College of Liberal Arts and Sciences

Wayne State University School of Medicine

National Institutes of Health

Substrate Dependence and Tunneling Operation of MoS2 Nanotransistors

Arthur Bowman III, Zhixian Zhou
Nanofabrication and Electron Transport Laboratory
Department of Physics and Astronomy

College of Liberal Arts and Sciences

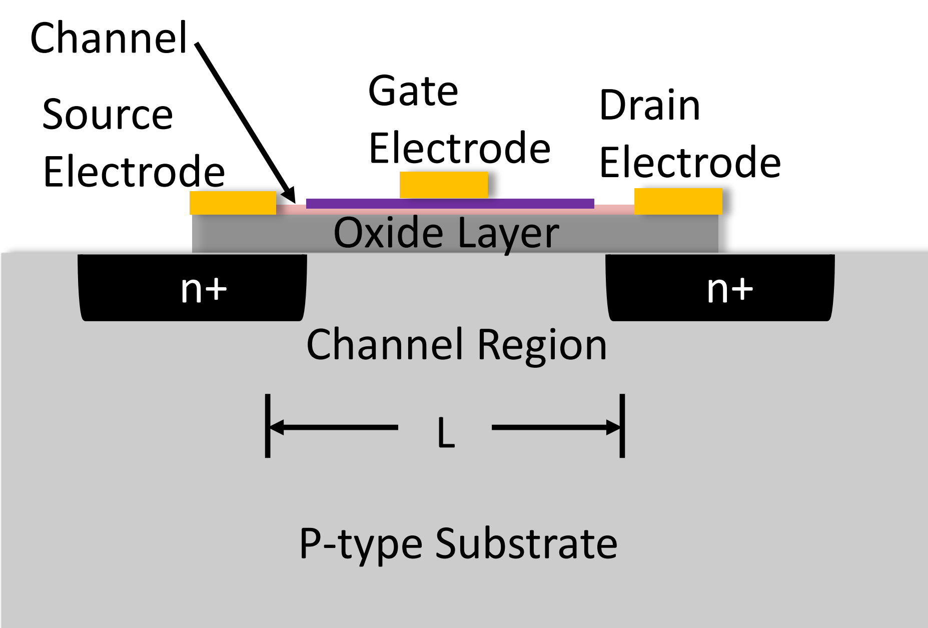
Overview

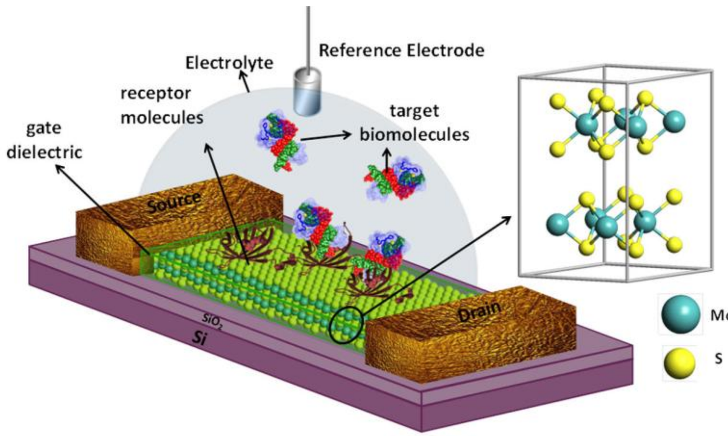
- Motivation
- Device Fabrication
- Results
- Conclusions

Motivation

Metal Oxide Field Effect Transistors (MOSFETs):

Source → Gate → Channel → Drain





Sarkar et al, ACS Nano (2014)

At the Nanoscale:

- Electrostatic effects
- Quantum Mechanical effects

Understanding them → Next-generation biosensors

College of Liberal Arts and Sciences

Motivation

Atomically thin, 2 Dimensional Channel Materials
→ **Transition Metal Dichalcogenides** (TMD)

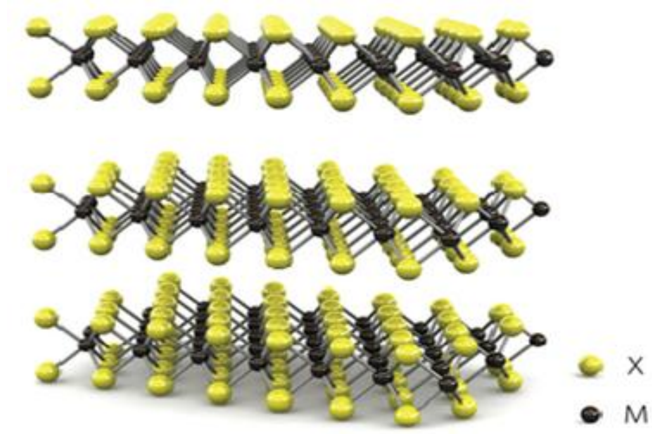
Transitional metal
Mo, W, Ti
(d-block elements)

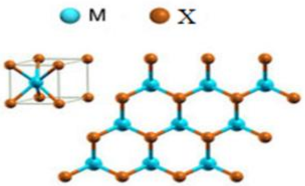
Chalcogen
S, Se, Te
(Oxygen group)

MX_2
e.g. MoS_2, $MoSe_2$, WS_2, WSe_2 etc.

Chemically stable, flexible and super strong with a reasonable band gap!

Hexagonal Layer Structure



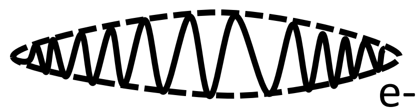


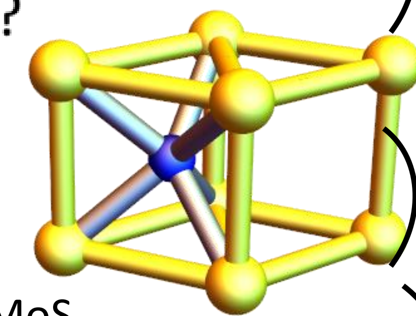
College of Liberal Arts and Sciences

Motivation

How do we measure TMD FET performance?

Carrier Mobility μ





MoS_2

Scattering Mechanisms that limit μ:

- Optical phonons
- Acoustic phonons

} Intrinsic

- Charged impurities at substrate/dielectric interface
- Surface "traps" due to roughness
- Channel defects

} Extrinsic

→ Achieve high μ with ultra smooth, high k dielectric substrate

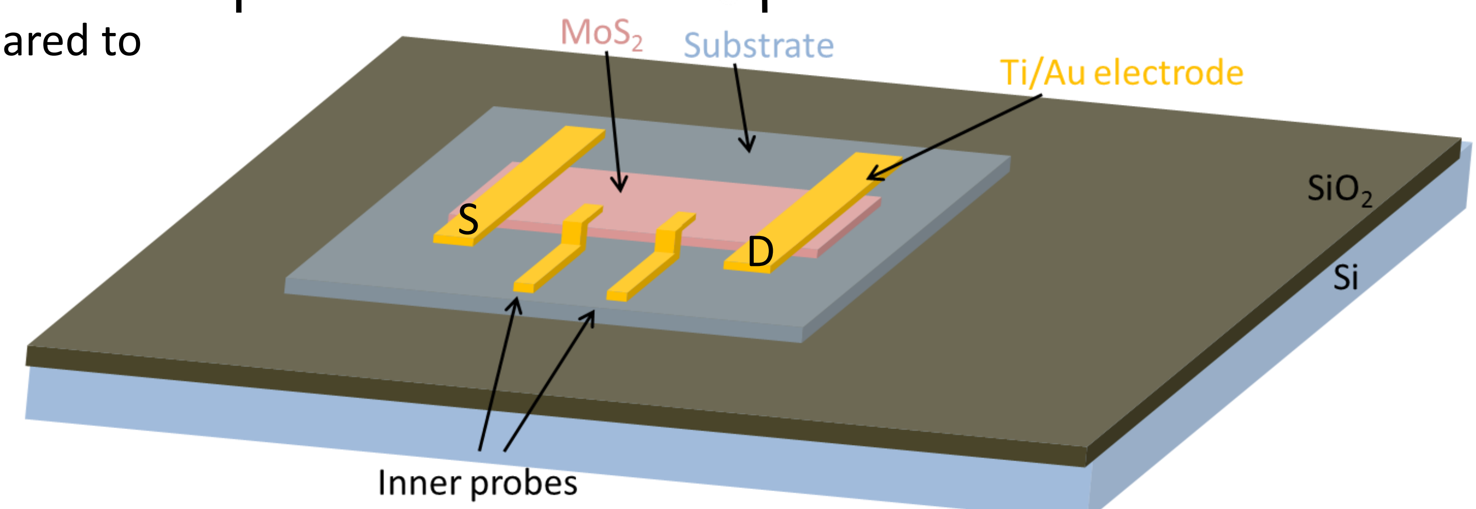
Kis et al. reported μ ~ 60 $cm^2V^{-1}s^{-1}$ at 240 K with high–k dielectric for monolayer MoS_2.
(Nature Materials **2013**)

Motivation

College of Liberal Arts and Sciences

Which Substrates Should We Study?

~290 nm clean SiO_2	OTMS SAM treated SiO_2	h-BN
Al_2O_3 on Si/SiO_2 ❖ Atomic Layer Depostion ~60 nm ❖ Higher dielectric constant compared to SiO_2	❖ Si/SiO_2 substrates modified with OTMS SAMto create a hydrophobic surface	❖ Higher excitation energy of optical phonons ❖ High dielectric constant ❖ Ultra Smooth Surface ❖ Impurity free ❖ 2D layer structure similar to TMD

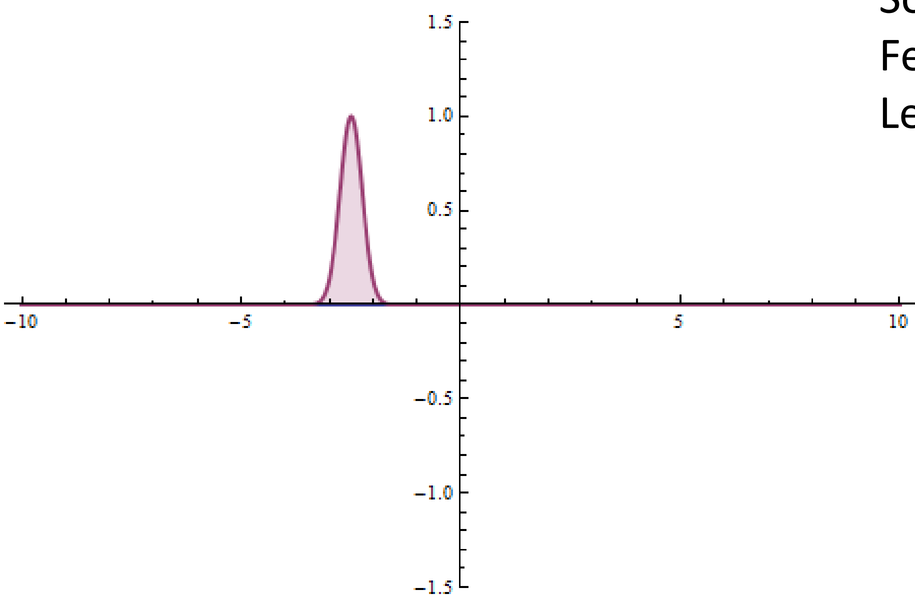


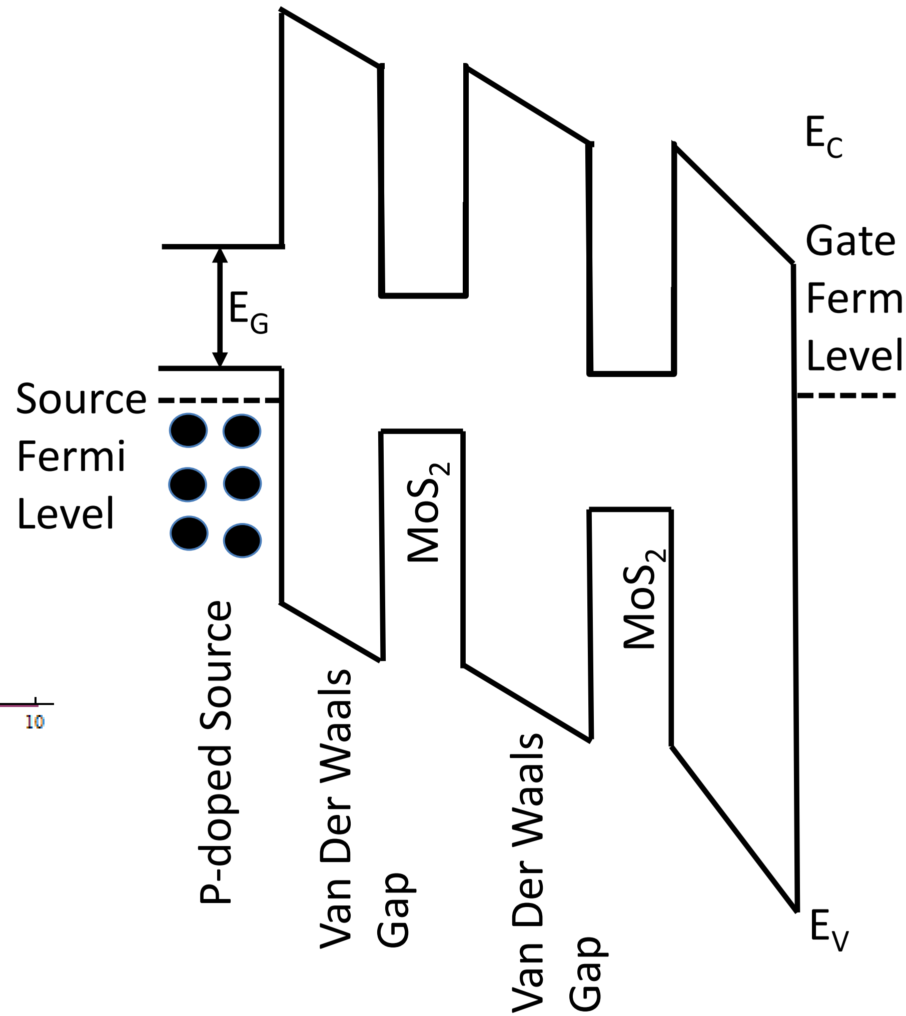
Motivation

Tunnel Field Effect Transistors (TFET)

- FET Operation through quantum tunneling
- Not much supply voltage needed

→ Low Power Applications





Motivation

How can we improve TFET Performance?

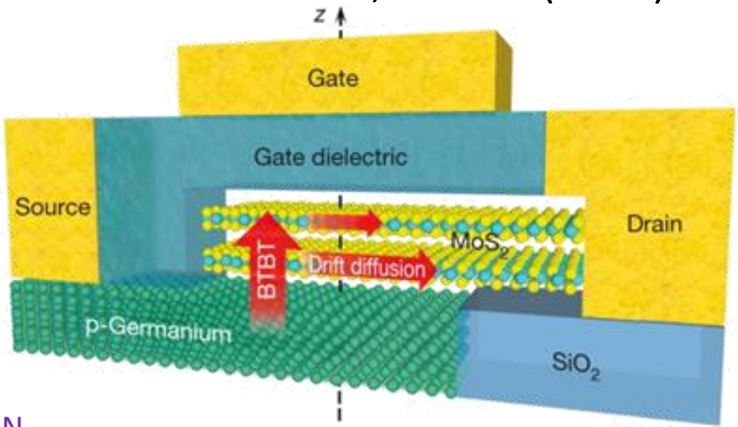
- **Subthreshold Swing (SS)**
- Thermionic limit

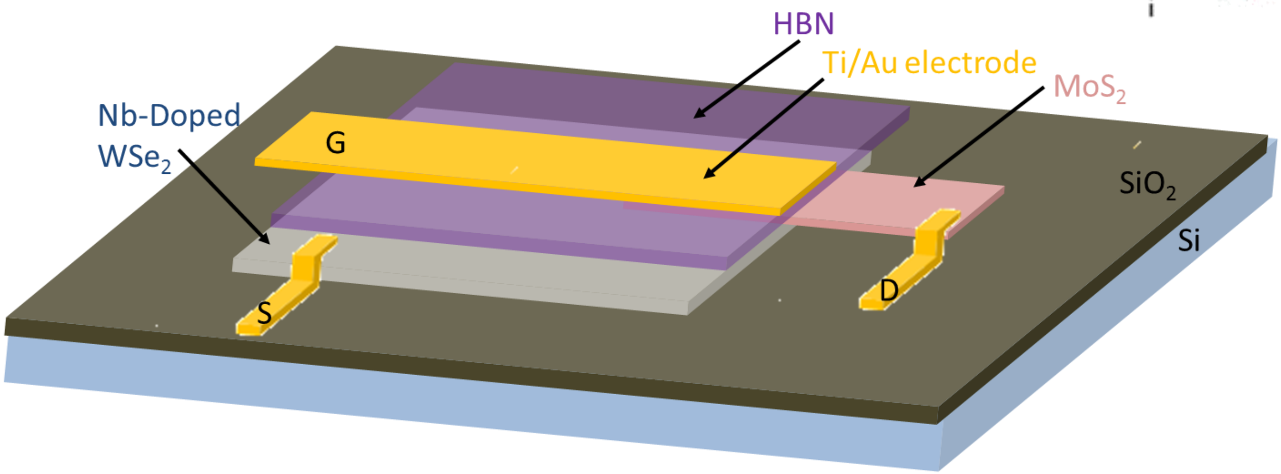
→ Achieve High Performance

Subthermionic TFET with

Nb-doped WSe_2 source, Novel Gates

Sarkar et al, Nature (2015)

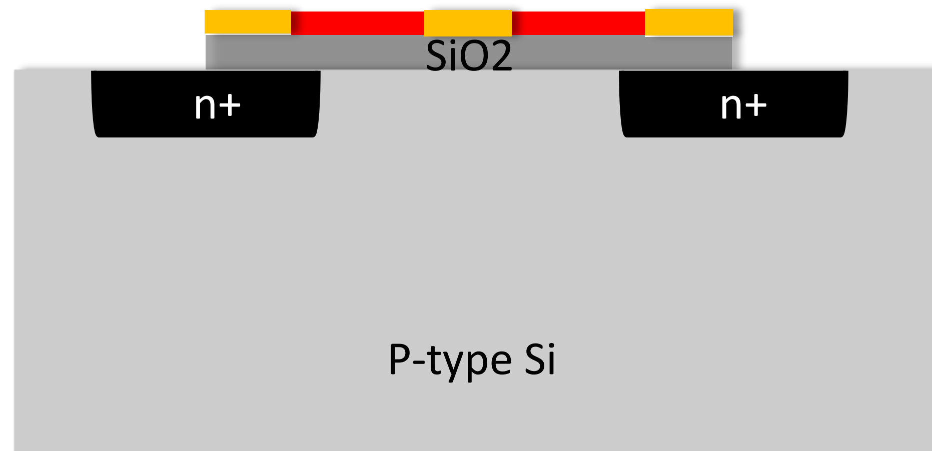


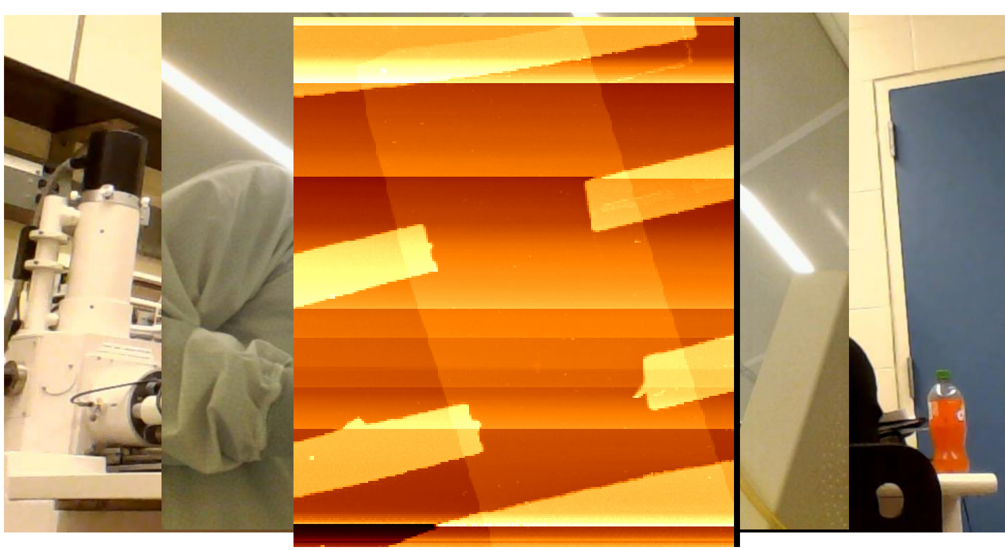


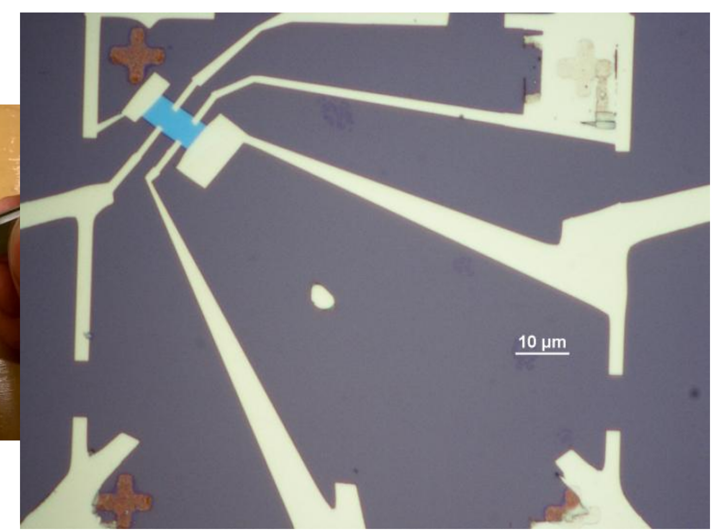
College of Liberal Arts and Sciences

Device Fabrication

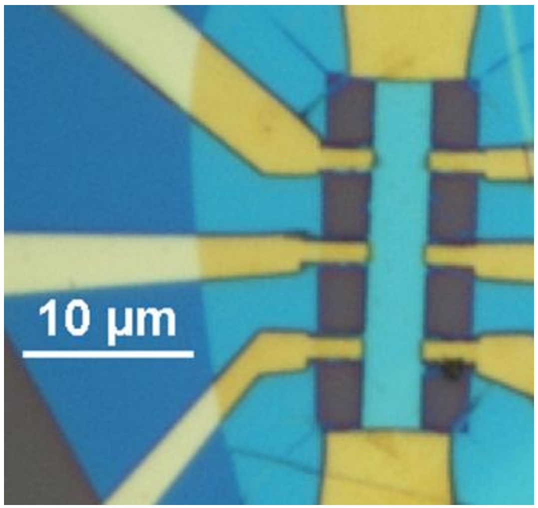
- Begin with commercial SiO_2 on P Type Si Substrate
- Mechanical Exfoliation of TMD
- Transfer onto Substrate
- Electron Beam Lithography
- Metal Deposition
- Liftoff



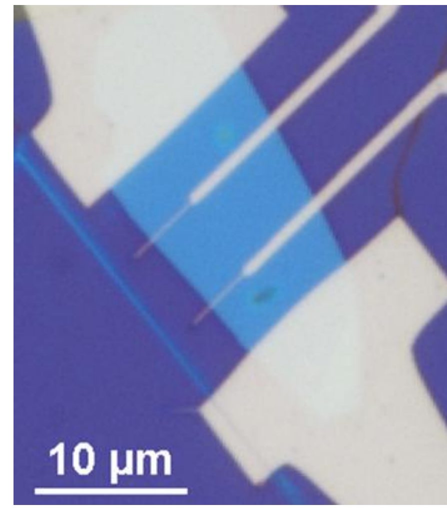


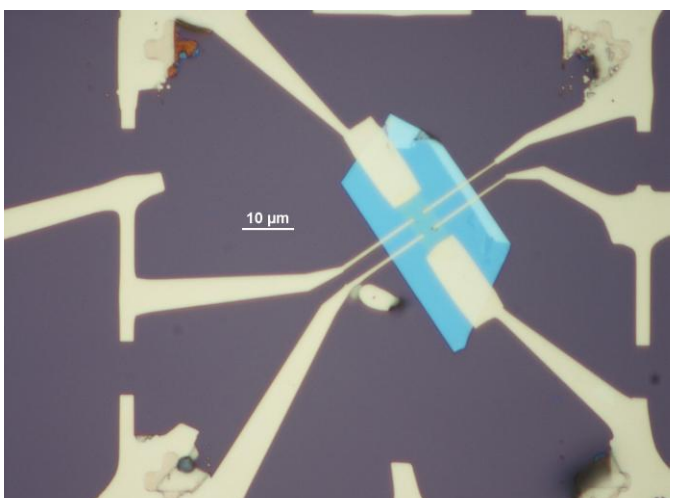


Results

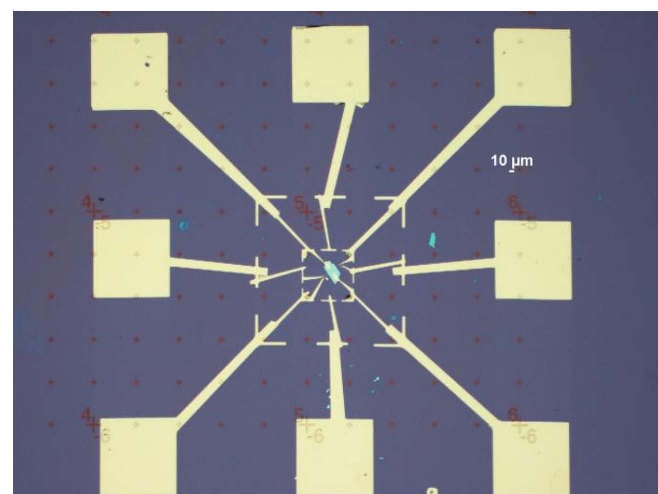


On HBN





On SiO_2

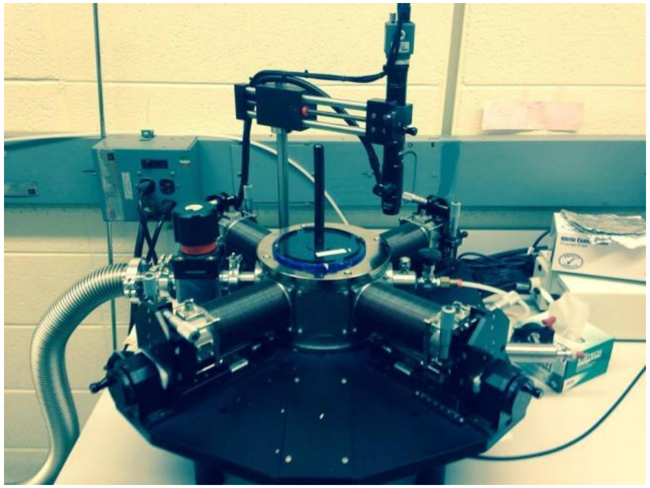


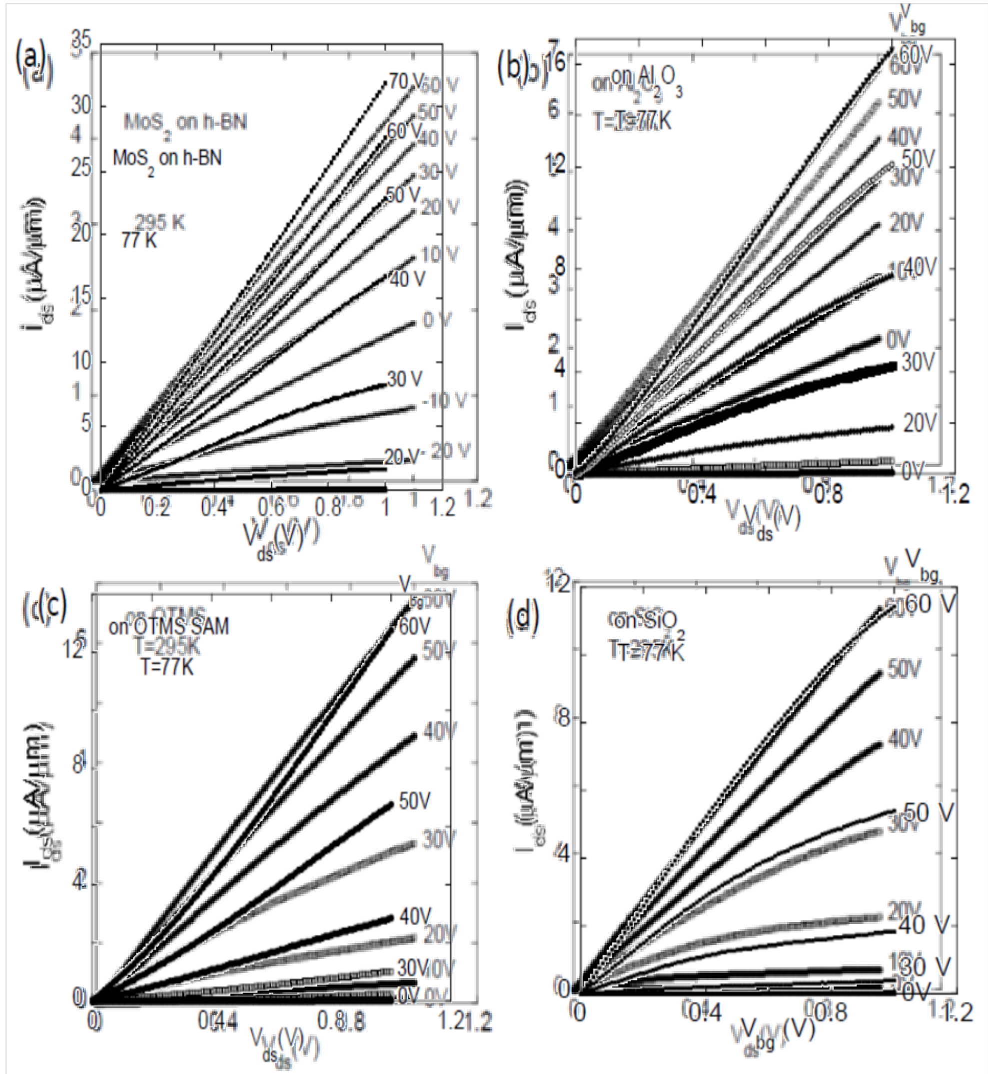
College of Liberal Arts and Sciences

Results

How do we know we've made a good device?

- Current Voltage Characteristics (I-V curves)
- Ohmic contact on all substrates
- HBN looks best





College of Liberal Arts and Sciences

Results

Field Effect Mobility

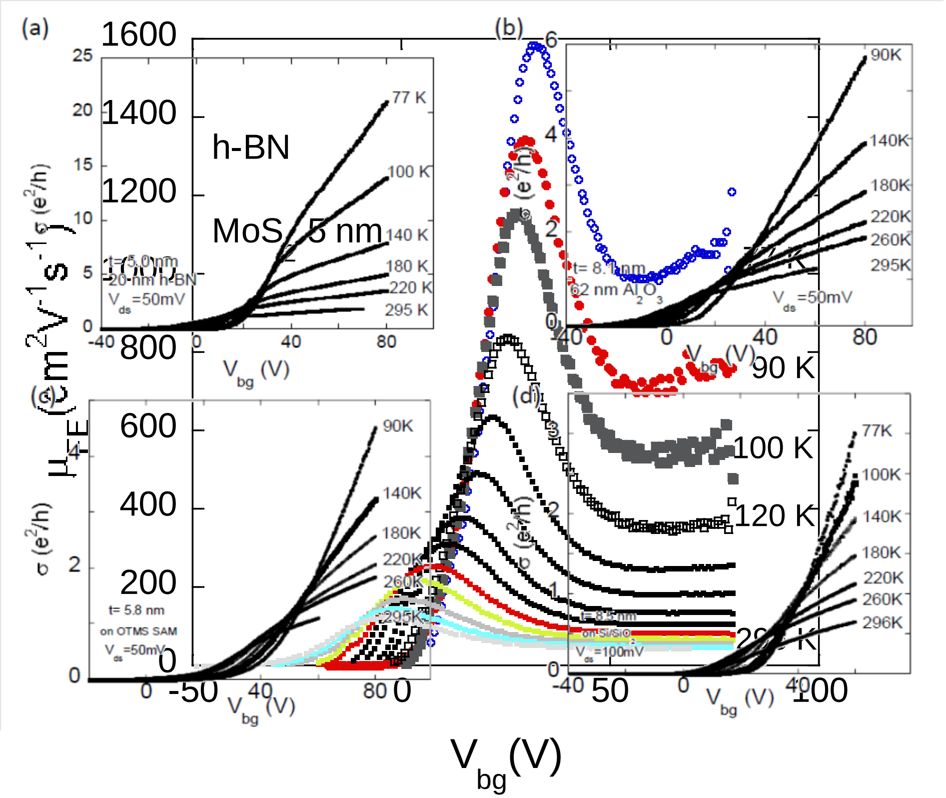
- Corresponds to bulk material
- I-V curve → Conductivity

→ Field effect mobility, geometric capacitance

- h-BN looks best

$$\sigma\ (\mu S) = \frac{I_{DS}}{V_3 - V_2}\frac{l}{w}$$

$$\mu\left(\frac{cm^2}{Vs}\right) = \frac{1}{C}\frac{\partial\sigma}{\partial V_{DS}}$$



Results

Hall Effect Mobility

- Corresponds to bulk + surface material
- I-V curve → Hall coefficient

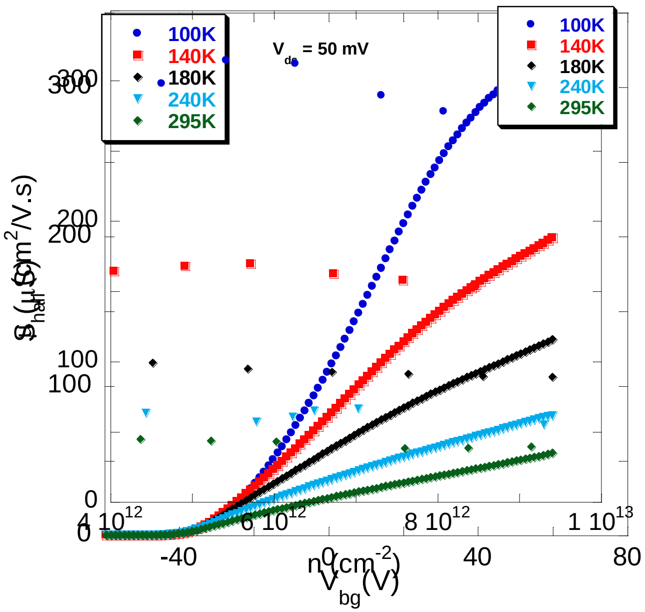
→ carrier density

→ (along with conductivity) Hall mobility

- Agrees well with field effect mobility on h-BN

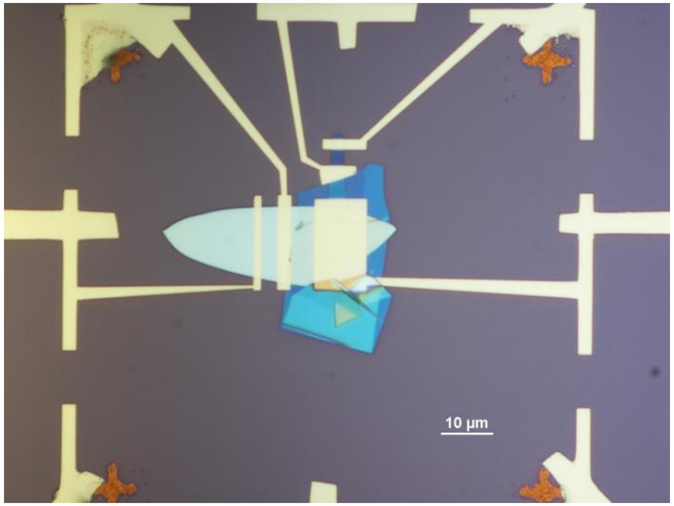
$$R\left(\frac{m^3}{C}\right) = \frac{V_{xy}}{I_{DS}} \qquad n(m^{-3}) = \frac{1}{eR}$$

$$\mu_H\left(\frac{cm^2}{Vs}\right) = \frac{\sigma}{ne}$$



College of Liberal Arts and Sciences

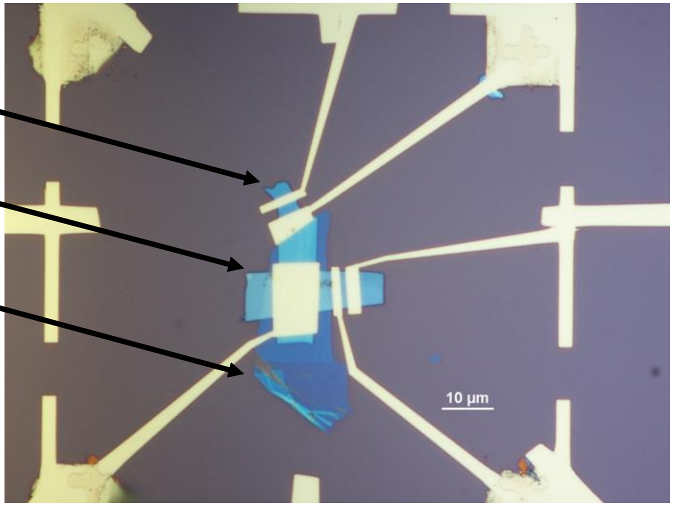
Results

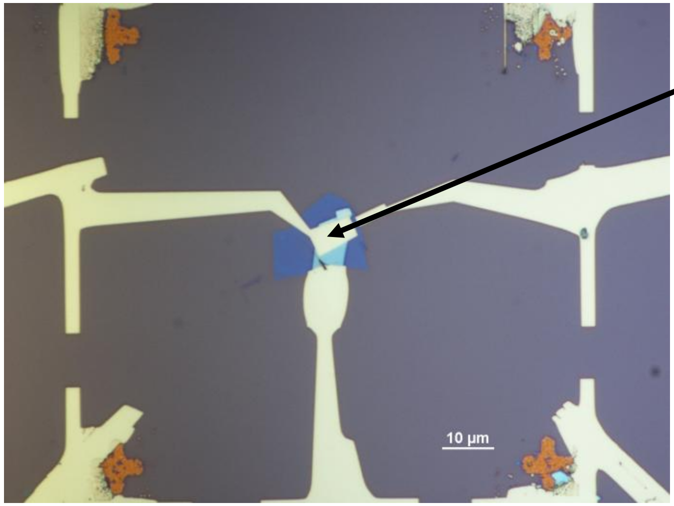


MoS$_2$

Nb-doped WSe$_2$

HBN

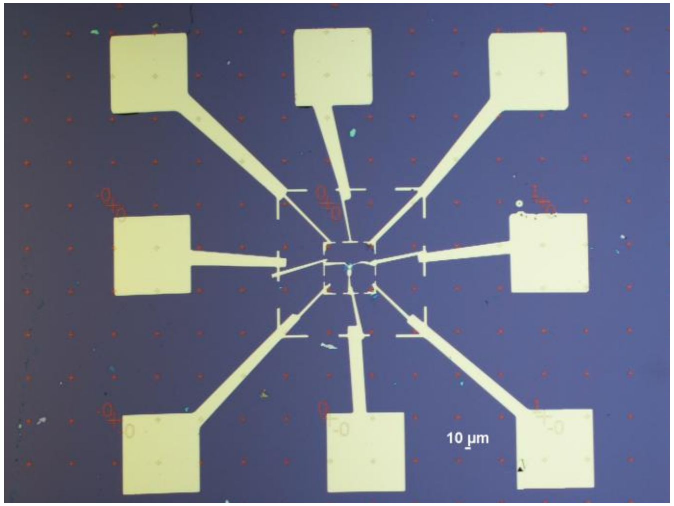




Junction Area

MoS$_2$ Channel Thicknesses:

- 9 nm
- 5 nm
- 2 nm



College of Liberal Arts and Sciences

Results

How do we prove tunneling operation?

Gate Dependence

- TFET channel thickness 9 nm:

SS = 147 mv/decade

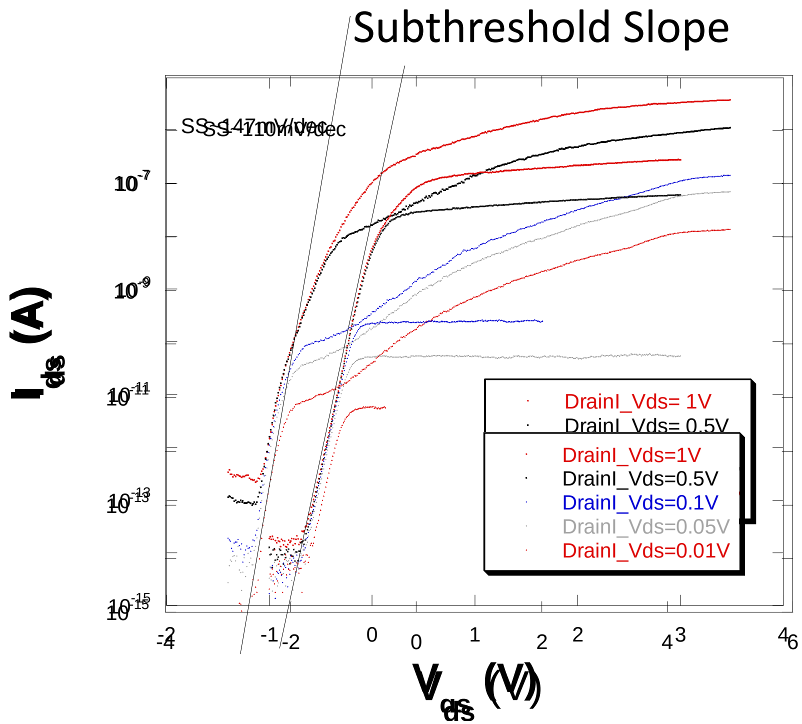
- Channel thickness 2.3 nm:

SS = 110 mv/decade

- Still above thermionic limit with HBN gate

$$SS\left(\frac{mv}{dec}\right) = \left[\frac{d}{dV_{GS}}\log(I_{DS})\right]^{-1}$$

9 nm



Conclusions

College of Liberal Arts and Sciences

Substrate Dependence

•Optical-phonon scattering remains dominant below ~ 100 K on h-BN

•On all other substrates extrinsic scattering mechanisms start to degrade the carrier mobility below ~ 200 K

• The ultra-smoothness and high k environment of h-BN improves mobility

IN THE FUTURE: PHASE-ENGINEERED DIELECTRICS

Tunneling Operation

•Subthreshold Swing of 0.05 % Nb-doped WSe_2/ MoS_2/h-BN devices were still above thermionic limit of 60 mv/decade

•This could be due to intrinsic limitations of h-BN gates or non ideal fabrication

•More h-BN gated devices, experiments with other gate materials needed

IN THE FUTURE: IONIC LIQUID GATING, BV DOPING

Acknowledgement

The authors would like to acknowledge:



- Nanofabrication and Electron Transport Labortatory Senior Students:
  Hsun Jen Chuang, Bhim P. Chamlagain, Meeghage M. Perera
- Wayne State Universtiy nFab core facility staff:
  William Funk, Dan Durisin
- Initiative for Maximizing Student Development (IMSD) Program
- National Institute of Health

For making this research possible