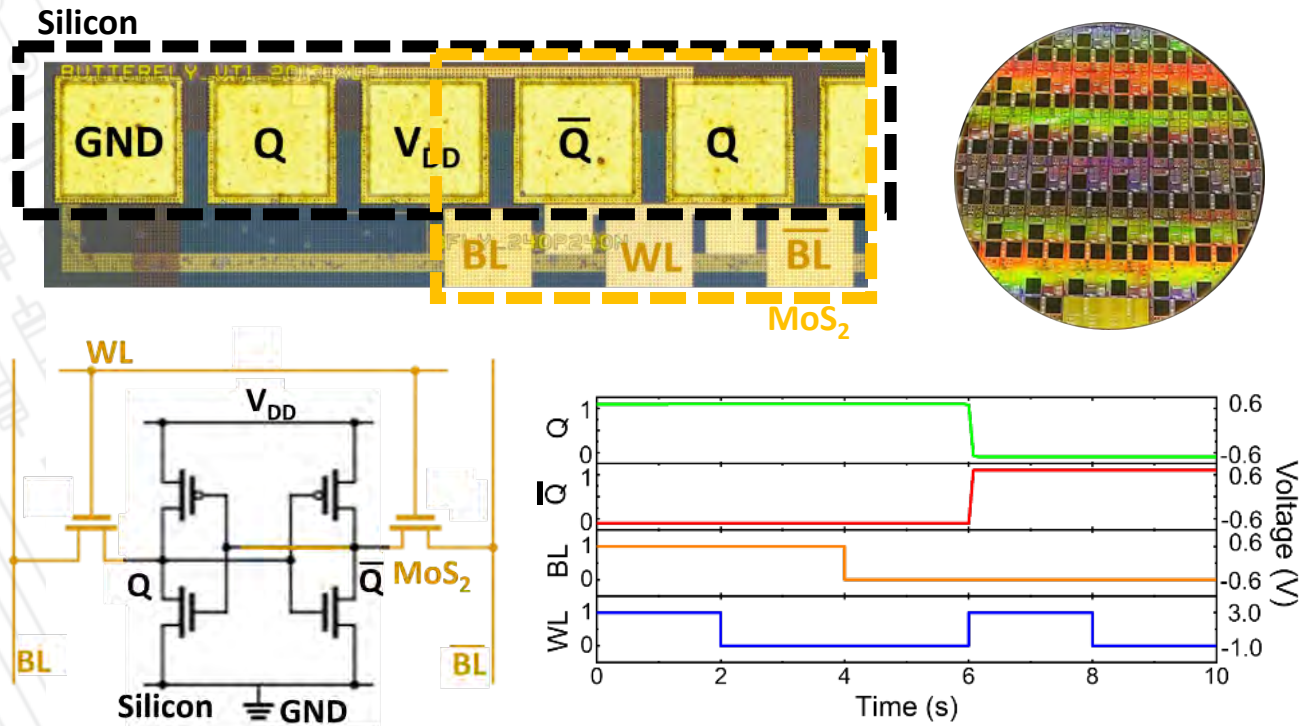


Low conc. (3%) 300 °C



Key-technology: Si BEOL integration

- MoS_2 -Silicon heterogeneous-integrated SRAM cell
- MoS_2 rectifiers integrated on silicon controlling circuits



Credit to Dr. Steven Vitale for LL 90nm Si Wafer

TSMC 65nm University Shuttle



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J. Zhu[†], J.-H. Park[†], et al, *Nat. Nanotechnol.* **18**, 456 (2023)



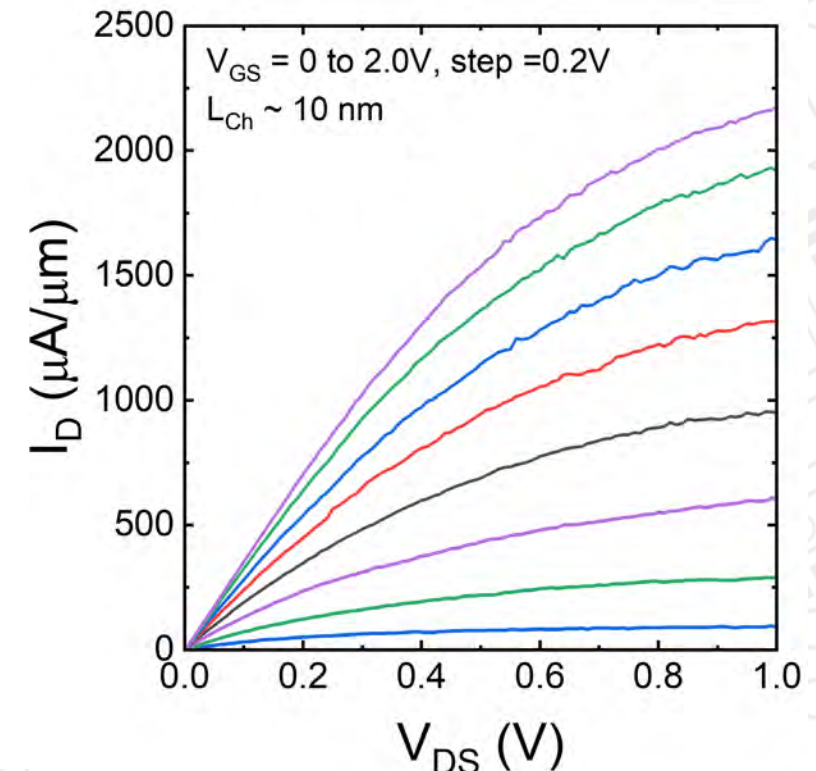
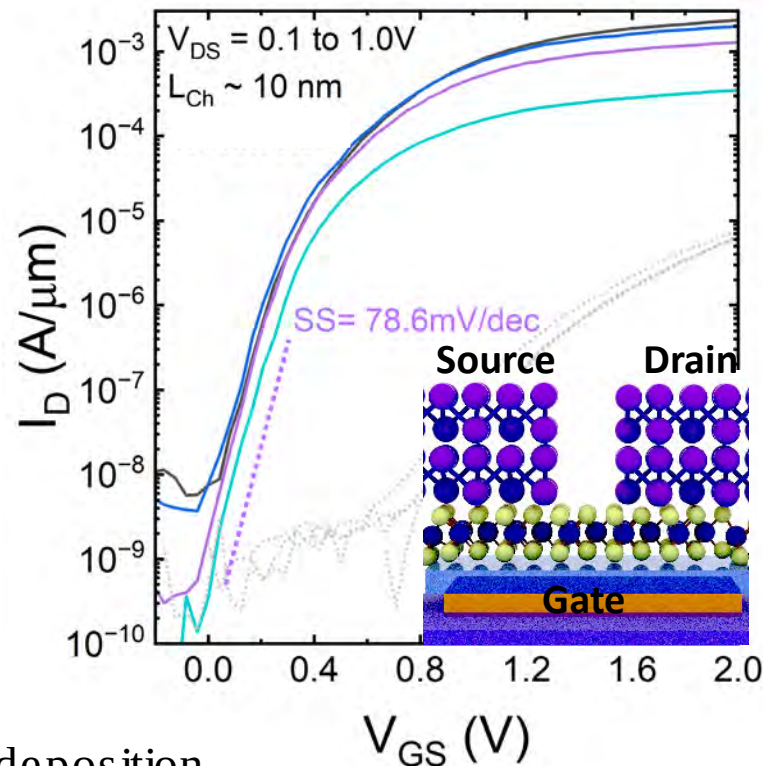
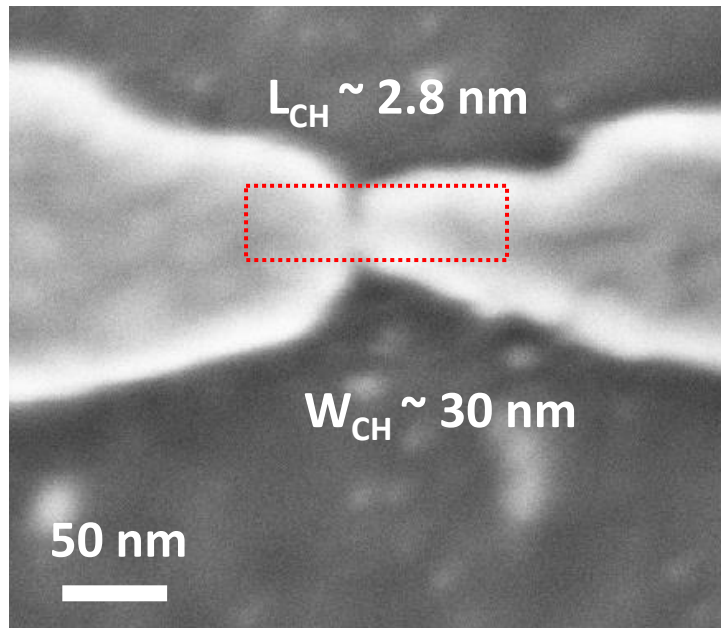
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Devices: Highly-scaled logic device

- Extreme device dimensions: $L_{ch} \sim 2.8$ nm, $W_{ch} \sim 30$ nm, EOT < 1nm
- Current exceed $1500 \mu\text{A}/\mu\text{m}$ even @ $0.6\text{V } V_{DS}$

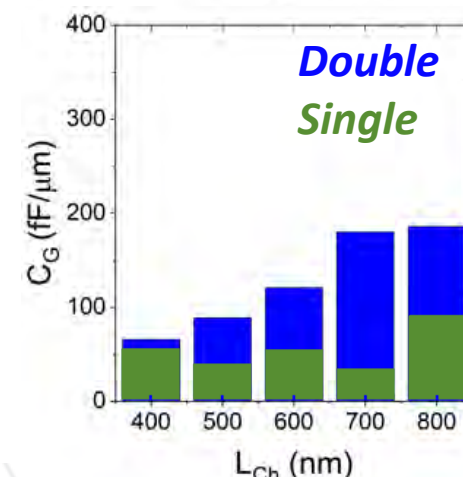
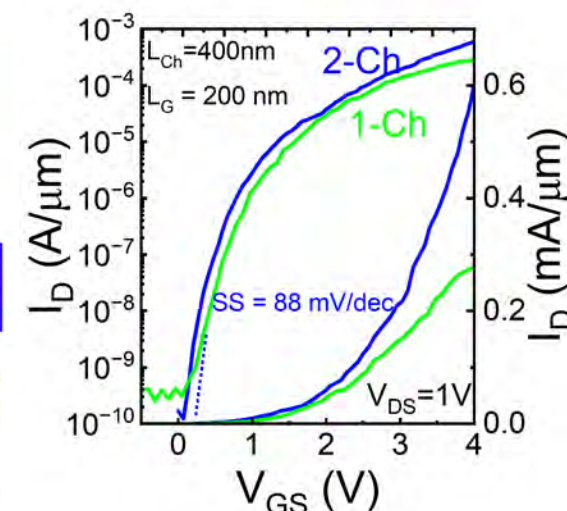
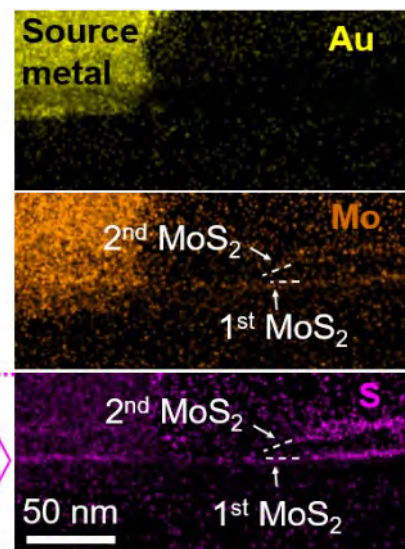
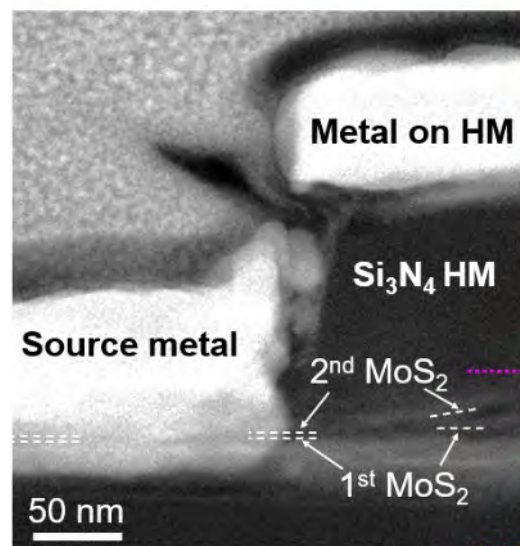
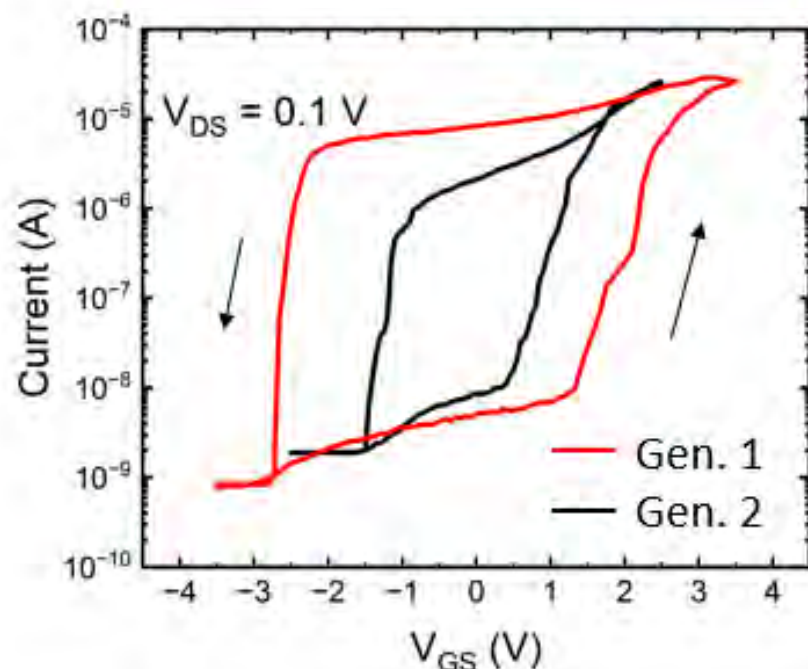
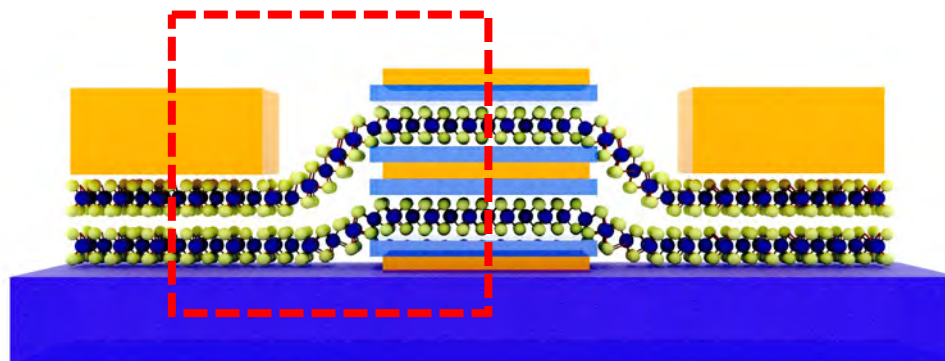
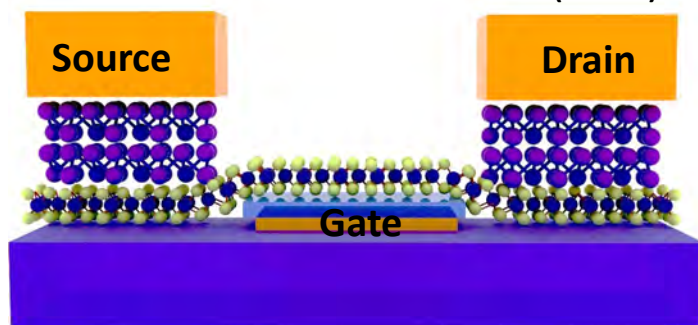


Credit to Dr. Kevin O'Brien for Sb deposition



Devices: In-memory and near-memory computing

Hafnium zirconium oxide (HZO)



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J. Zhu[†], et al, unpublished

J. Zhu[†], A. Yao[†], et al, IEDM 24-5 (2024)



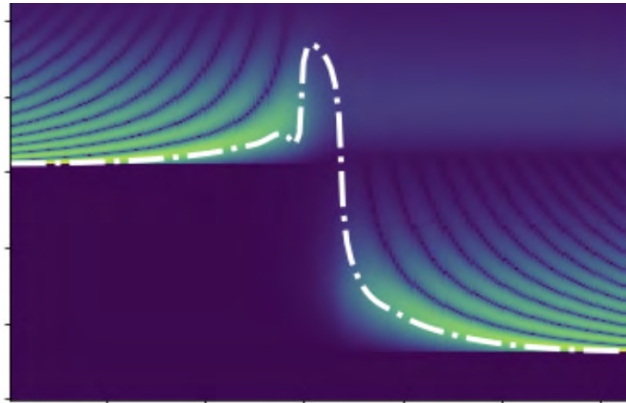
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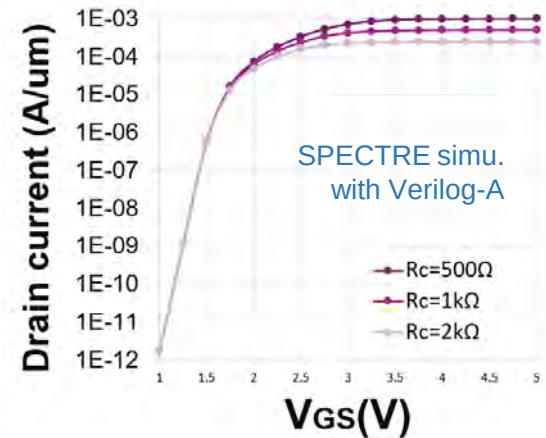
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Modeling: Physics model, PDK & DTCO

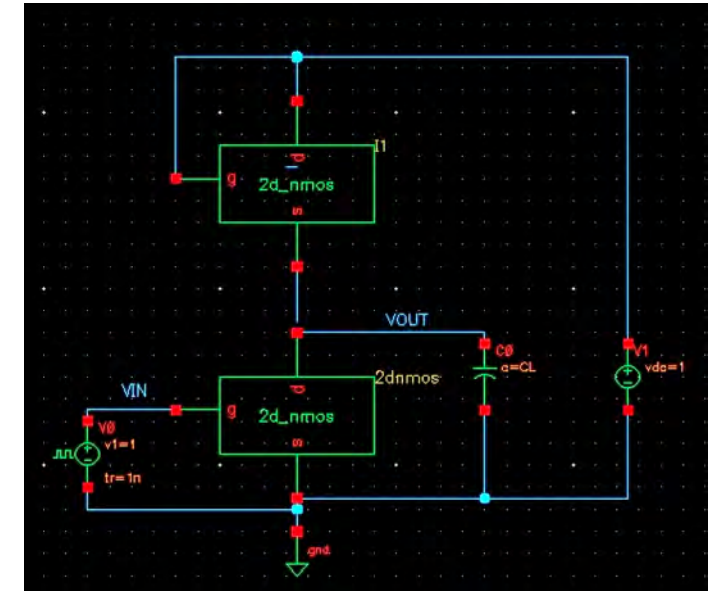
NEGF simulation



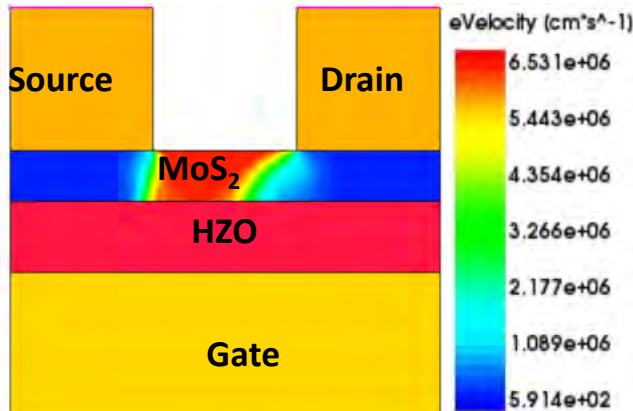
Performance extraction



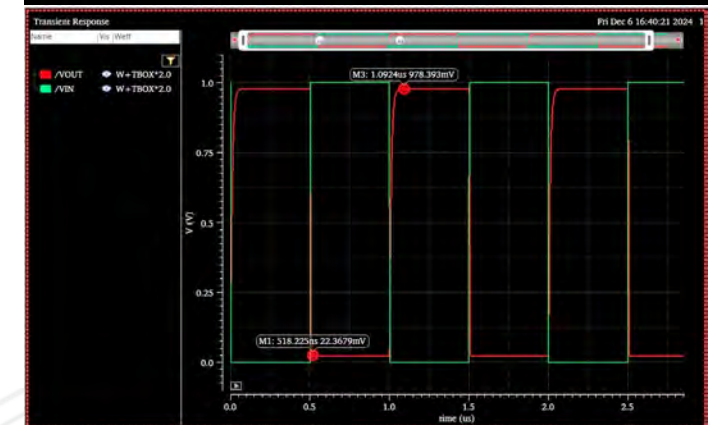
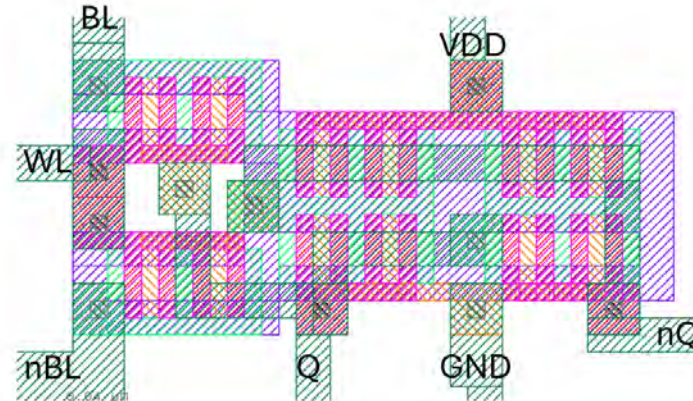
Proprietary 2D process design kit



Device simulation



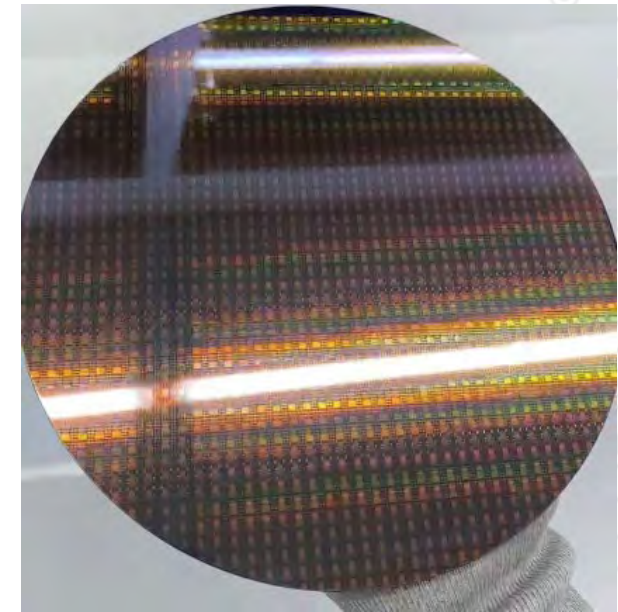
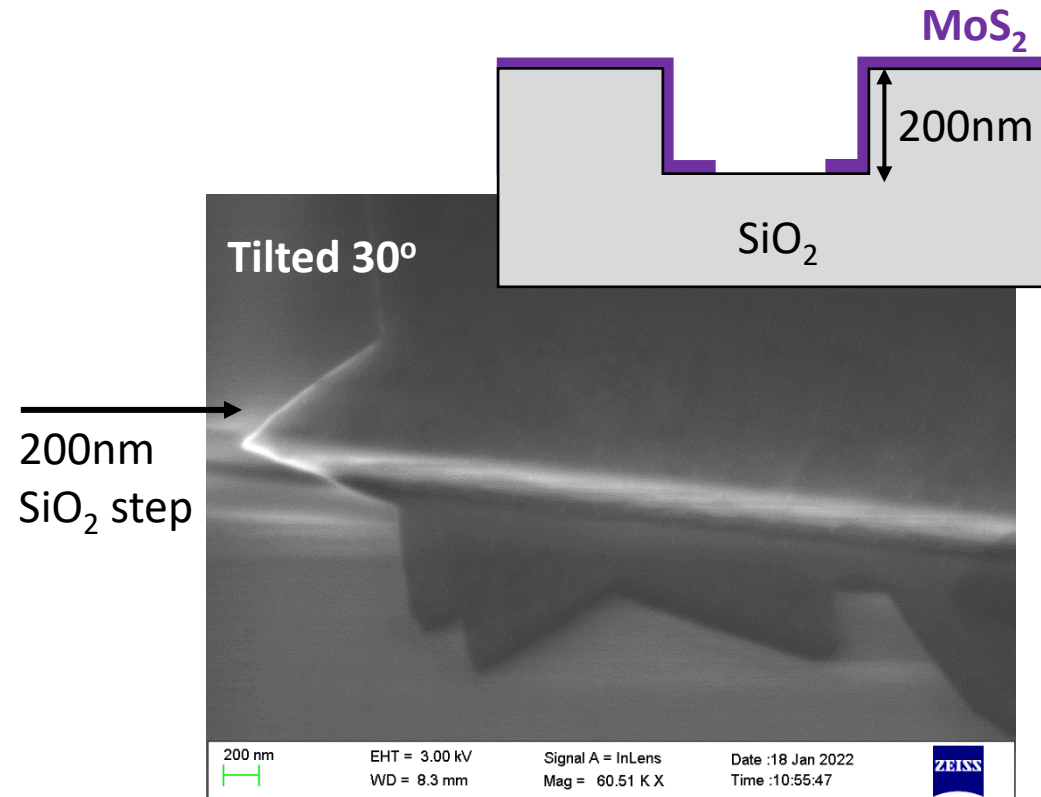
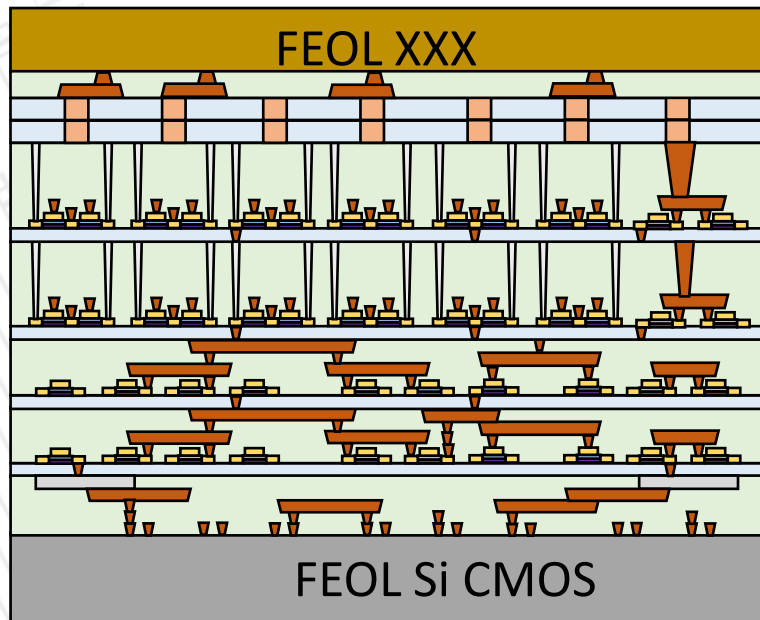
Layout & Design rules



Application: High-density memory array

- High-density 3D integration
- Side-wall coverage
- 3D unit cell

HPC Applications:
e.g., data centers

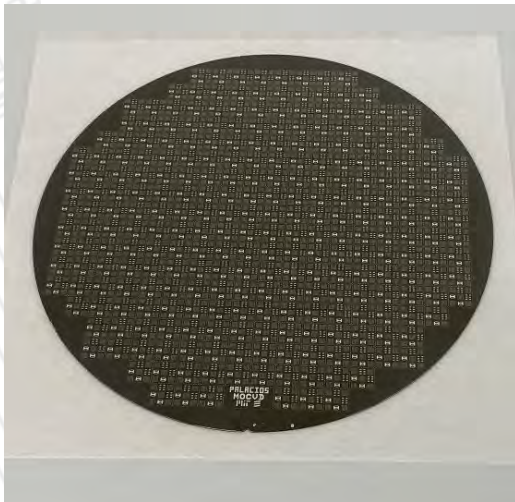


Application: AI inference and consumer electronics

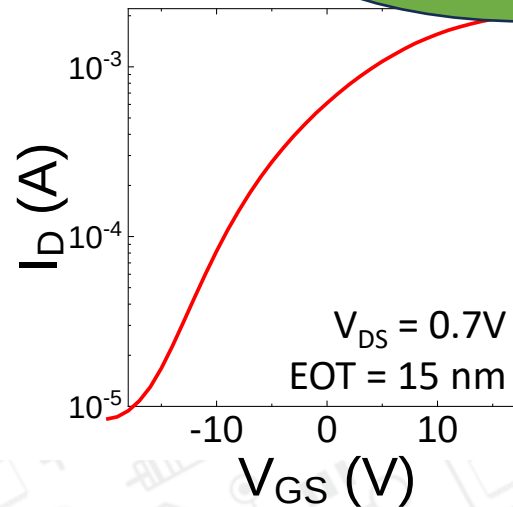
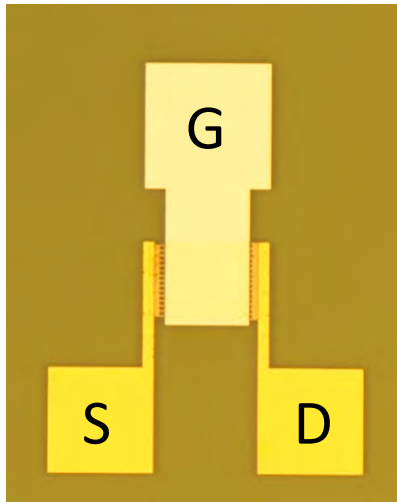
- AI inference will be the major application
 - Low-energy consumption
 - High-efficiency
- Edge intelligence for federative learning

MoS₂ on 8" Polyimide (PI) substrate

8" PI with MoS₂ transistors



MoS₂ transistor on PI



ULP Applications:
e.g., wearable devices



Acknowledgements



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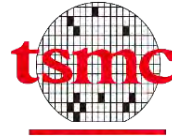
Dr. Ji-Hoon Park



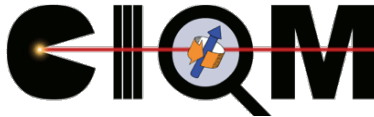
Aijia Yao



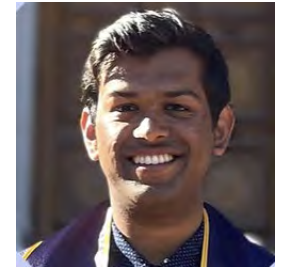
Yixuan Jiao



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