Applications of 2D Materials in Future CMOS Nodes

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April 3, 2023

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University of Minnesota
Driven to Discover℠

University of Minnesota

- The University of Minnesota - Twin Cities is public research university located in Minneapolis and Saint Paul, MN.
- It has the 9th largest main campus student body in the United States, with over 52,000 students at the start of the 2021–22 academic year.

Minnesota Nano Center

- The Minnesota Nano Center (MNC) is a state-of-the-art, open-access facility for advanced research and education in micro- and nano-scale technology:

https://cse.umn.edu/mnc

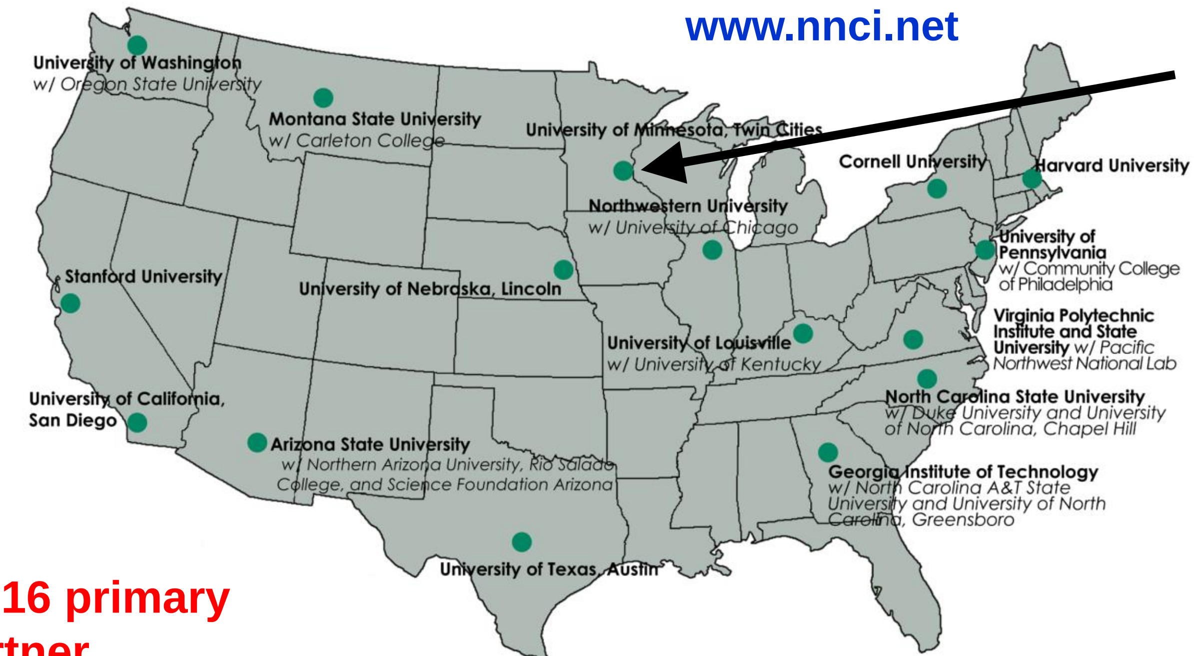
- **MNC is open to any qualified user, with significant use from industry and other institutions.**
- **Annually serves ~400 total users, ~140 external and ~60 industry.**

NNCI

- MNC is part of one node of the National Nanotechnology Coordinated Infrastructure (NNCI), a network of university nanofabrication and characterization facilities across the US:

www.nnci.net

MiNIC
Midwest Nano Infrastructure Corridor



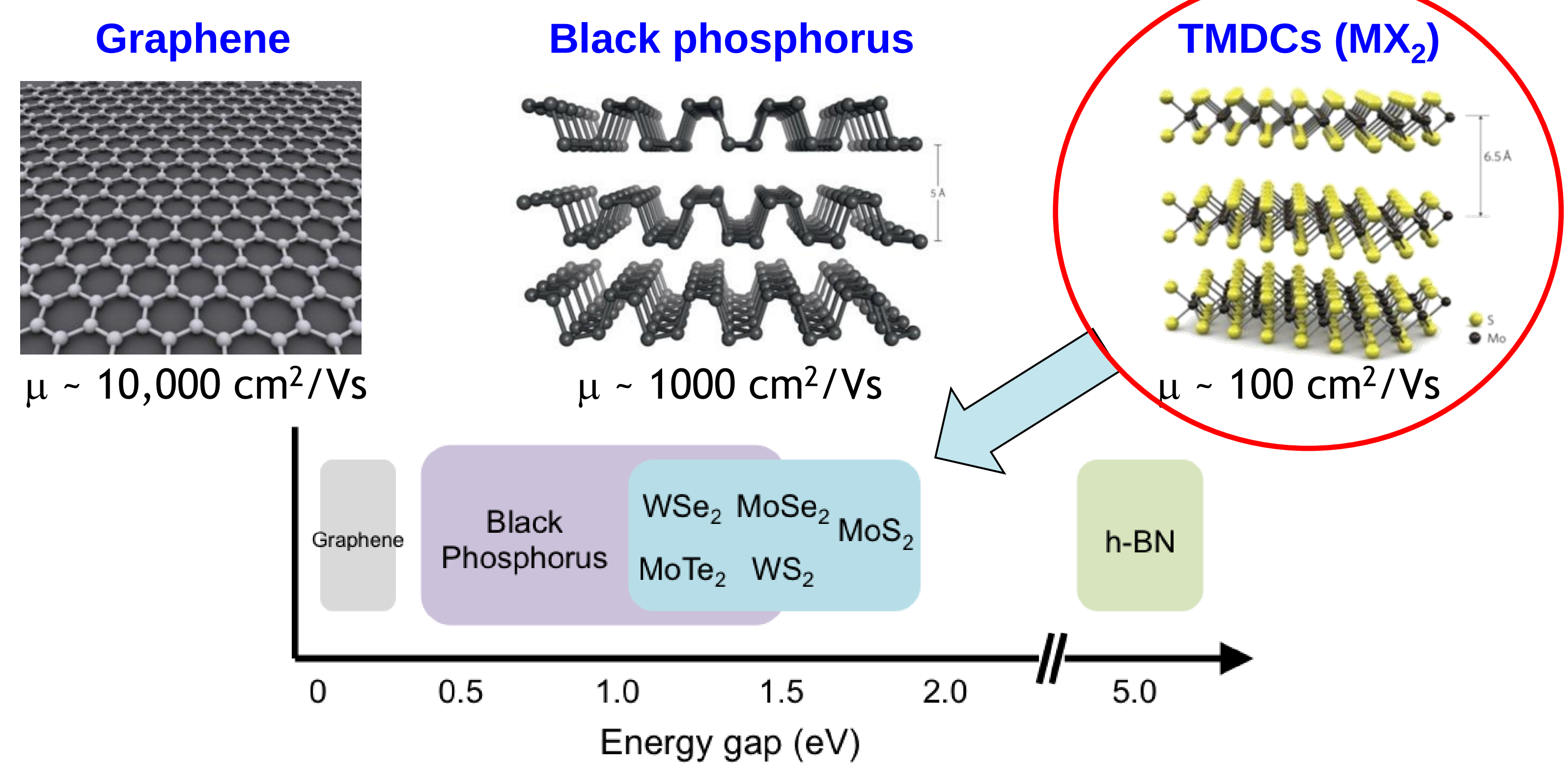
- **Consists of 16 primary sites, 13 partner institutions, and 69 facilities in total.**
- **Supports > 2000 individual nanofab tools.**

National Nanotechnology Coordinated Infrastructure

- **NSF has provided $165M in support between 2015-2025.**

2D Materials

- 2D materials are crystalline solids where the in-plane bonding is much stronger than in the out-of-plane direction. Can exist as single monolayers. Span a range of band gaps from 0 to 6 eV.

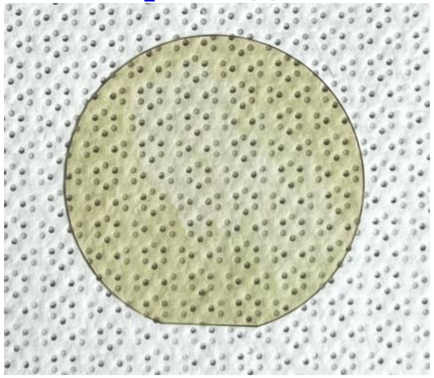


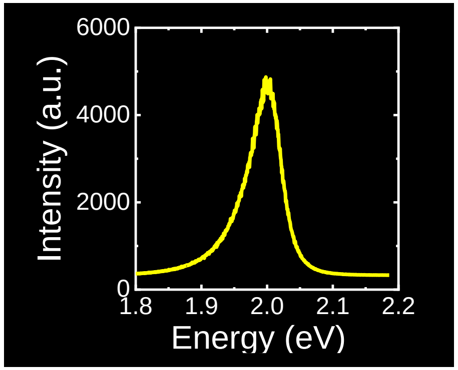
- **TMDCs have emerged as front-runners for use in future CMOS.**

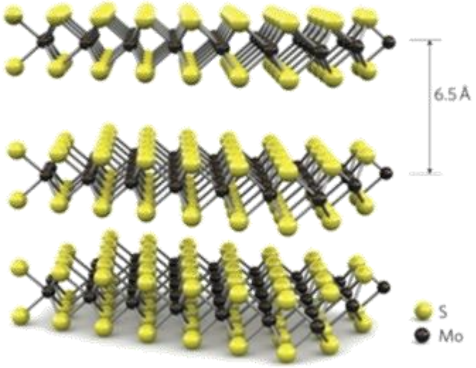
Advantages of TMDCs

- TMDCs meet the necessary criteria for being a candidate for end-of-roadmap CMOS:
  - Scalable to monolayer thickness (where μ can beat Si).
  - Electron and hole effective mass and mobilities are similar.
  - Capable of meeting IRDS off-current targets (due to E_G ~ 1-2 eV).
  - Stable in atmosphere and under high processing temperatures.
  - Capable of large-area (up to 300-mm) growth with high-degree of uniformity over an entire wafer.

WS_2 on sapphire

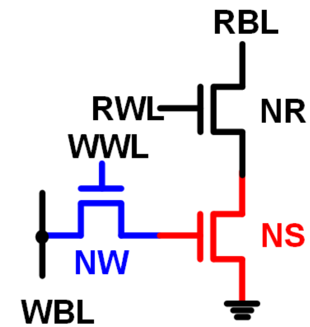




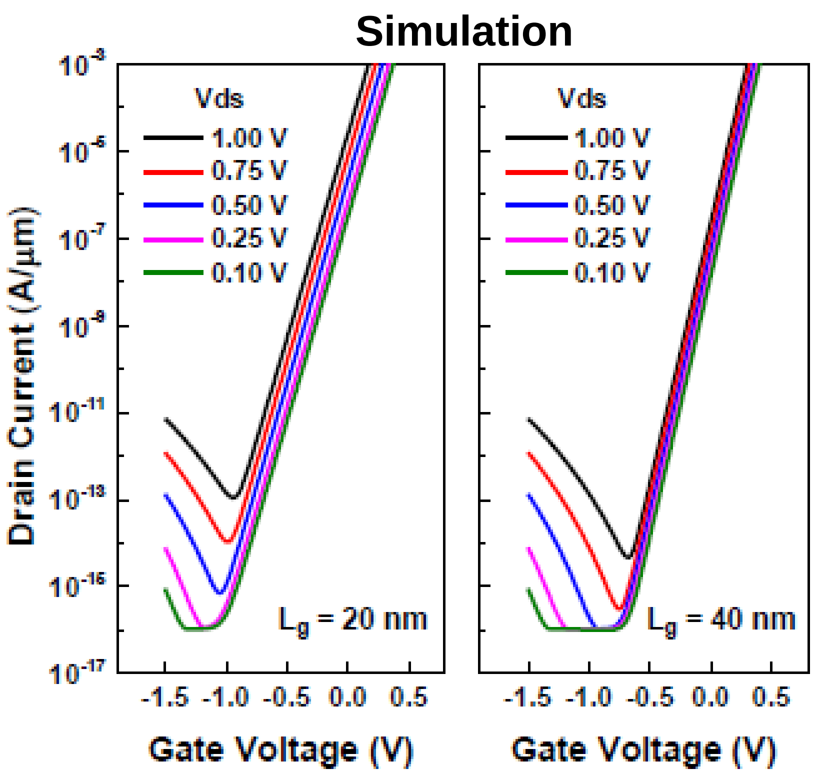


TMDCs for Dynamic Memories

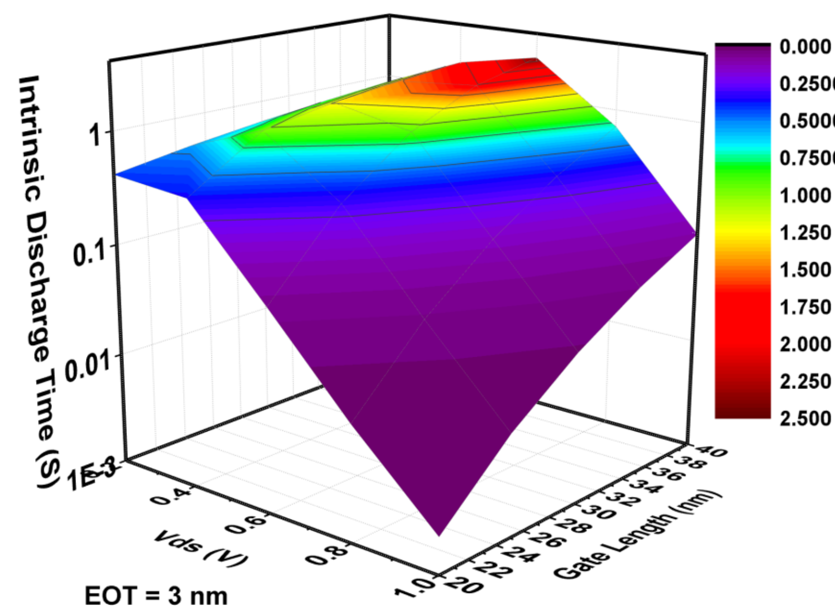
- TMDCs are ideal for embedded DRAM due to the extremely-low leakage currents possible:



C. Kshirsagar…S. J. Koester, et al., DRC, 2014.



Results from large band gap (E_G ~ 2 eV) and heavy effective mass.

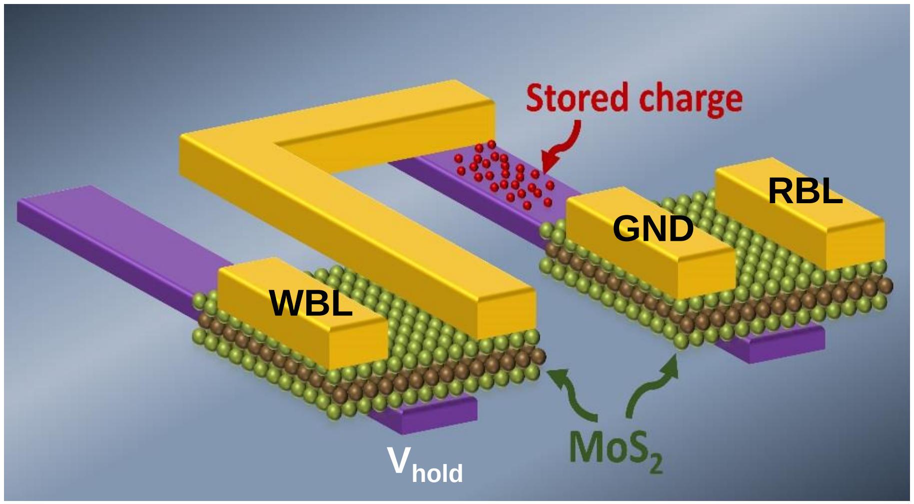


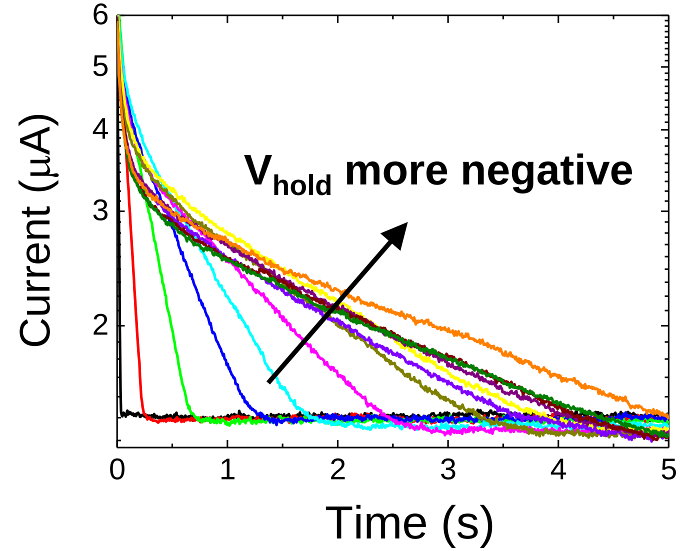
- **Device simulations show sub-fA leakage currents possible for MoS_2. When used in a 3T "gain cell", can achieve retention times > 1 sec.**

TMDCs for Dynamic Memories

- Demonstrated 2T DRAM using few-layer MoS_2:

C. Kshirsagar…S. J. Koester, et al., *ACS Nano* 10, 8457 (2016).





- **Extracted characteristic retention time as a function of gate voltage on access transistor (V_{hold}).**
- **Retention time can then be converted into an equivalent leakage current, to understand leakage limitations of MoS_2.**

TMDCs for Dynamic Memories

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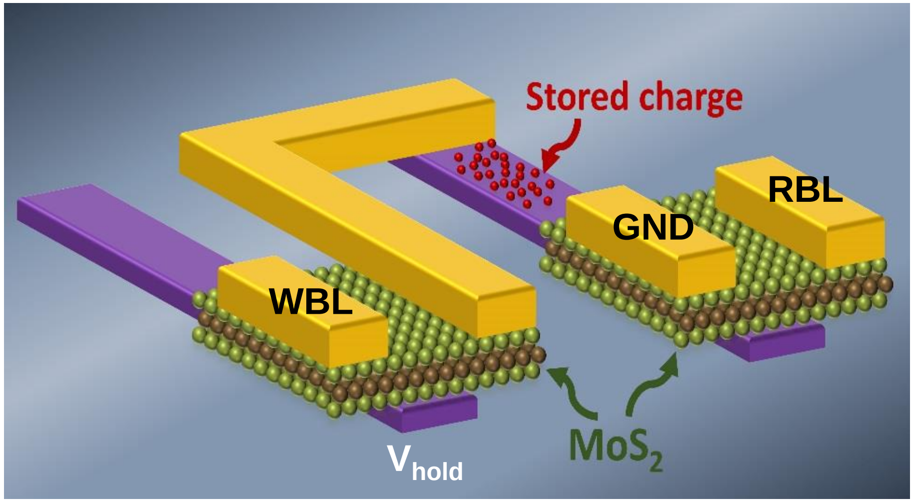
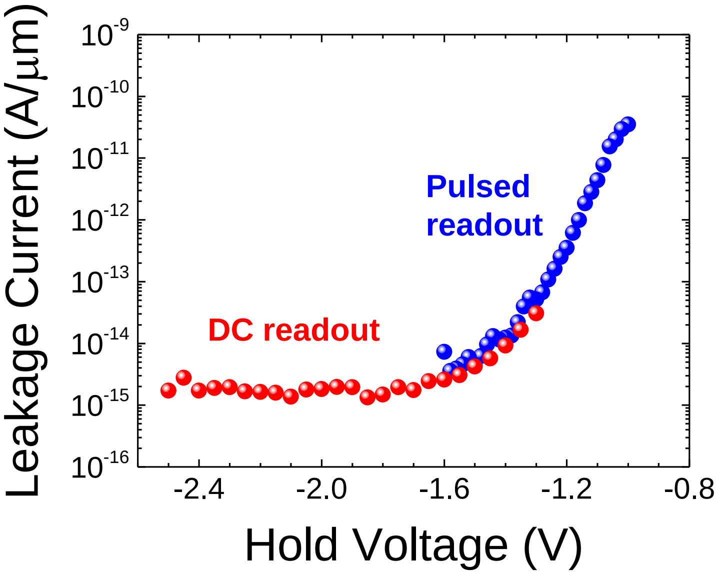
C. Kshirsagar…S. J. Koester, et al., *ACS Nano* 10, 8457 (2016).



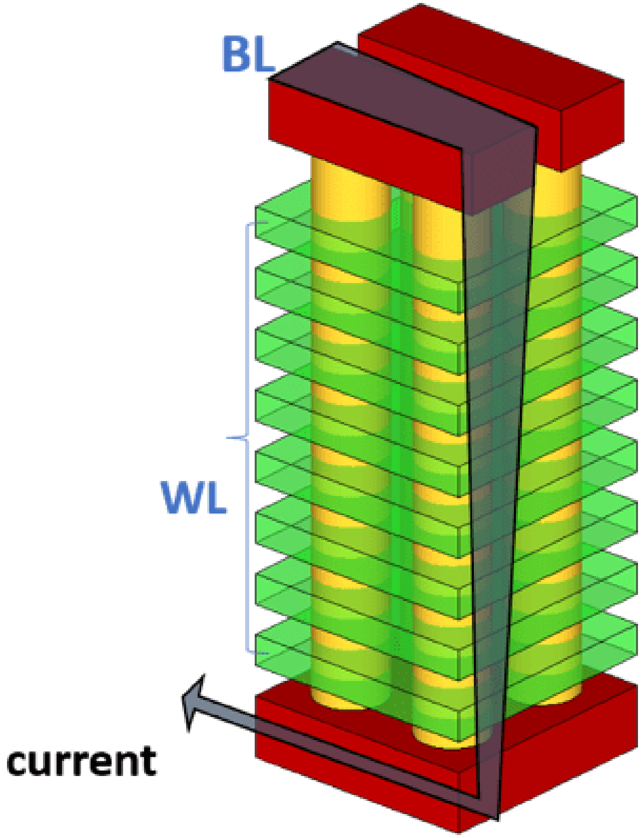


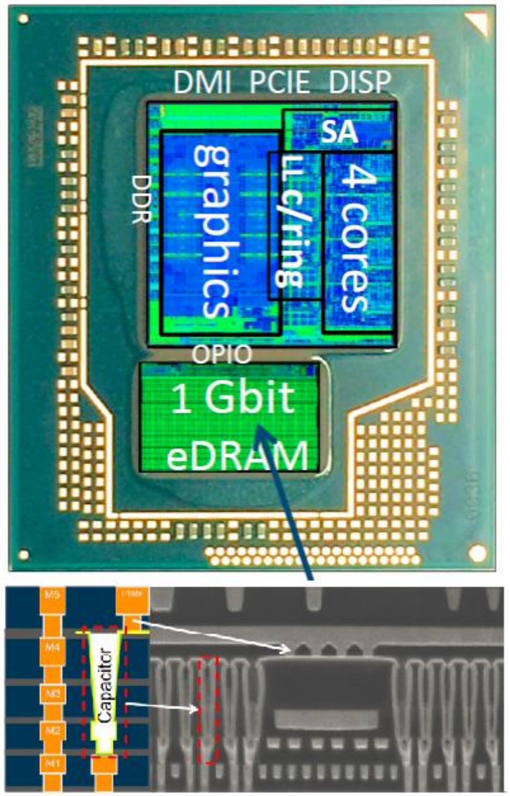
- **Demonstrated 2T memories with equivalent leakage currents approaching 1 fA/μm.**
- **Several orders of magnitude improvement possible using <u>single-layer</u> MoS_2 and optimizing design.**

Future DRAM Applications

- 2D semiconductors have potential for use in 3D DRAM or ultra-scaled embedded DRAMs:

Source: SemiconductorEngineering

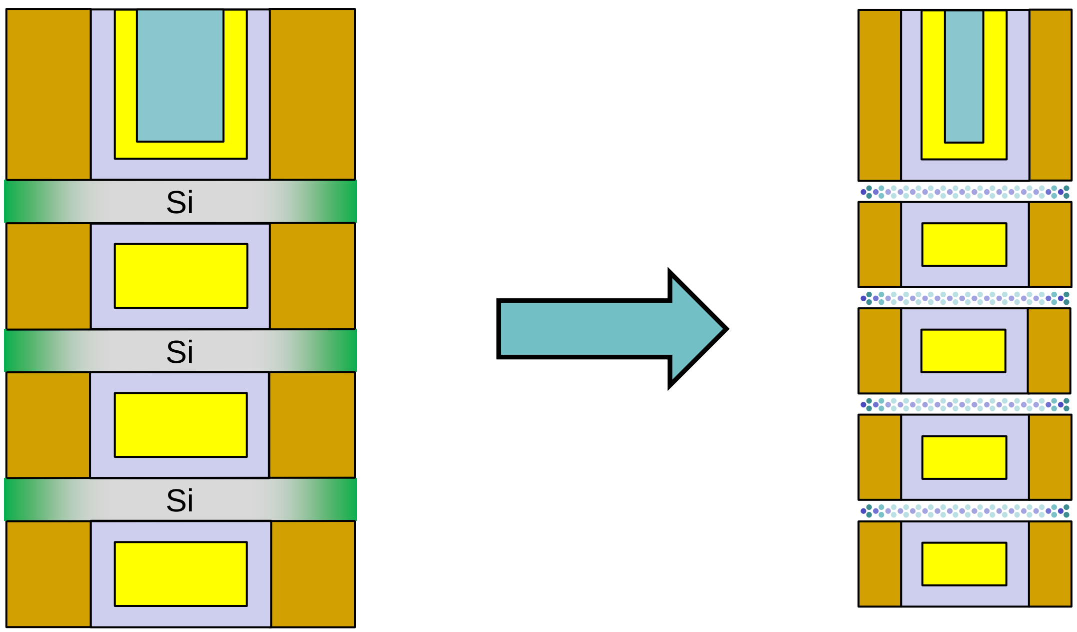




2D Nano-Sheet MOSFETs

- 2D materials are being considered for sub-1-nm node CMOS. These devices will be nanosheet FETs:

Si NS-FET (1-nm node) **2D NS-FET (0.7-nm node)**

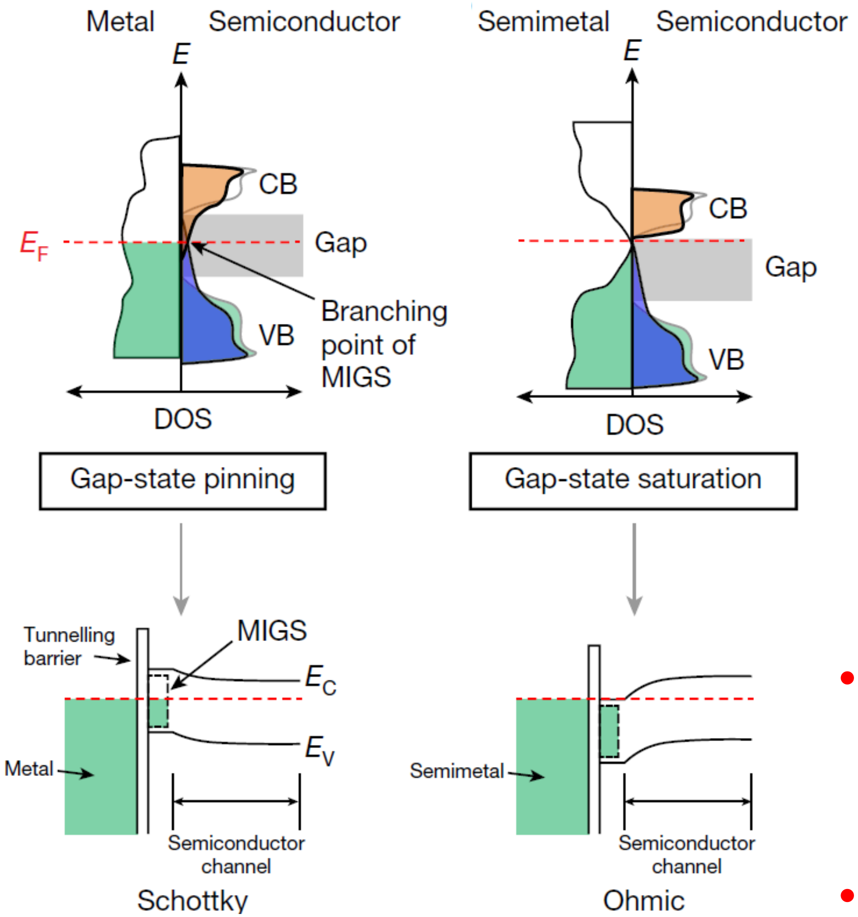


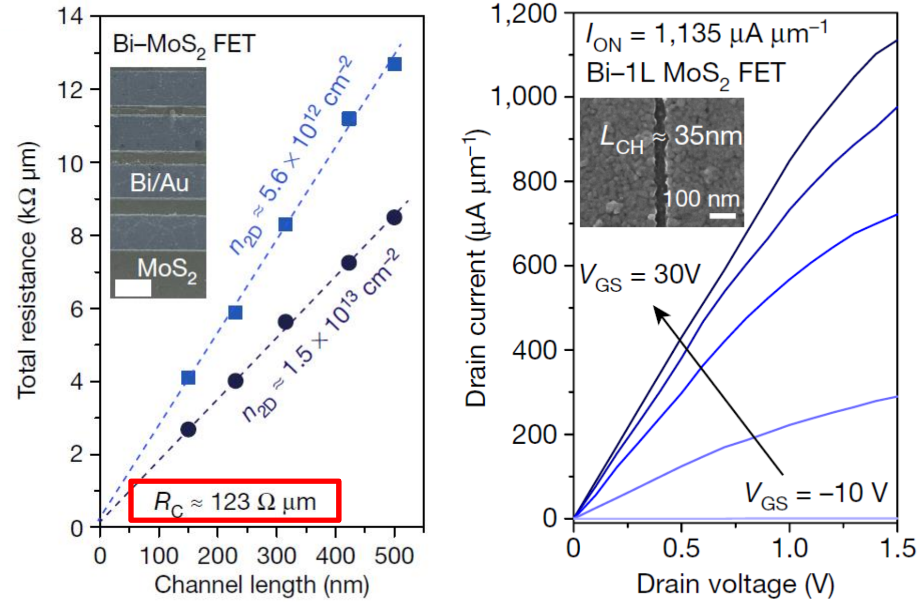
- **One key challenge is need for low contact resistance to meet IRDS targets for on-current (R_C ~ 60 Ω-μm needed).**

Semi-Metallic Contacts to 2D Semiconductors

- Breakthrough reported in 2021 → semi-metallic contacts to MoS_2 can overcome Fermi-level pinning that limits contact resistance:

P.-C. Shen, et al., Nature, 593, 211 (2021).



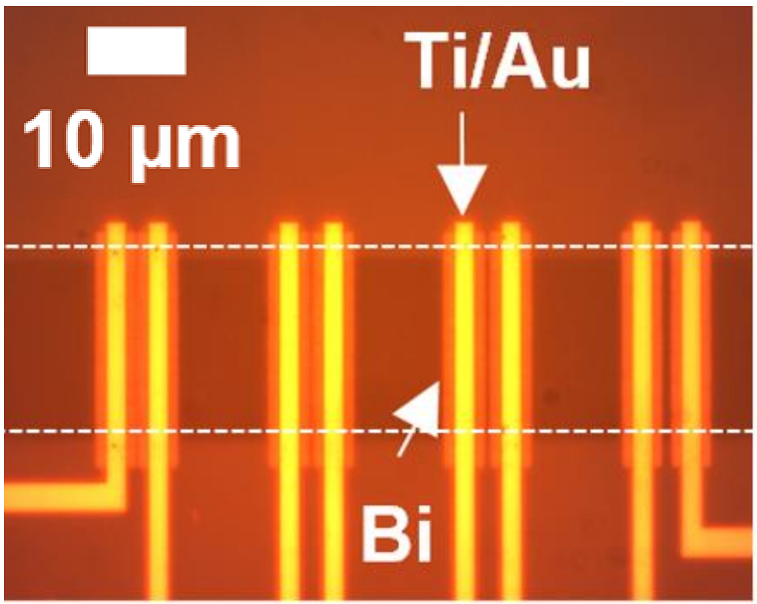


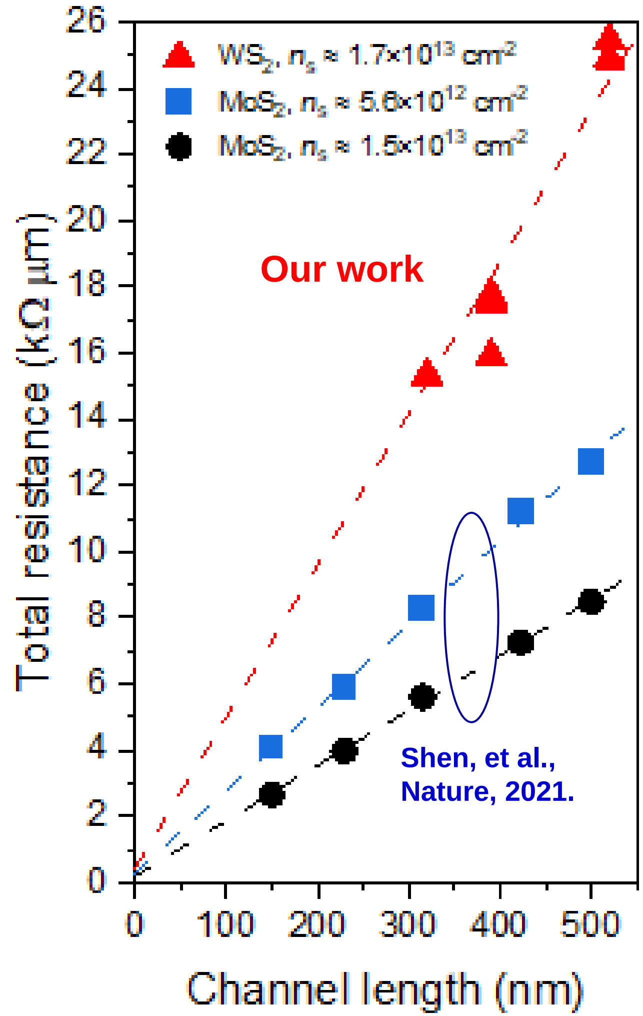
- **Semi-metallic contacts have low density of states near Fermi level, mitigating the effect of MIGS.**
- **Bi has lowest barrier height, followed by Sb and As.**

Our Work on Semi-Metallic Contacts to WS_2

- We have been investigating semi-metallic contacts to WS_2, which is more promising for CMOS:

L. Jin and S. J. Koester, IEEE EDL 43, 639-642 (2022).





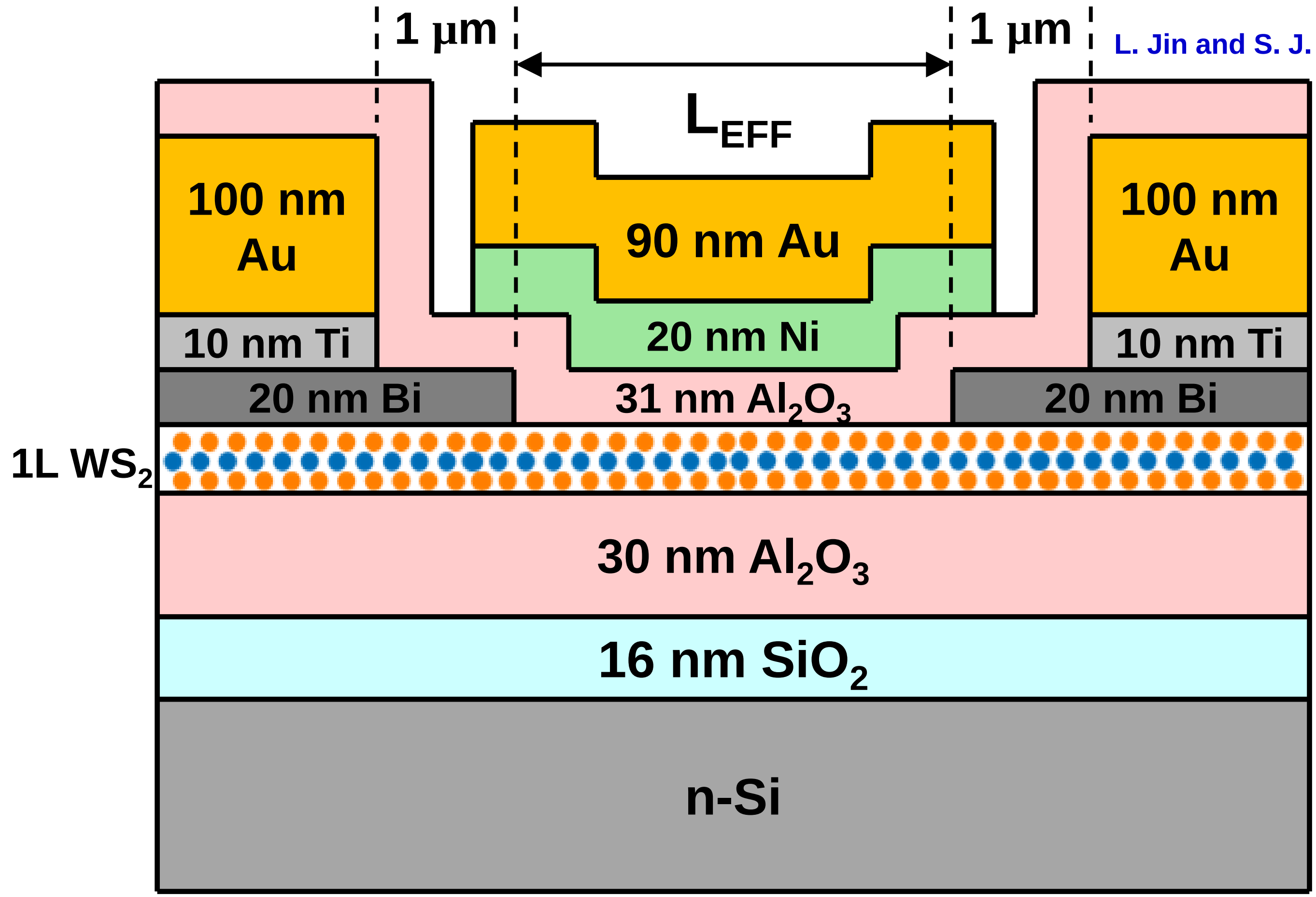
- **Demonstrated contact resistance as low as of R_C = 220 Ω-µm, consistent with results of Shen, et al. on MoS_2.**

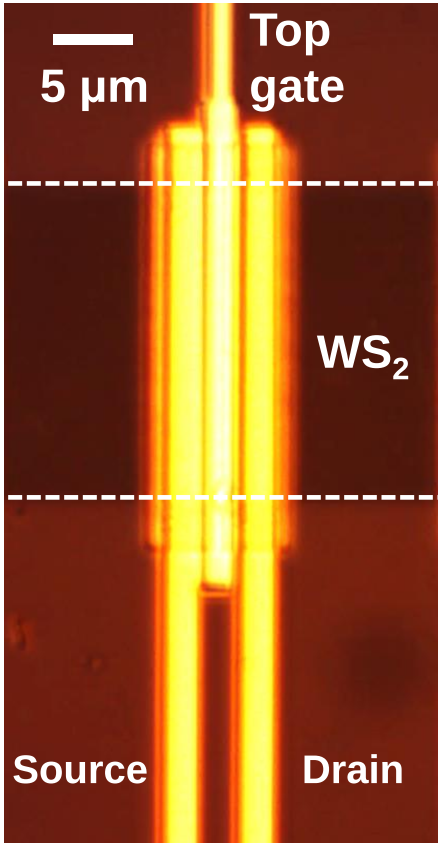
Work funded by Intel.

WS_2 MOSFETs with Bi Contacts

- Fabricated WS_2 MOSFETs with semi-metallic Bi contacts:

L. Jin and S. J. Koester, IEEE EDL 43, 639-642 (2022).





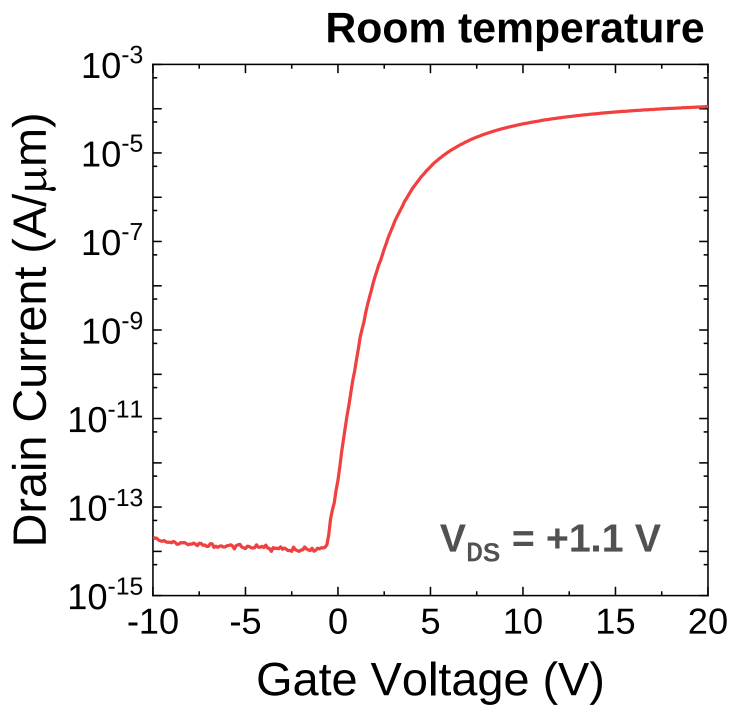
- **Devices used a dual-gate geometry to better study contacts.**

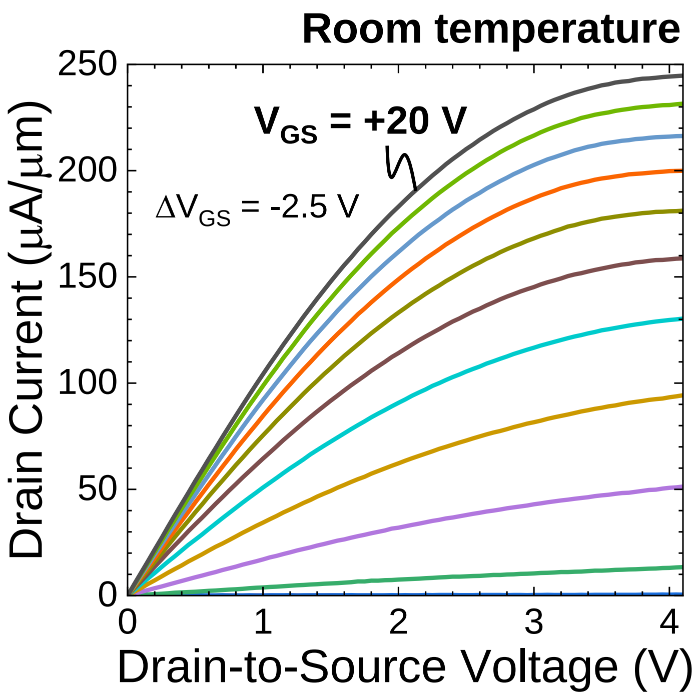
Work funded by Intel.

WS_2 MOSFETs with Bi Contacts

- Dual-gated results for devices with L_{EFF} = 0.32 μm:

L. Jin and S. J. Koester, IEEE EDL 43, 639-642 (2022).



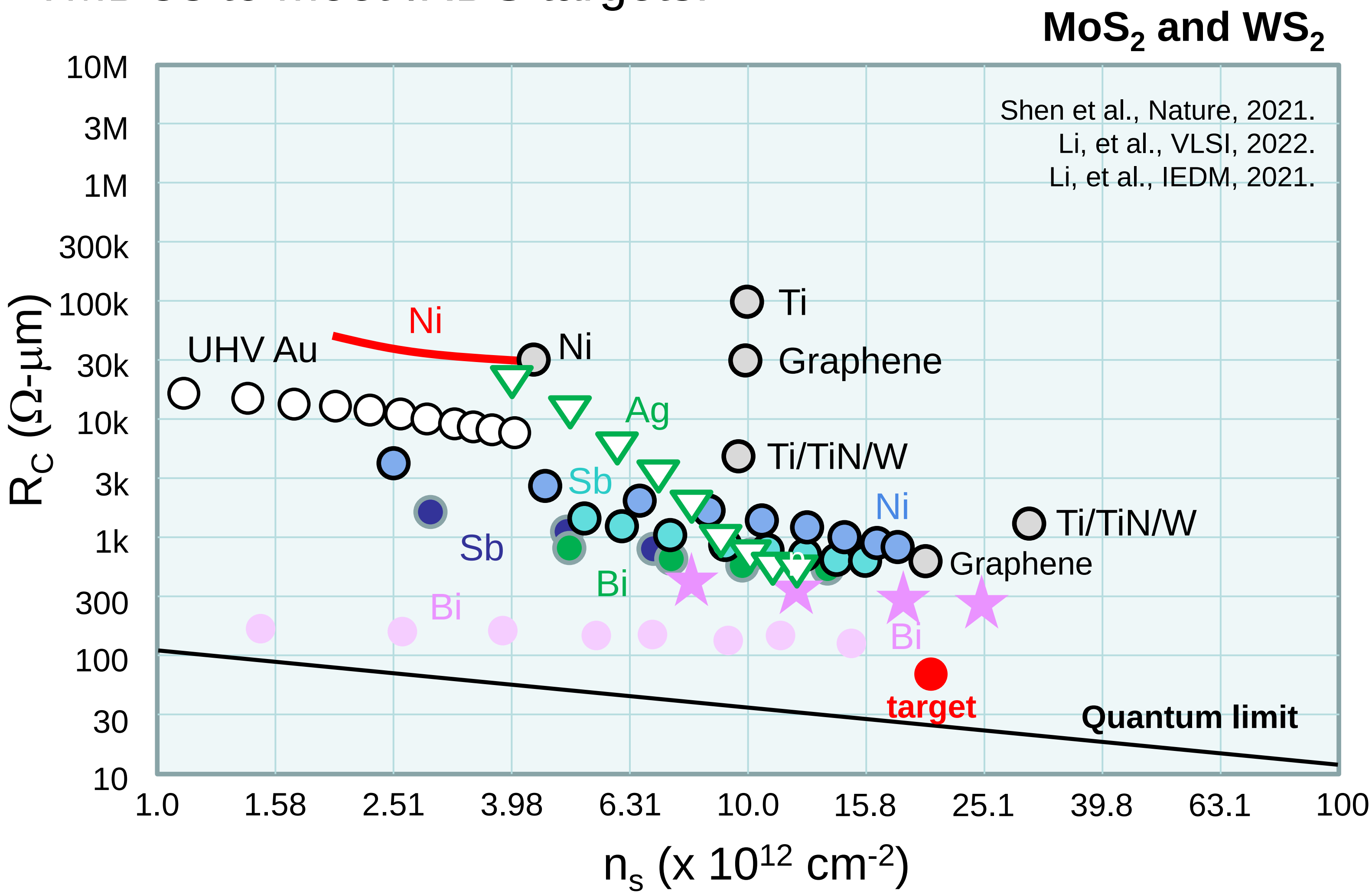


- **Devices have large (10^{10}) ON/OFF ratio and high drive current of 245 μA/μm (for relatively long gate length).**

Work funded by Intel.

2D Contact Resistance Progress

- Semi-metallic contacts have greatly improved prospects for TMDCs to meet IRDS targets:



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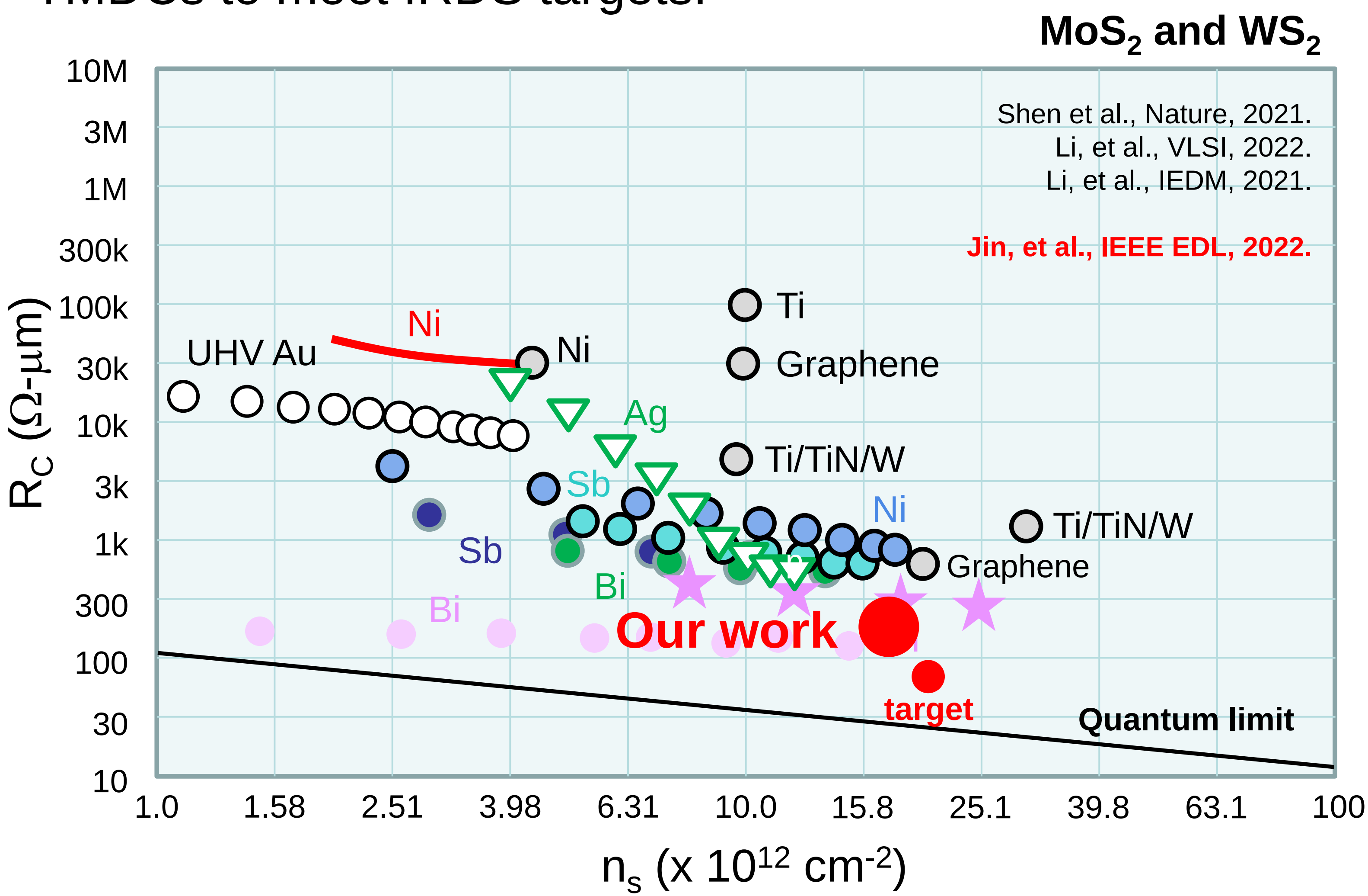
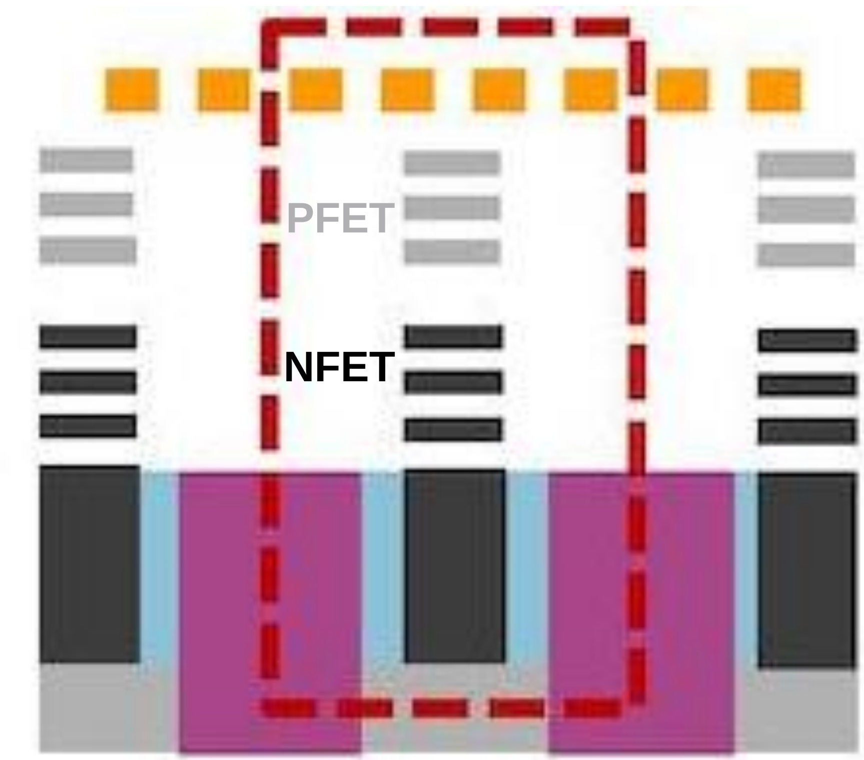


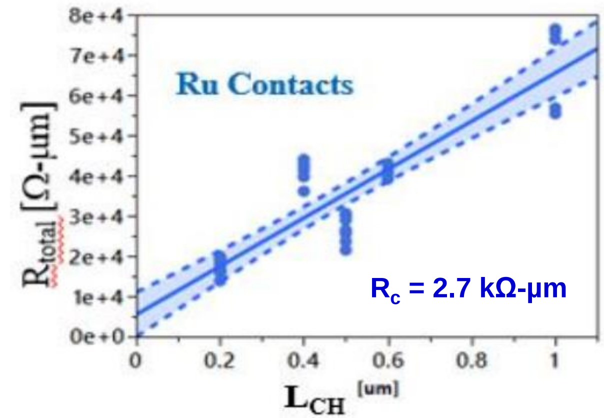
Future Logic Outlook

- Ultimate goal is stacked nanosheet CMOS.
- Recent work has started to address outstanding challenges for PFETs and 3D device structures.

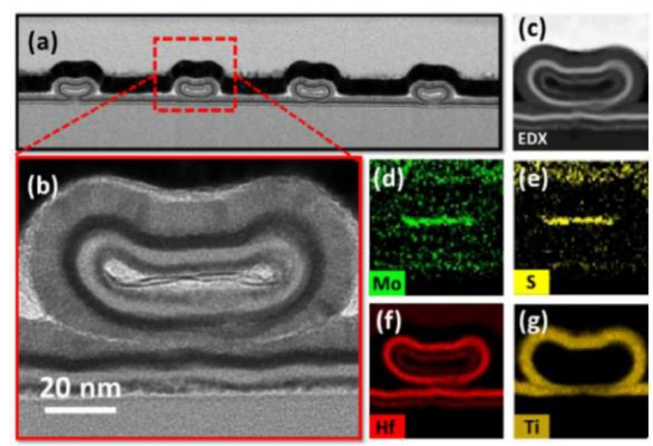
Source: imec



K. O'Brien, et al., IEDM, 2021.
Chiang et al., EDL, 2022.



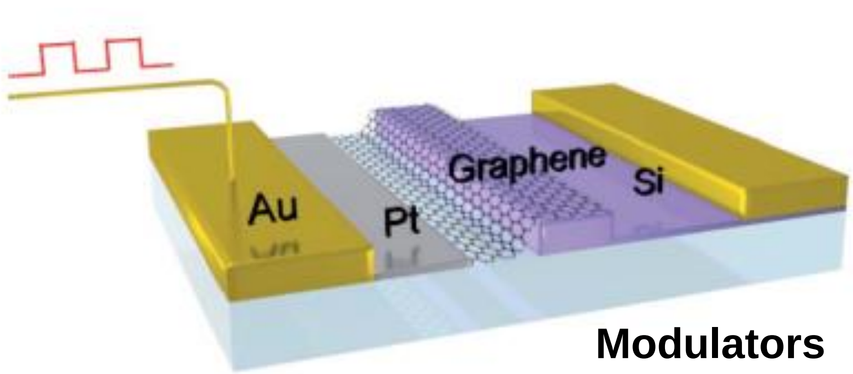
Y.-Y. Chung, et al., IEDM, 2022.



2D Integrated Optoelectronics

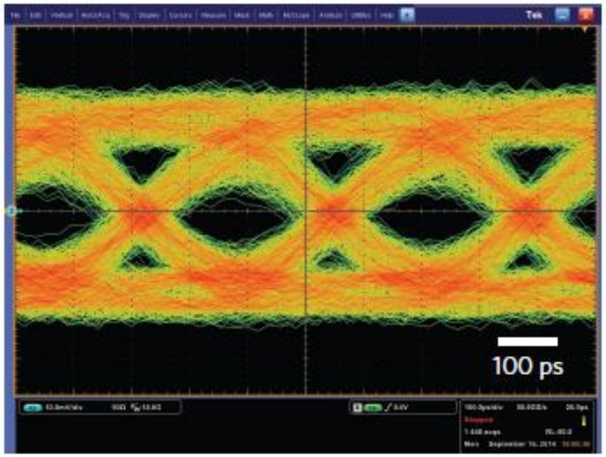
- 2D materials have a wide range of optoelectronic applications:

M. Liu, et al., Nature, 2021.



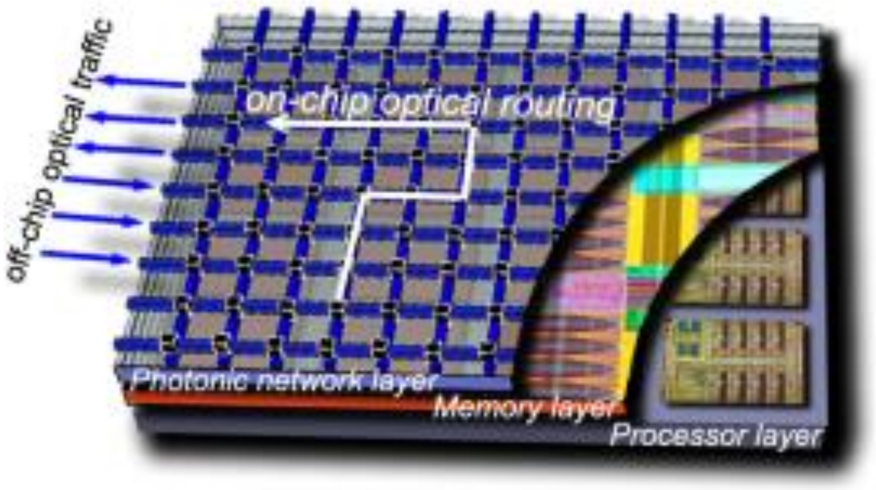
Modulators

N. Youngblood...S. J. Koester, et al., Nat. Photon. 9, 247, 2015.



Detectors

Source: IBM

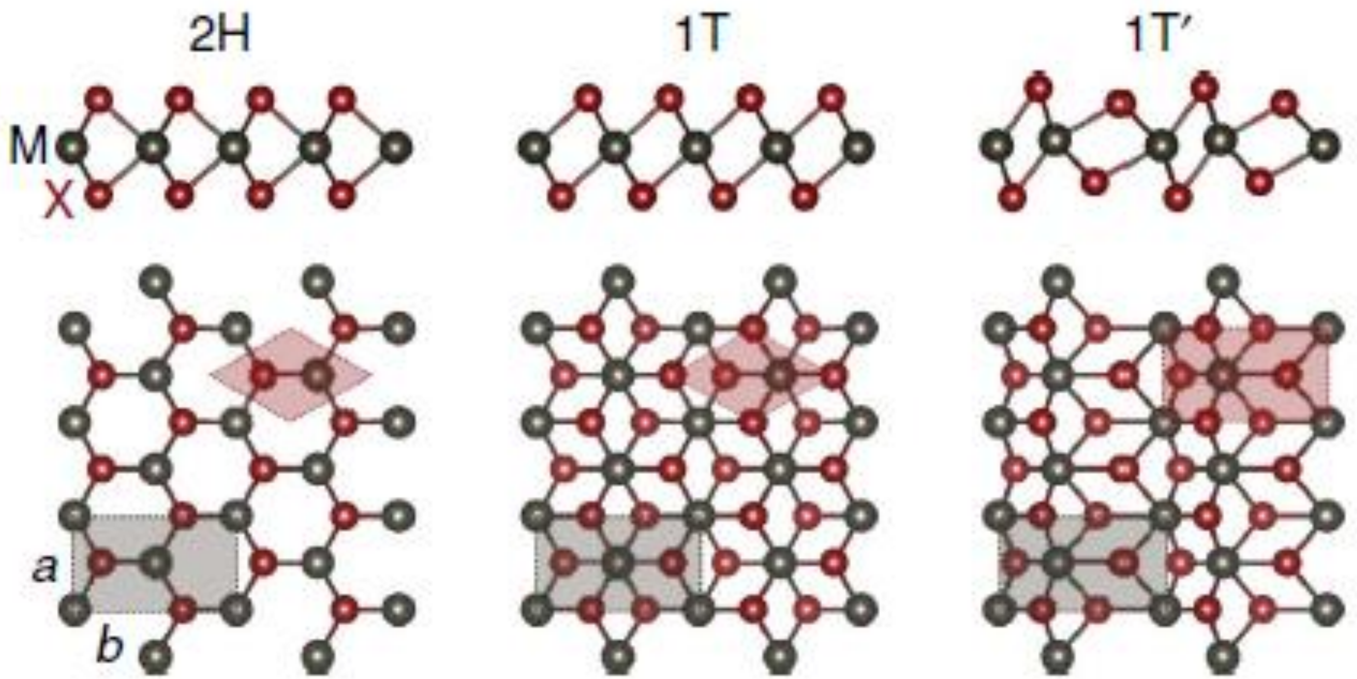


- **Could be used BEOL-compatible optical interconnects with high speed and large spectral bandwidth.**

Phase Engineering in 2D Materials

- TMDCs have the interesting property that can exist in either a semiconducting or metallic phase:

Y. Li, et al., Nat. Commun., 2015.



Hexagonal (2H)
Semiconducting

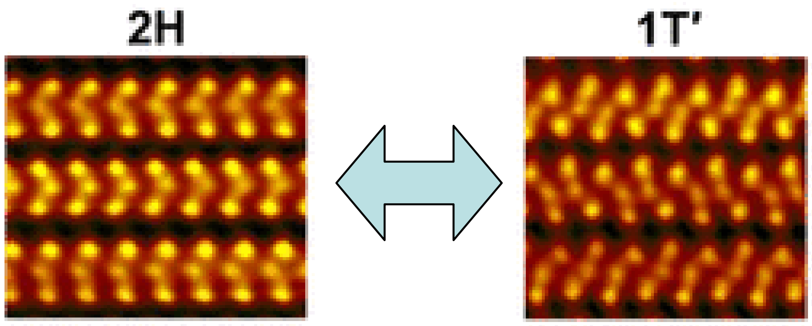
Tetragonal (1T)
Metallic

Monoclinic (1T')
Semi-metallic

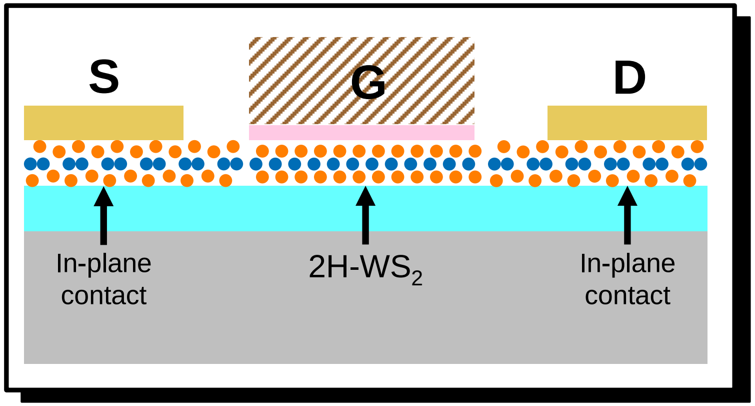
Phase Engineering in 2D Materials

- Ability to control TMDC phase could open the door to a multitude of applications:

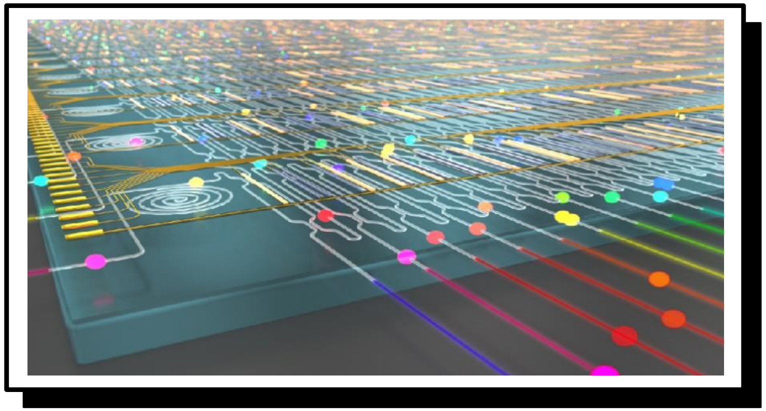
R. Ma...S. J. Koester, et al., ACS Nano 13, 8035-8046 (2019).



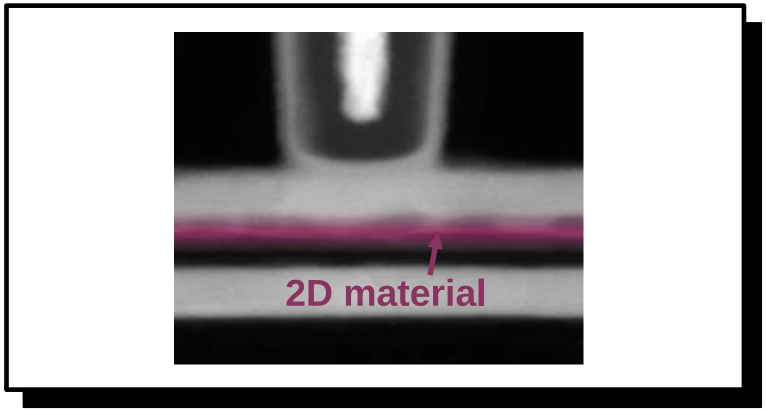
High-performance MOSFETs



Reconfigurable optics



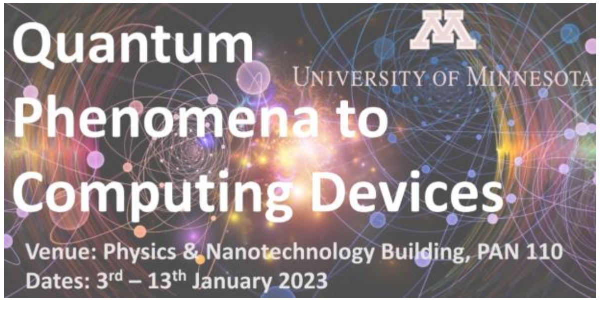
Memristors



Conclusions / Interactions

- 2D semiconductors have significant potential 3D / embedded memories and sub-1-nm-node CMOS applications.
- 2D materials also have potential for many emerging applications such as integrated optoelectronics and memristors.

- US / Korea research interactions could help to enhance technology development in 2D materials. Current interactions:
  - UNIST – Collaboration on novel 2D optoelectronic devices.
  - Organized Quantum Phenomena winter school at UMN in 2023, with support from Kyunghee University, Korean Science Foundation and NSF Global Quantum Leap program.
  - President Joan Gabel of the UMN signed with Hanyang University and KIST, working to expand these interactions Seoul National University as well.



Thank you for your attention!