2D FETs with MoS_2, WSe_2, and black phosphorous toward practical electronics

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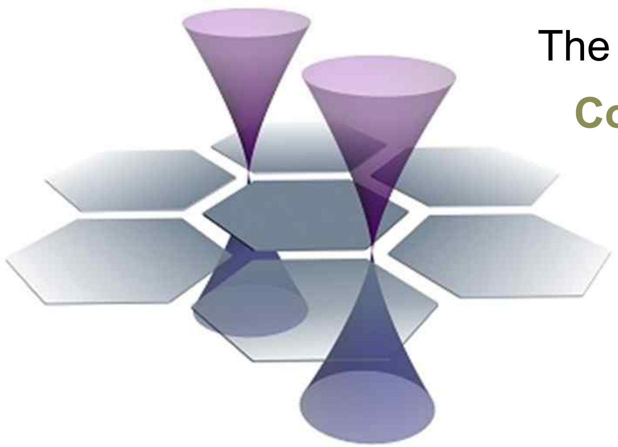
Yonsei University Electron Device Lab.

YONSEI UNIVERSITY

Introduction



The most **widely studied** 2-D material

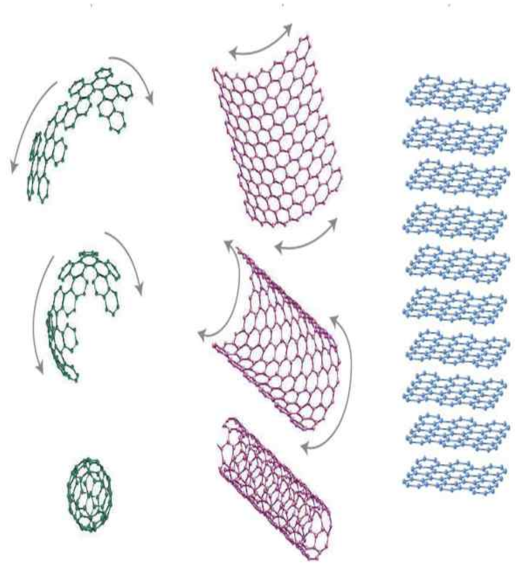
Conical Dirac spectrum

Energy states **without a bandgap**

High mobility (< 100000cm^2/Vs)

More **conductive** than copper

Attractive **optical** phenomena

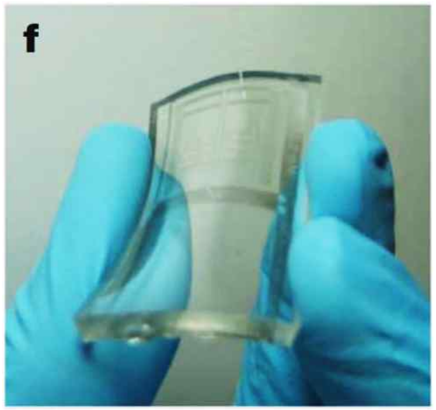


More **Flexible** than rubber

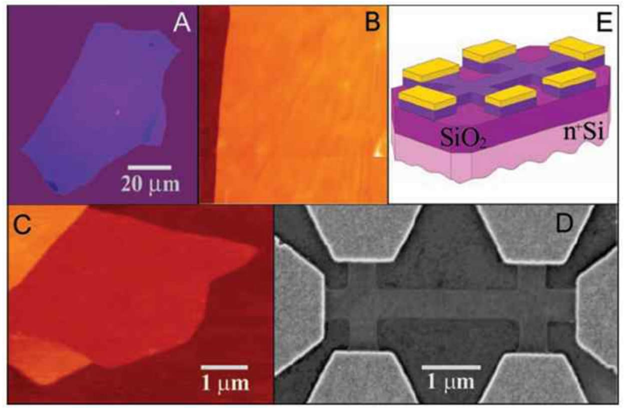
Stretchable material

Stronger than diamond

Various formation (ribbon, tube, ball...)



K. S. Kim *Nature* **457**, 706 (2009)



K. S. Novoselov et al.Science **306**, 666 (2004)

Limitation of Graphene

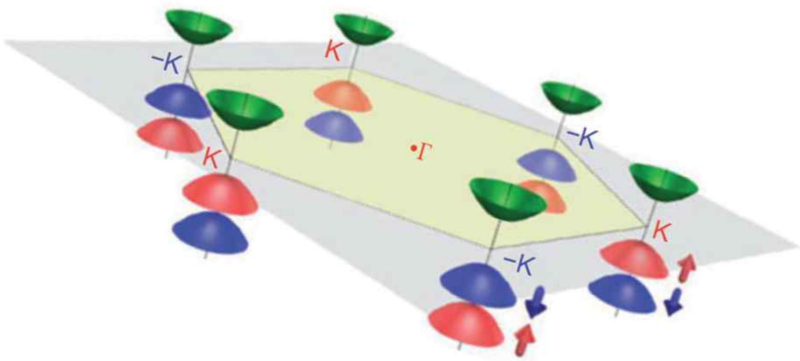
Gapless Band Structure → Unsuitable for **switching devices**

Transition Metal Dichalcogenides

Transition Metal Dichalcogenides (MX_2)

- Similar storyline of the **graphene family**
- 2D and **layered** (thin-film) structures
- **Covalently bonded** X-M-X
  - held together by **Van der Waals interactio..**
- **Broken symmetry** in atomic basis

↪ can make **Band Gap** of ~ 1 eV



M. Chhowala et al. *Nature Chem.* **5**, 263 (2013)

	$-S_2$	$-Se_2$	$-Te_2$
Nb	Metal	Metal	Metal
Ta	Metal	Metal	Metal
Mo	Semiconducting (1L : 1.8eV, Bulk : 1.2eV)	Semiconducting (1L : 1.5eV, Bulk : 1.1eV)	Semiconducting (1L : 1.1eV, Bulk : 1.0eV)
W	Semiconducting (1L : 1.9eV, Bulk : 1.4eV)	Semiconducting (1L : 1.7eV, Bulk : 1.2eV)	Semiconducting (1L : 1.1eV)

modified version of Q. H. Wang et al. *Nature Nanotech.* **7**, 699 (2012)

Recent Progress on 2D Nanosheet in World Researches

FET –countless many reports (e.g. A. Kis in Nat Nano. 2011)

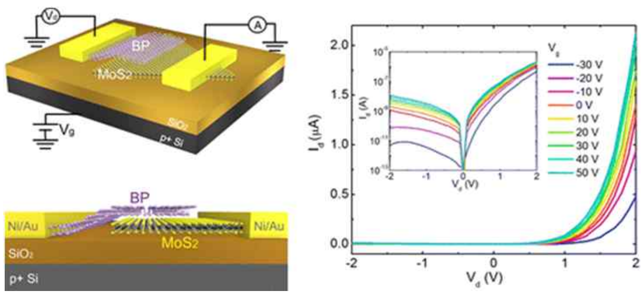
1. Field-Effect Transistors Built from All Two-Dimensional Material Components, ***ACS Nano, 8***, 6259 (2014)
2. Impact of Contact on the Operation and Performance of Back-Gated Monolayer MoS_2 Field-Effect-Transistors, ***ACS Nano, 9***, 7904 (2015)
3. Highly Stable, Dual-Gated MoS_2 Transistors Encapsulated by Hexagonal Boron Nitride with Gate-Controllable Contact, Resistance, and Threshold Voltage, ***ACS Nano*, 9**, 7019 (2015)

CMOS –several reports

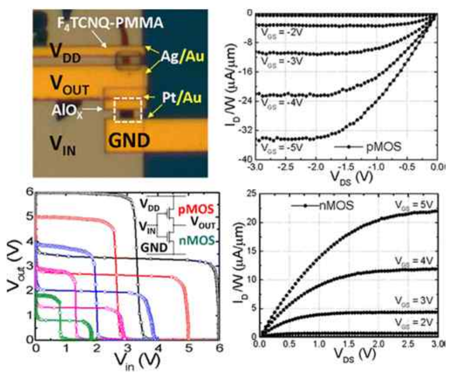
1. High gain, low noise, fully complementary logic inverter based on bi-layer WSe_2 field effect transistors, ***Appl. Phys. Lett.***, **105**, 083511 (2014)
2. High Gain Inverters Based on WSe_2 Complementary Field-Effect Transistors, ***ACS Nano*, 8**, 4948 (2014)
3. High-Performance WSe_2 Complementary Metal Oxide Semiconductor Technology and Integrated Circuits, ***Nano Letters*, 15,** 4928 (2015)

pn diode-several reports

1. Dual-Gated MoS_2/WSe_2 van der Waals Tunnel Diodes and Transistors, ***ACS Nano*, 9**, 2071 (2015)
2. Black Phosphorus–Monolayer MoS_2 van der Waals Heterojunction p–n Diode, ***ACS Nano*, 8**, 8292 (2014)
3. Epitaxial growth of a monolayer WSe_2-MoS_2 lateral p-n junction with an atomically sharp interface, ***Science*, 249,** 524 (2015)
4. Vertical Heterostructure of Two-Dimensional MoS_2 and WSe_2 with Vertically Aligned Layers, ***Nano Letters*, 15**, 1031 (2015)
5. Lateral epitaxial growth of two-dimensional layered semiconductor heterojunctions, ***Nat. Nanotechnol.*, 9**, 1024 (2014)



ACS Nano, **8**, 8292 (2014)



Nano Letters, **15,** 4928 (2015)

Outline

- Introduction : Outline and Motivation
- Progress on 2D Nanosheets in World Researches

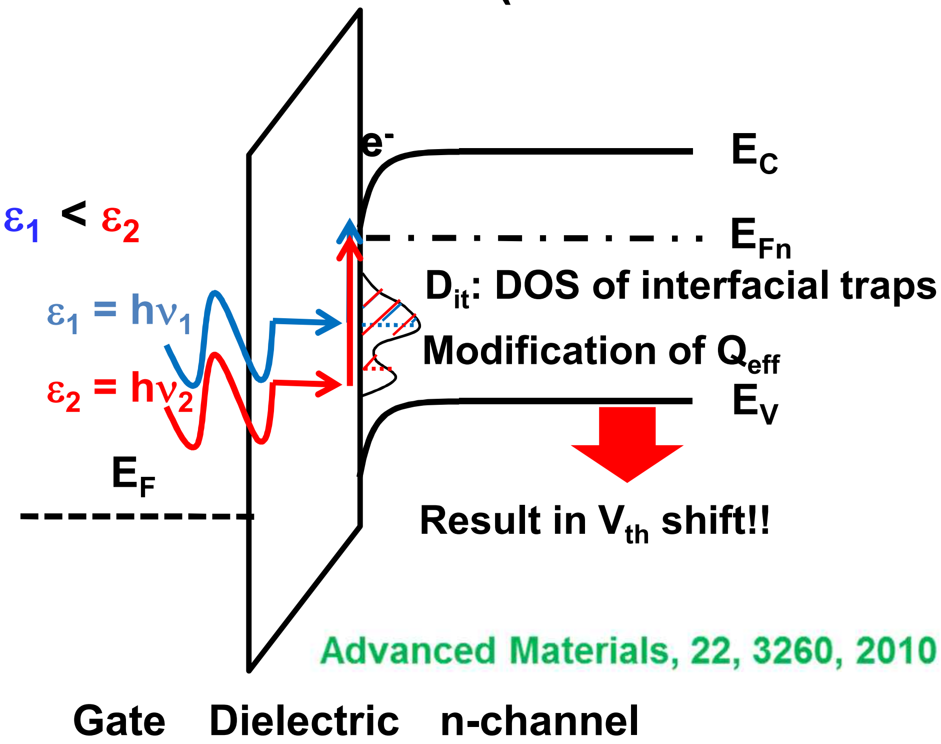
- Progress on 2D Nanosheets in our Lab
  - Top-gate MoS_2 FET, Nonvolatile Memory FETs and P-N diode
  - 2D-2D, 2D-1D, 2D-Organic Hybrid Complementary Inverter
  - Black Phosphorous Dual Gate FETs
  - NiOx-MoS_2 van der Waals junction MESFET
- Summary

Photo-Excited Charge Collection Spectroscopy

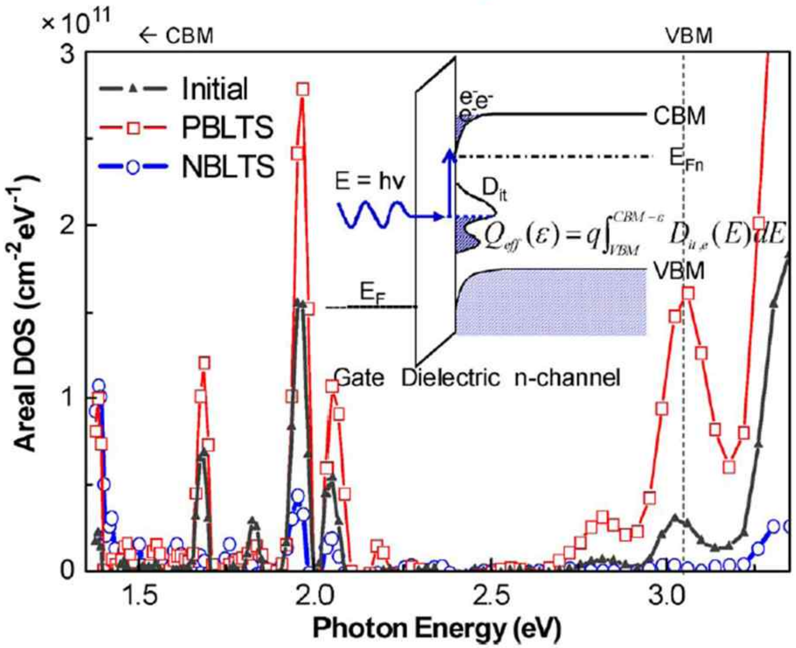
For n-channel FET (i. e. oxide semiconductor)

IGZO

LG Display



Advanced Materials, 22, 3260, 2010



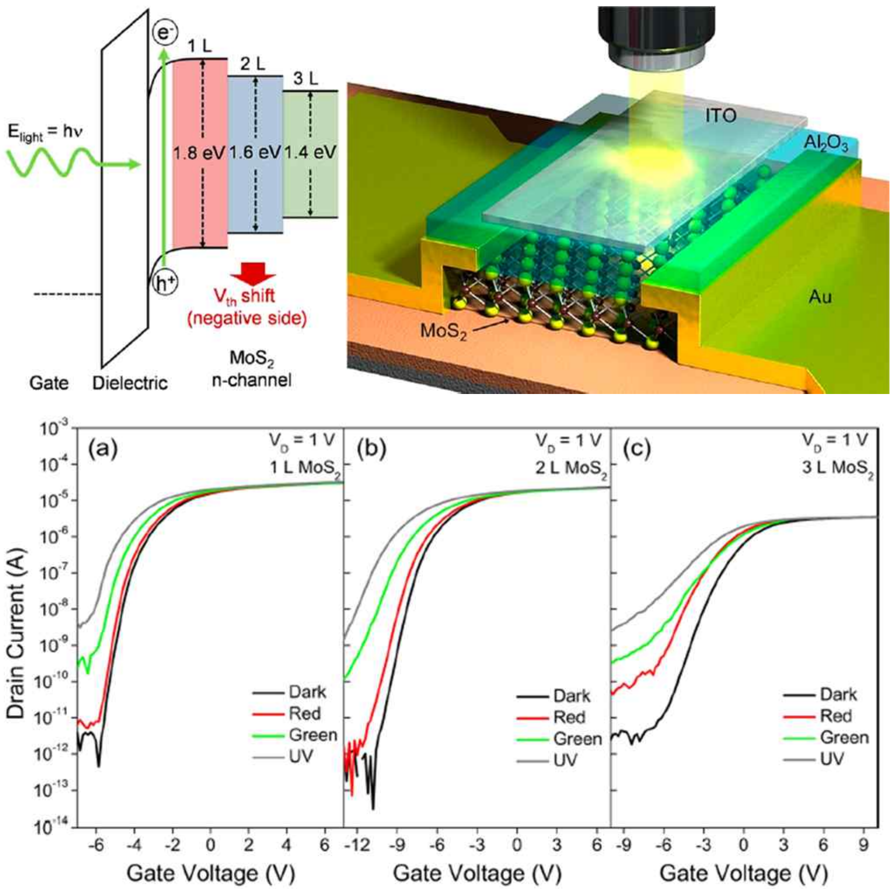
Making on-state (accumulation) ➡ All interfacial (electron) traps are occupied…

$$\Delta V_{th}(\varepsilon) \Rightarrow \Delta Q_{eff} = C\,\Delta V_{th} \Rightarrow D_{it}(CBM-\varepsilon) = \frac{C_{ox}}{q}\frac{\partial V_{th}(\varepsilon)}{\partial \varepsilon}$$

Recent Progress on 2D Nanosheet (IM)

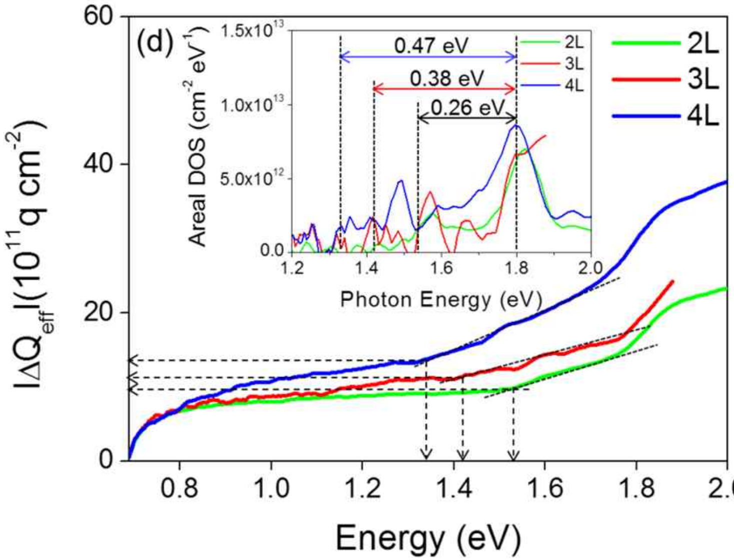
1.Nanosheet Band-Gap & Thickness Modulation

MoS_2 Nanosheet Phototransistors with Thickness-modulated Optical Energy Gap, *Nano Lett.* (2012)



2. Nanosheet-Dielectric Interface Trap

Trap density probing on top-gate MoS_2 Nanosheet field-effect transistors by photo-excited charge collection spectroscopy, *Nanoscale* (2015)

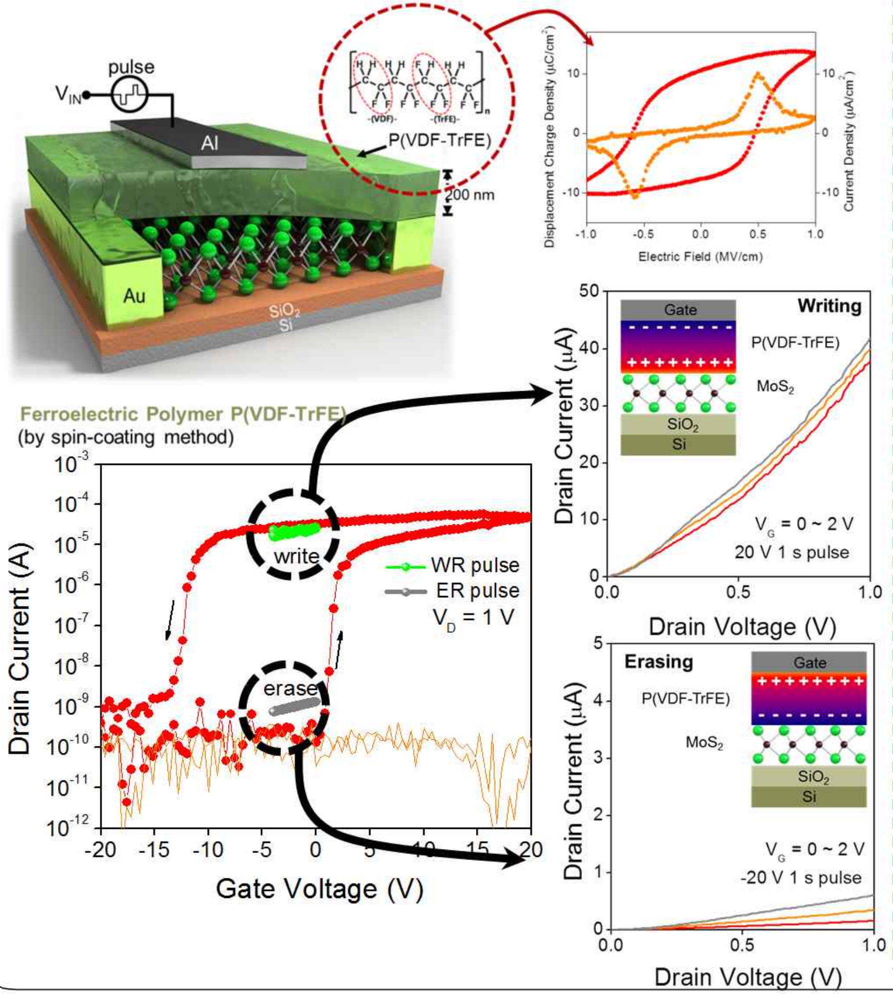


Number of MoS_2 layer	Trap density ($X10^{12}$ cm^{-2}) obtained from			
	Hystere-sis	PECCS	Hysteresis & PECCS	SS
2	1.92	1.00	2.92	6.67
3	1.26	1.15	2.41	7.10
4	2.47	1.37	3.84	7.69

Recent Progress on 2D Nanosheet (IM)

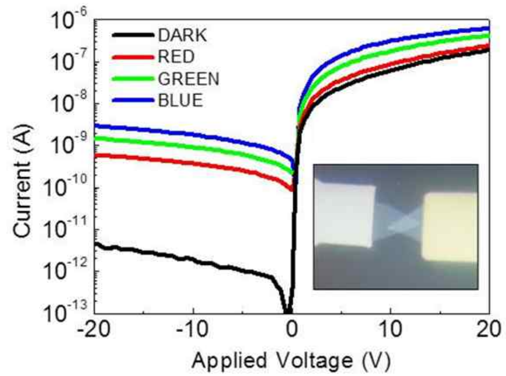
3. Nonvolatile Memory FETs

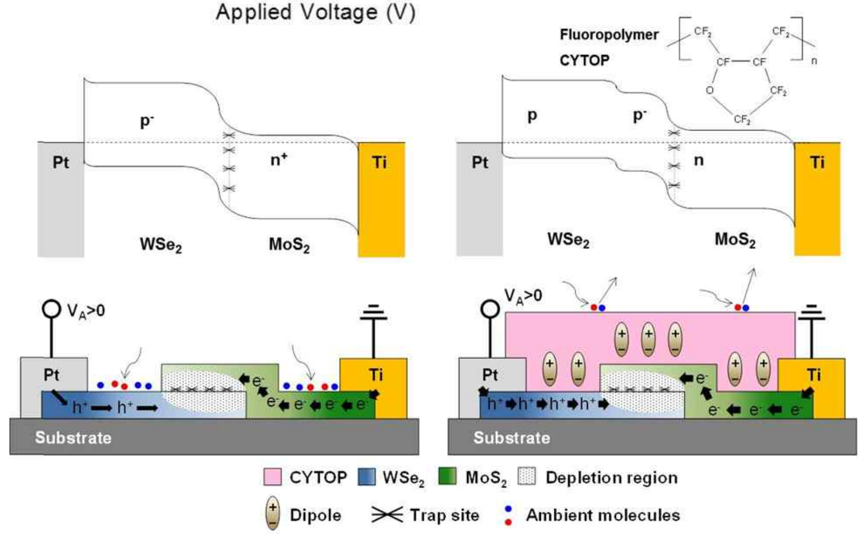
MoS_2 Nanosheets for Top-Gate Nonvolatile Memory Transistor Channel, *Small* (2012)



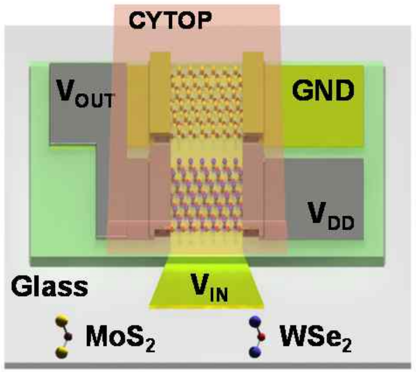
4. 2D-2D van der Waals p-n diode

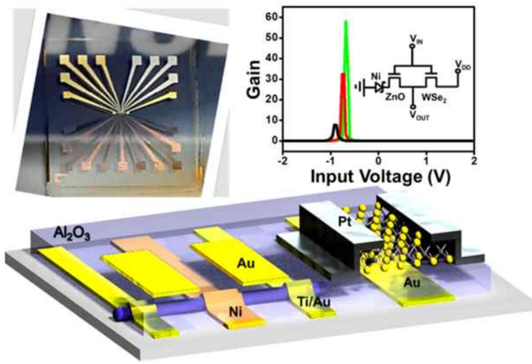
Enhanced device performance of WSe_2-MoS_2 van der Waals junction p-n diode by fluoropolymer encapsulation, *JMC C* (2015)

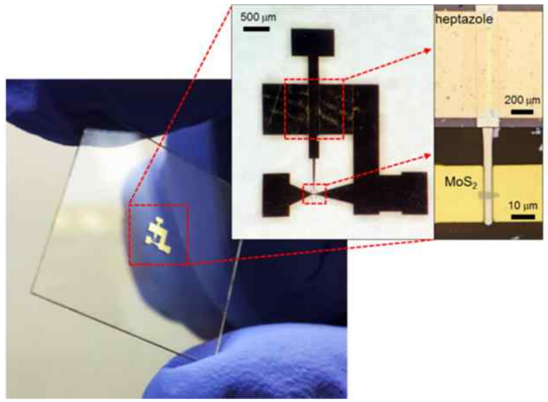




2D-2D, 2D-1D, 2D-Organic Hybrid Complementary Inverter





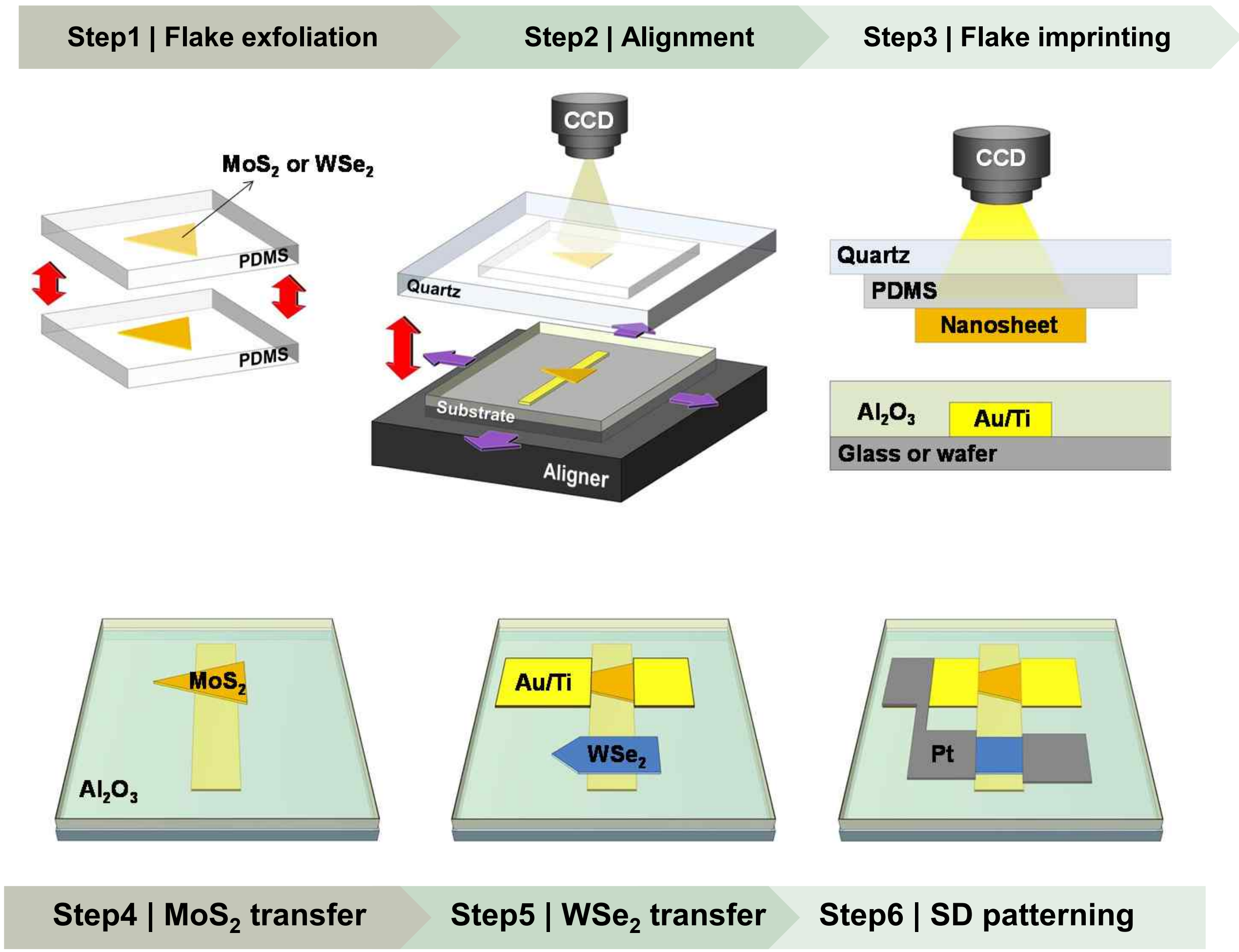


P. J. Jeon et al. *ACS Appl. Mater. Interfaces,* DOI: 10.1021/acsami.5b06027 (2015)

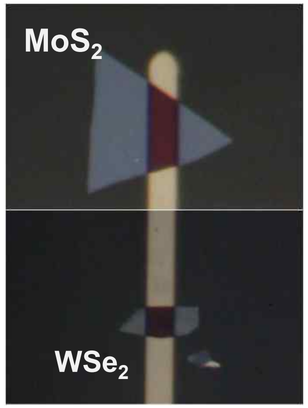
S. H. Hosseini Shokouh et al., *Adv. Mater.* **2015,** *27*, 150 (2015)

H.S. Lee et al. *Small,* **11**, 2132 (2015)

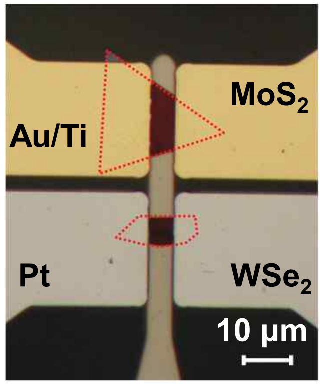
Fabrication : Direct Imprinting Method



Transferred flakes on patterned-gate

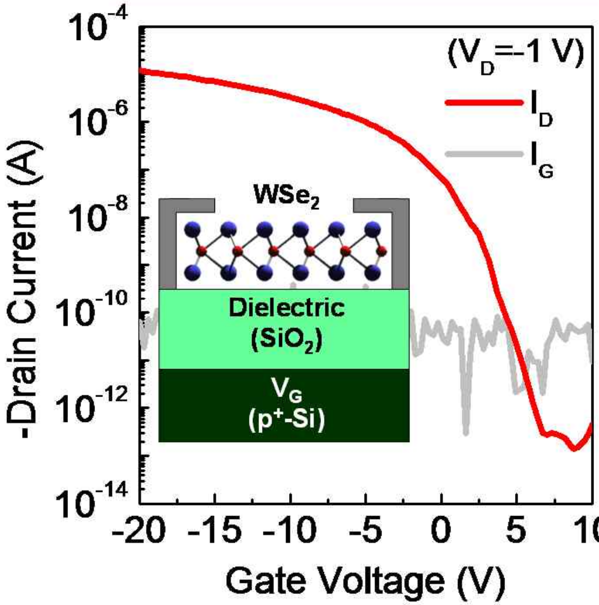


Source/Drain patterning

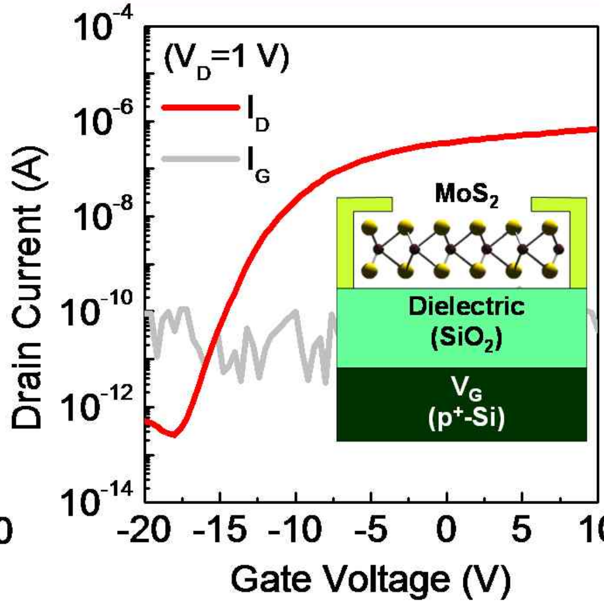


2D p-WSe_2 and n-MoS_2 FETs on Wafer

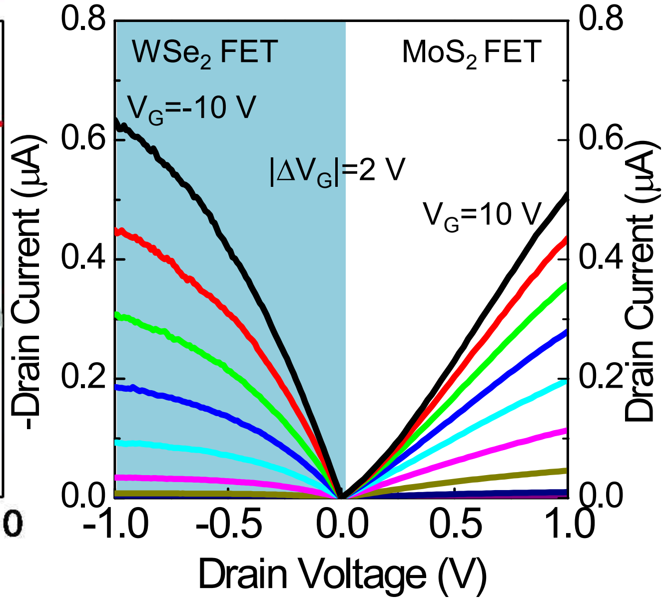
WSe_2 FET Transfer Curve



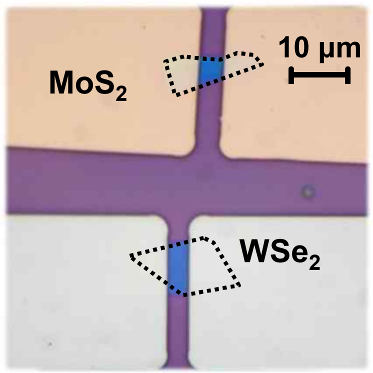
MoS_2 FET Transfer Curve



Output Curves

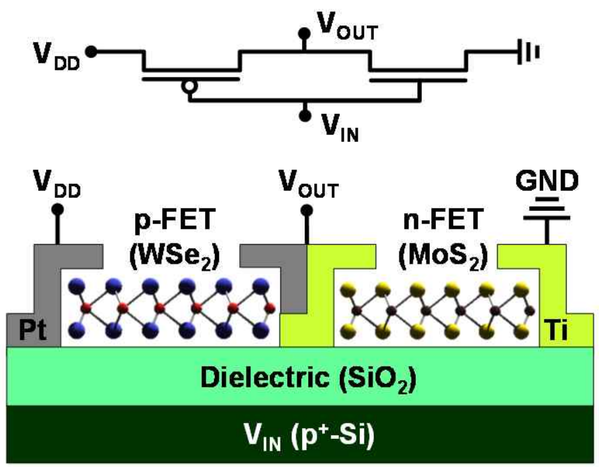


- 285 nm-thick SiO_2/p^+-Si substrate
- Large operation voltage in a range of V_G=-20~10 V
  (V_{TH}=+5 V for p-WSe_2, V_{TH}=-15 V for n-MoS_2)
- Large gate-source leakage current of I_{GS}~100 pA
- Large overlap area between un-patterned gate and source/drain electrodes

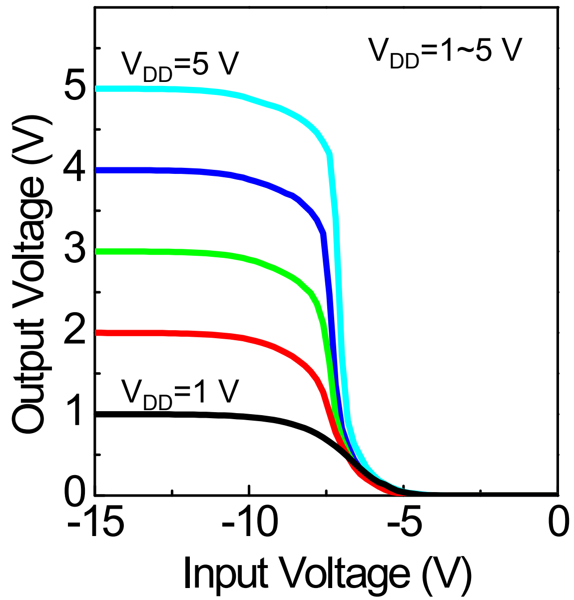


Complementary Inverter on Wafer

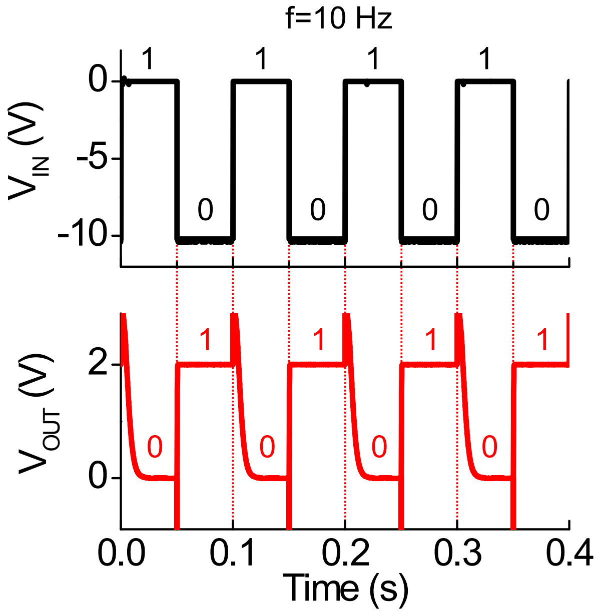
Complementary inverter



VTC



Dynamic switching

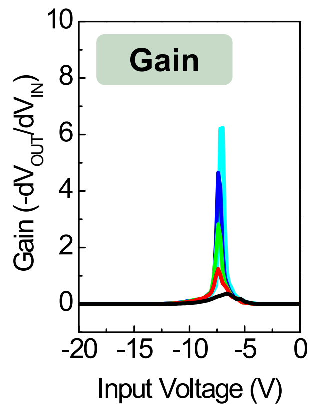


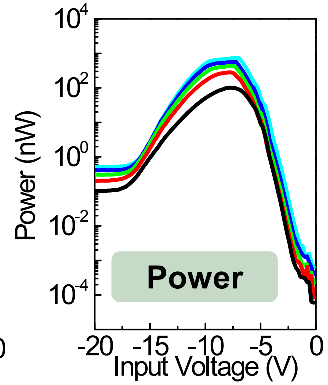
- Negative transition voltage of **V_{TR}=-7.5 V**

  (not suitable for practical applications

- Voltage gain ($-dV_{OUT}/dV_{IN}$) : **~6**
- Peak power consumption ($P=V_{DD}xI_{DD}$) : **~1 μW**
- Large switching delay of **10 ms**

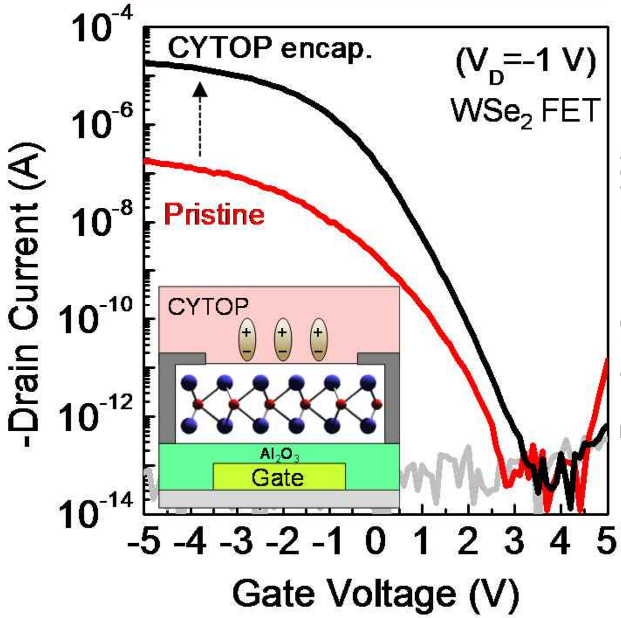
  due to overlap capacitance-induced booster effects



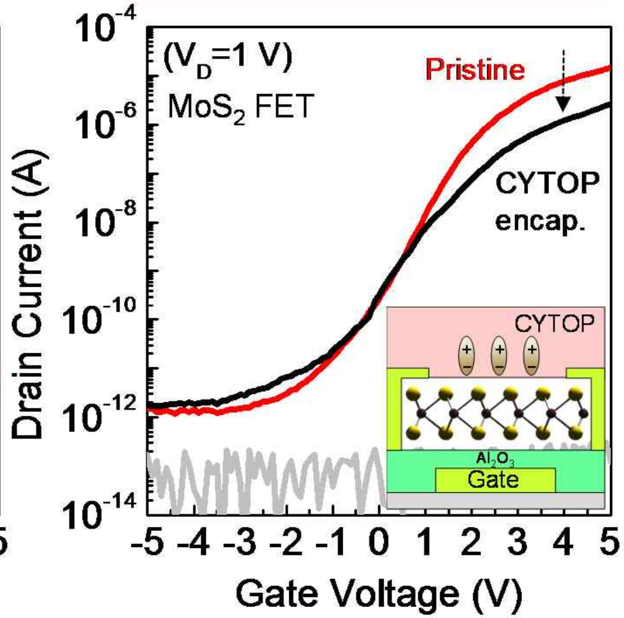


2D p-WSe_2 and n-MoS_2 FETs on Glass

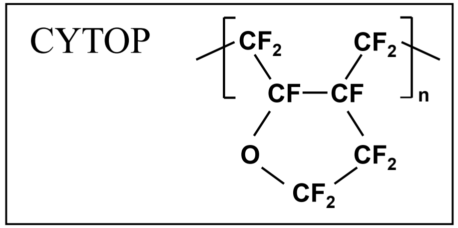
WSe_2 FET Transfer Curve

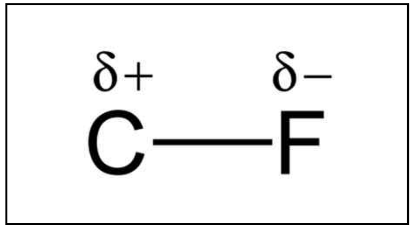


MoS_2 FET Transfer Curve

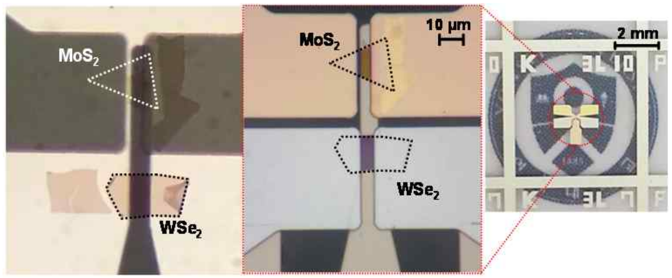


Fluoropolymer CYTOP



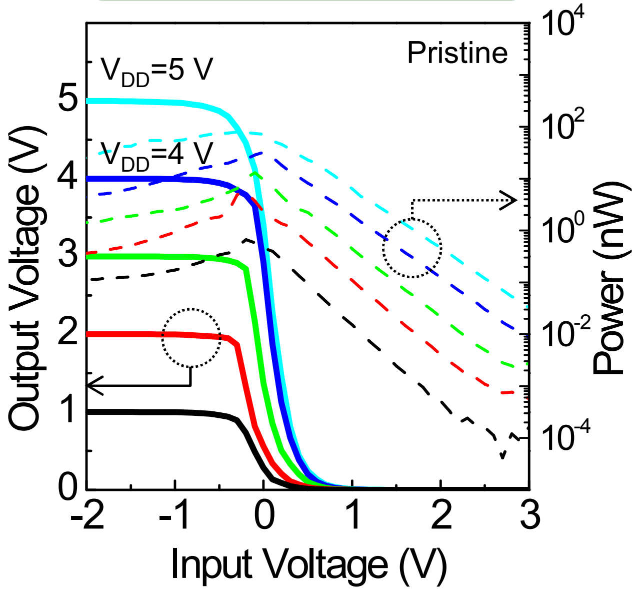


- 50 nm-thin Al_2O_3 (ALD)/**Patterned gate** on **glass** substrate
  : Low operation voltage of V_G=-5 ~ +5 V
  : Low gate-source leakage current of <100 fA
- Fluoropolymer CYTOP encapsulation **(C-F bond-induced dipoles)**
  : **Induced** more **hole carriers** into thin p-WSe_2 (positive V_{TH} shift)
  : **Reduced electrons** in thin n-MoS_2 (reduced on-current).

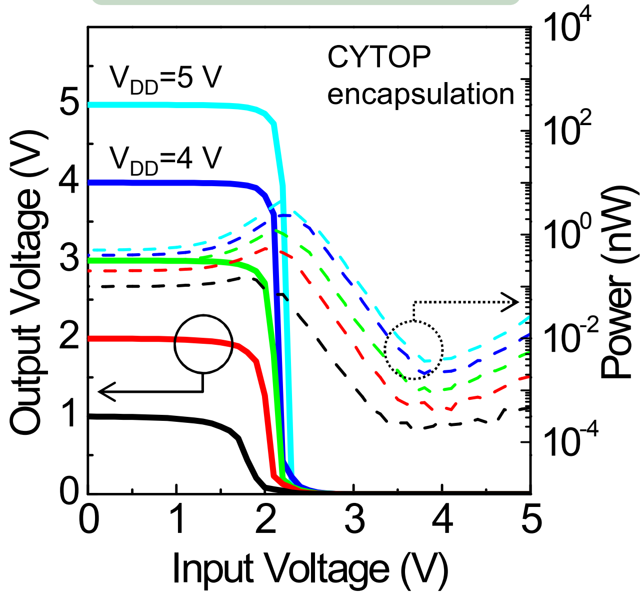


Complementary Inverter on Glass

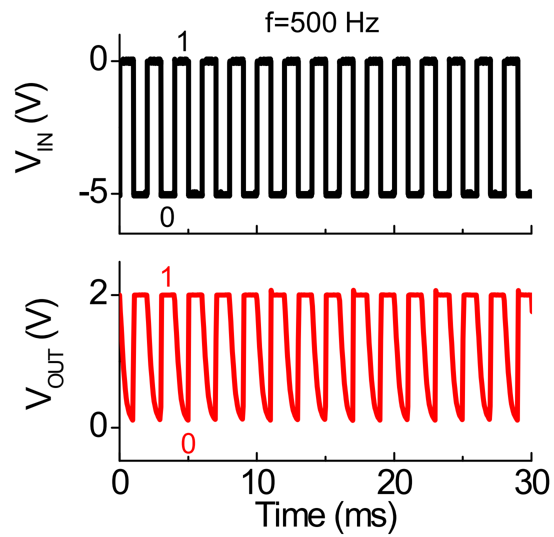
VTC before CYTOP



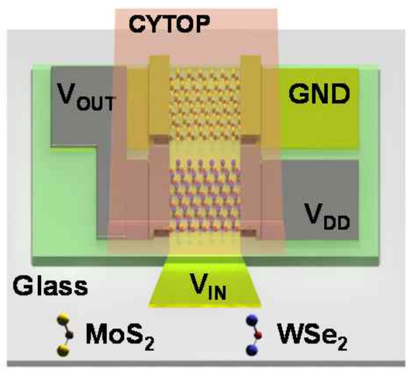
VTC after CYTOP



Dynamic Switching

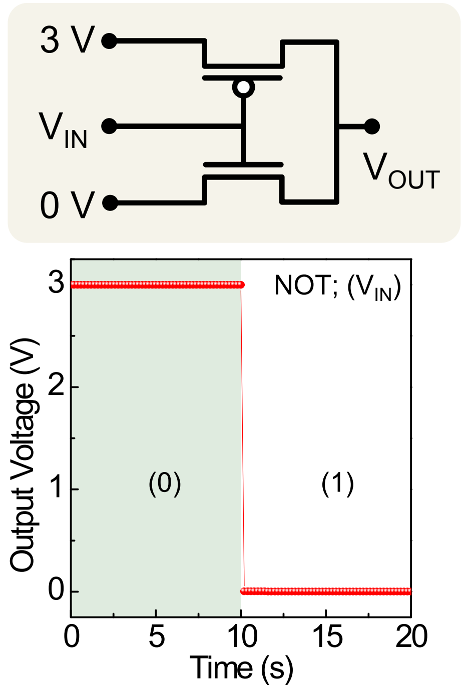


- **Positive transition voltage shift** after CYTOP encapsulation (V_{TR}; 0.1 V → 2.3 V)
- High **voltage gain of 23** at V_{DD}=5 V
- Subnanowatt power consumption : **P_{peak}~1 nW**
- Ideal noise margin (**NM_L=0.385xV_{DD}, NM_H=0.495xV_{DD}** at V_{DD}=5 V)
- Switching delay : **~800 μs**



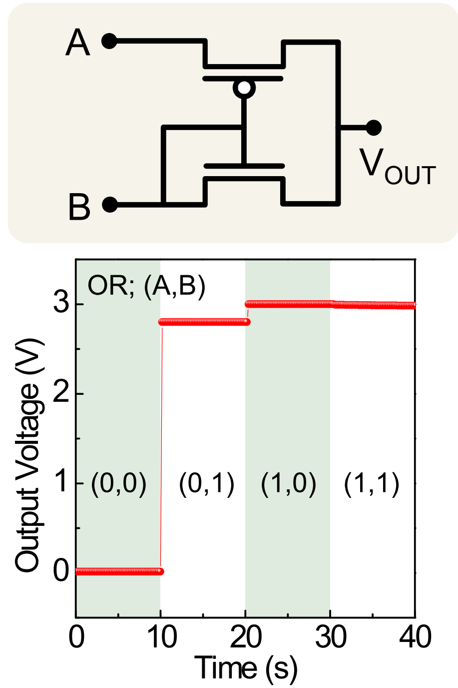
Pass Transistor Logic Gates

NOT gate



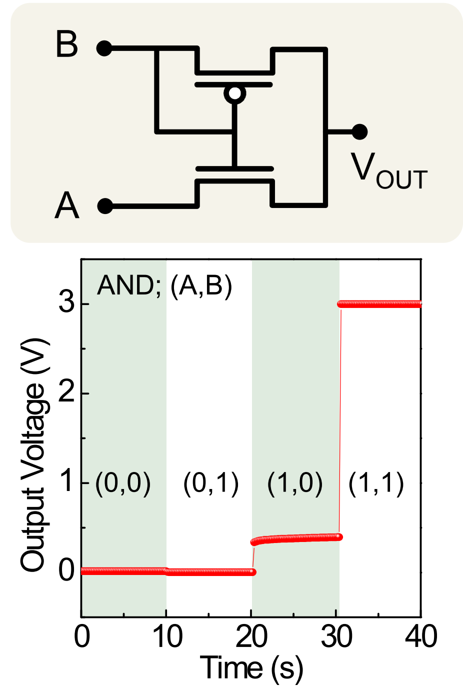
V_{IN}	V_{OUT}
0	1
1	0

OR gate



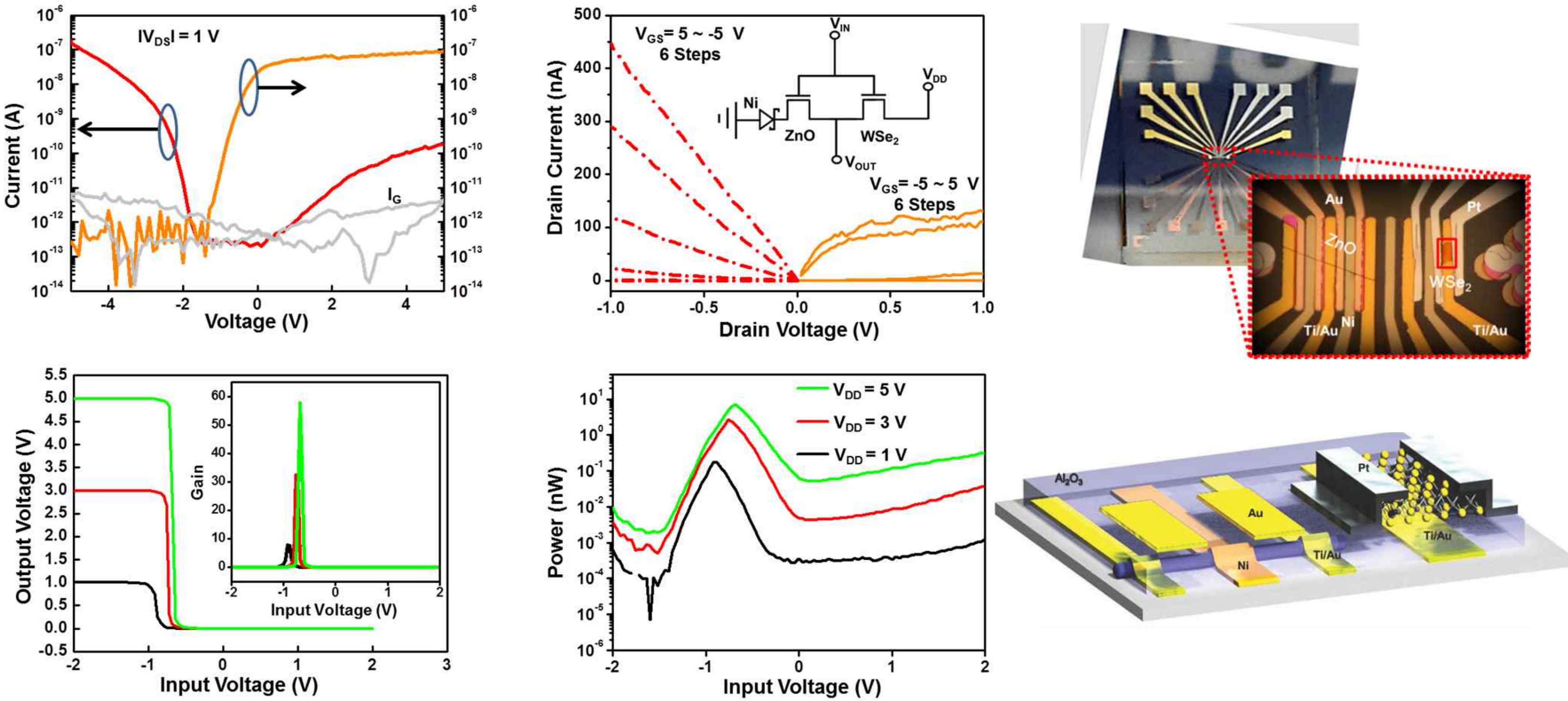
A	B	V_{OUT}=A+B
0	0	0
0	1	1
1	0	1
1	1	1

AND gate



A	B	V_{OUT}=AxB
0	0	0
0	1	0
1	0	0
1	1	1

2D-1D Hybrid Complementary Inverter

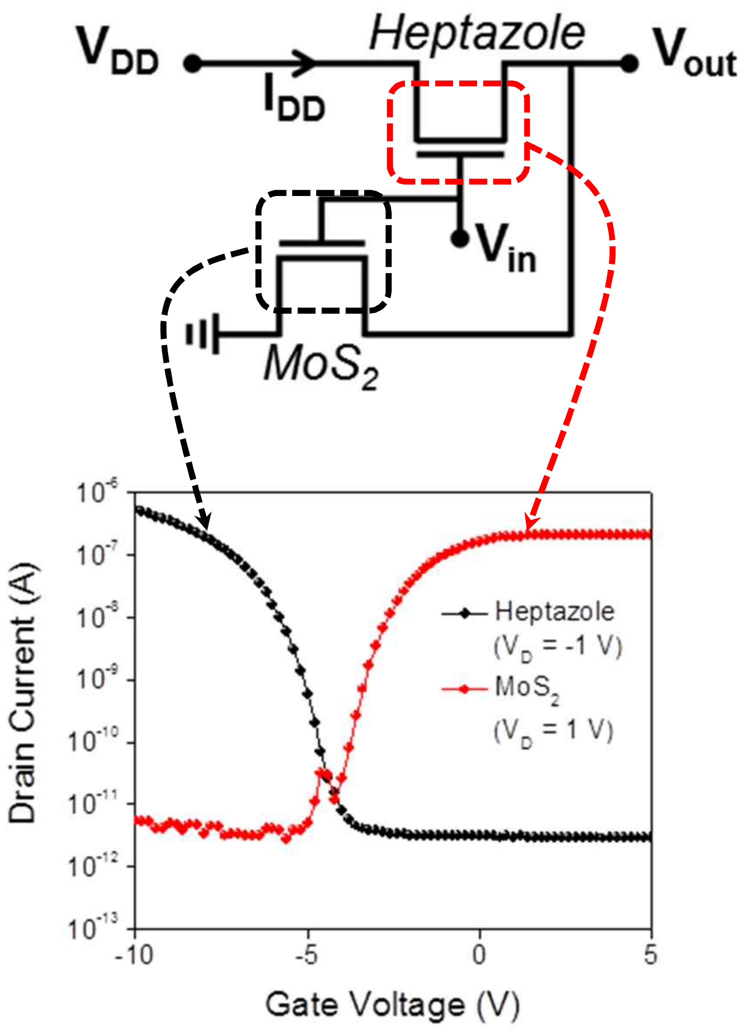


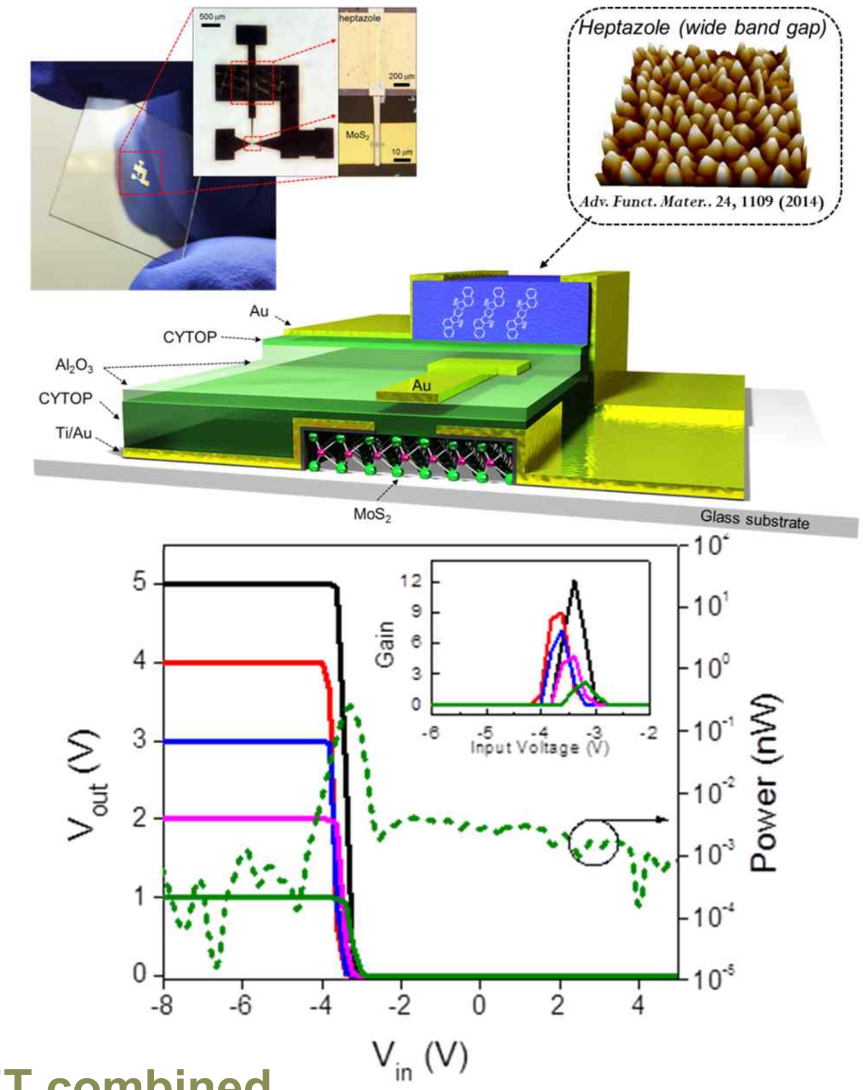
Voltage gain of 60 and subnanowatt power consumption at static states

→ Highest gain and lowest power consumption for reported 2D material based inverter

S. H. Hosseini Shokouh et al., *Adv. Mater.* **2015,** *27*, 150 (2015)

2D-Organic Hybrid Complementary Inverter

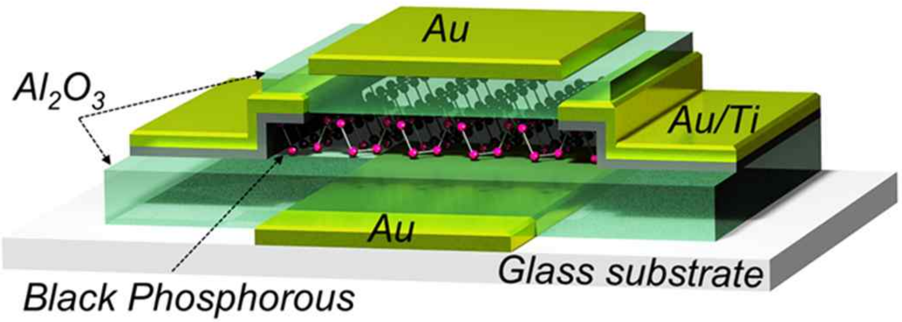


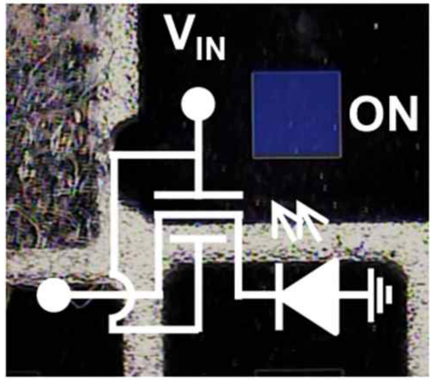


Forecast some possibility to use 2D FET combined with Org. Elec. ?

H.S. Lee et al. *Small,* **11**, 2132 (2015)

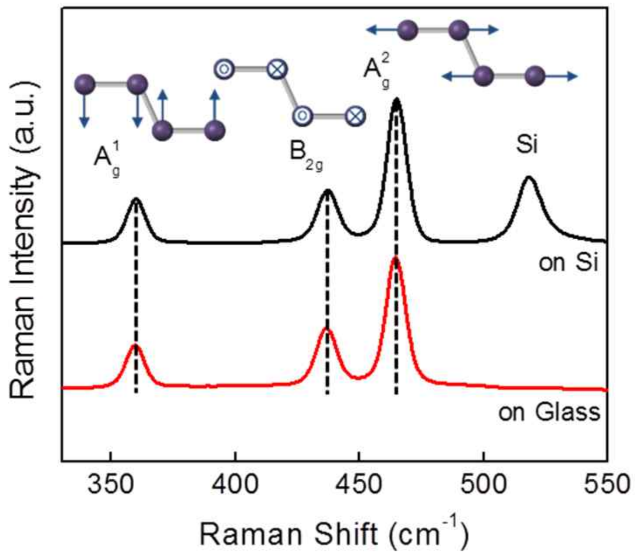
Dual gate black phosphorous field effect transistors on glass for NOR logic and organic light emitting diode switching

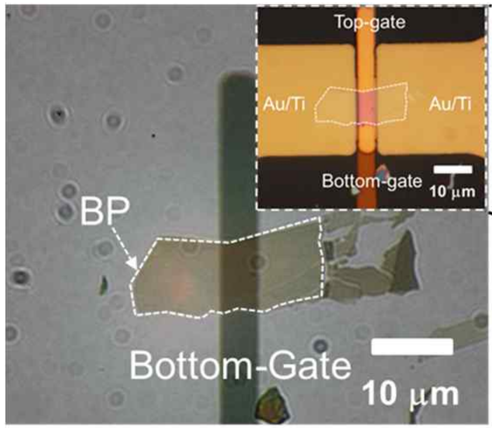


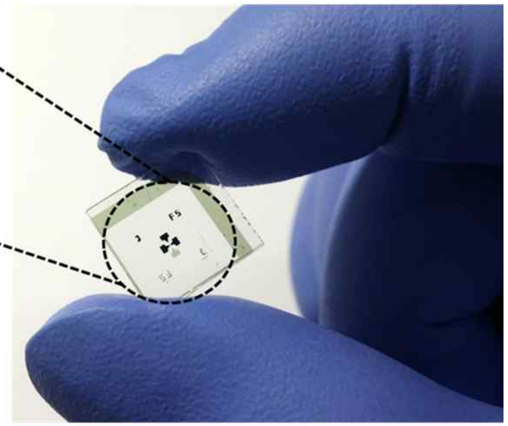


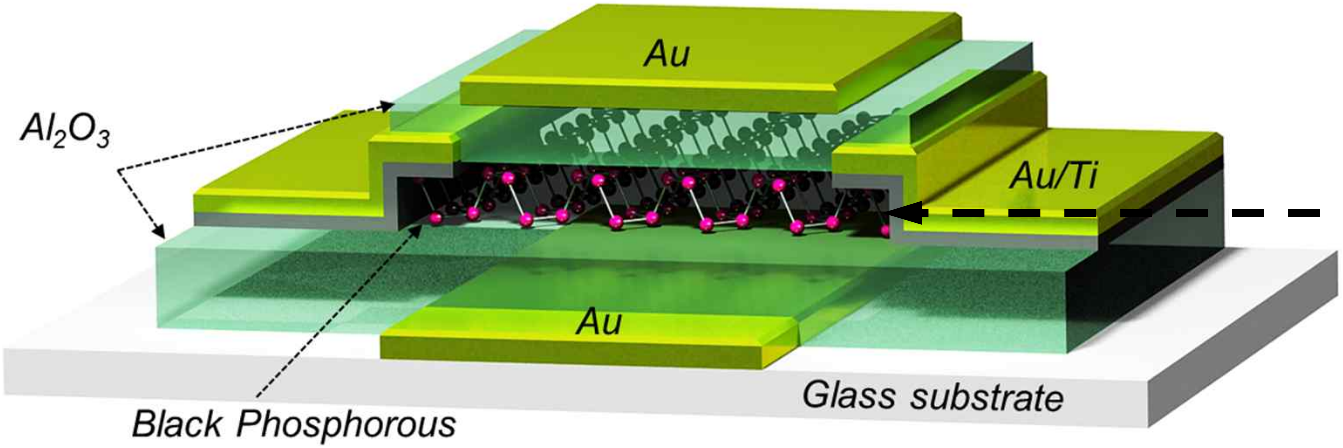
J. S. Kim et al. *Nanoletters,* **15**, 5778, (2015)

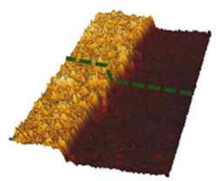
Images and Raman spectra





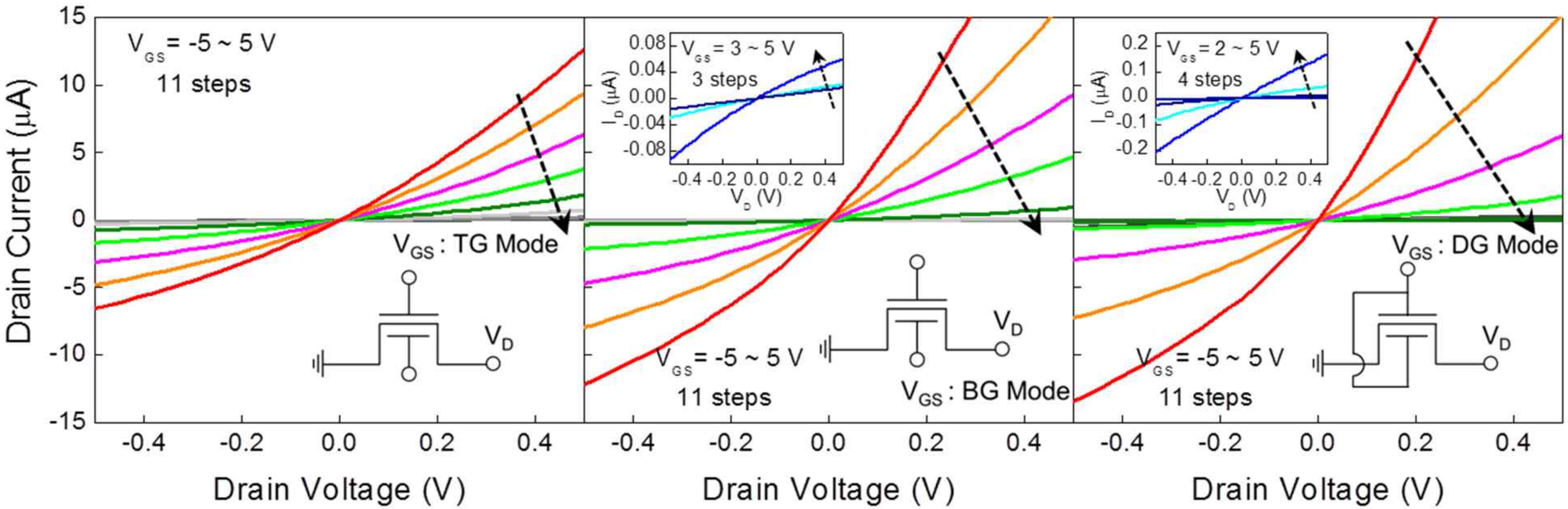


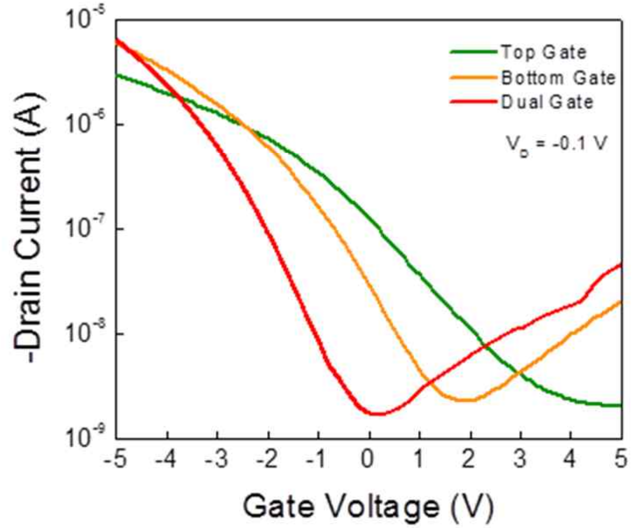


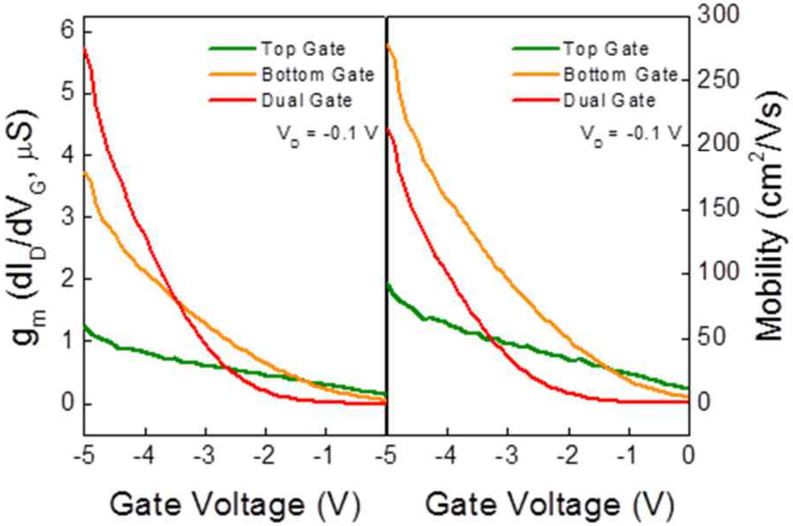


Thickness
~ 12 nm

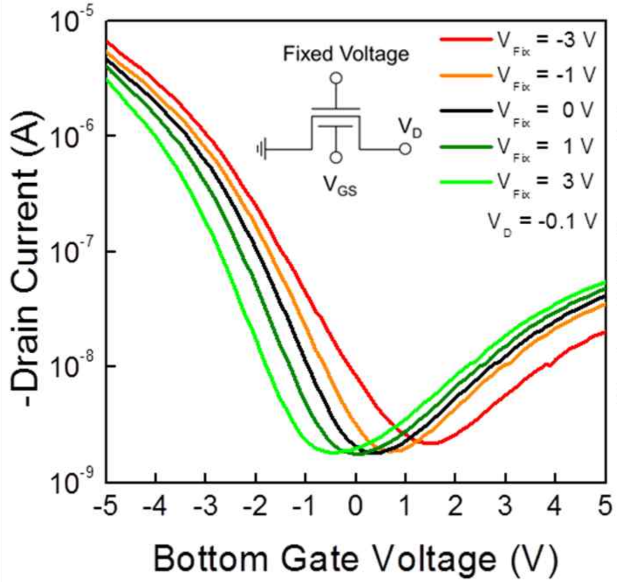
I-V Characteristics of Dual gate FET

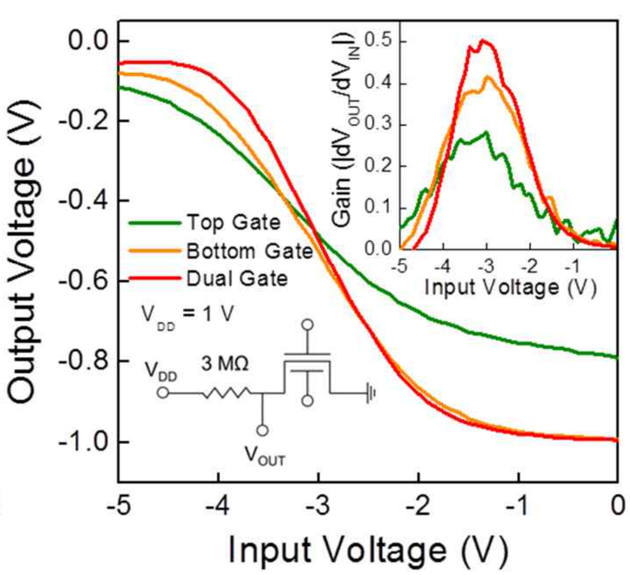


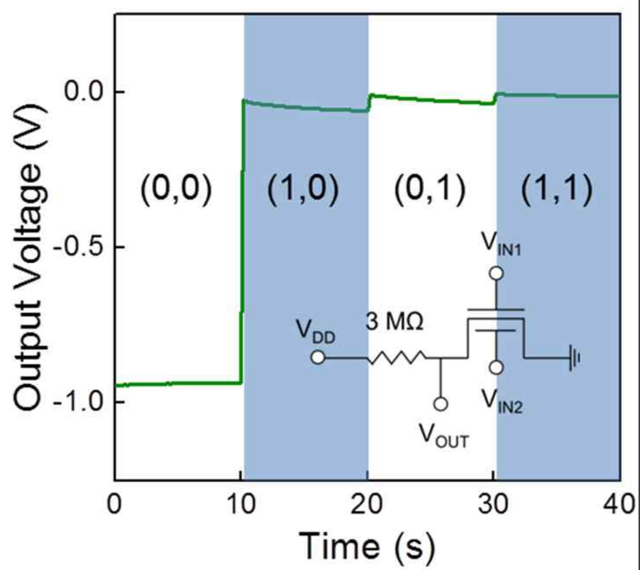




Voltage shifts & Logic gate





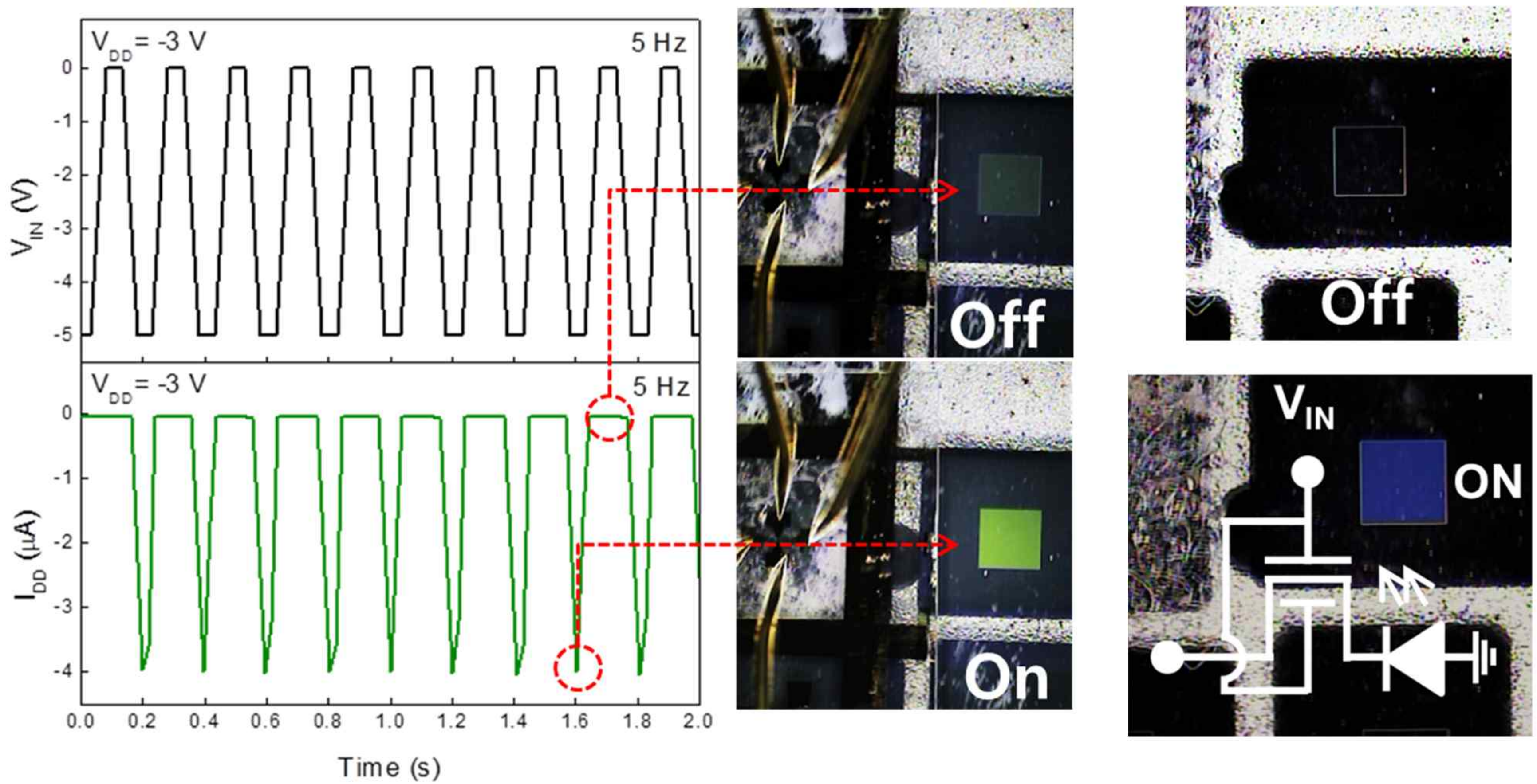


NOT logic

NOR logic

ambipolar transition voltage shifts from -0.5 to 1.5 V by applied top gate bias

Dynamic OLED Switching

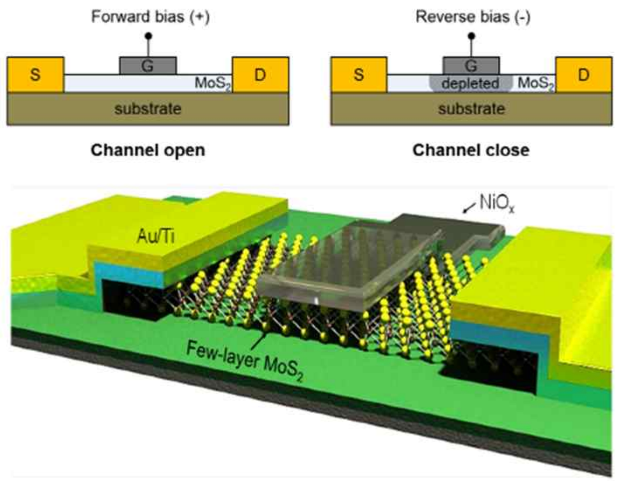


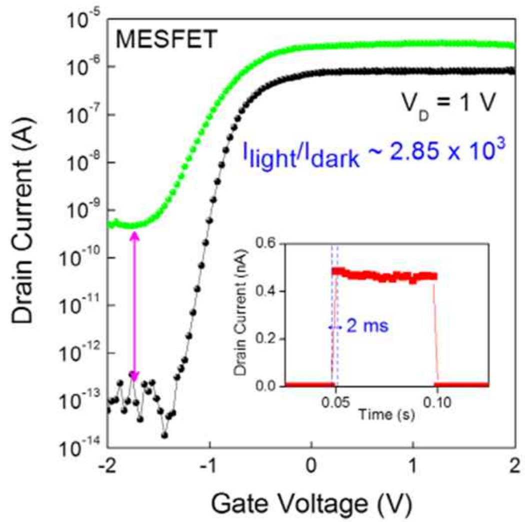
Well switching operated as Green, blue OLED pixel

Dynamic OLED Switching

[redacted]

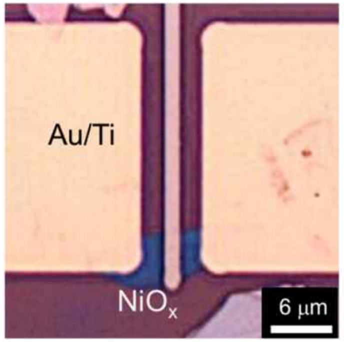
NiO_x-MoS_2 metal-semiconductor field-effect transistor for high mobility and photoswitching speed

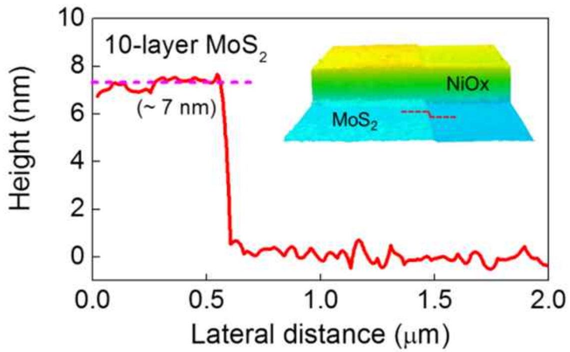


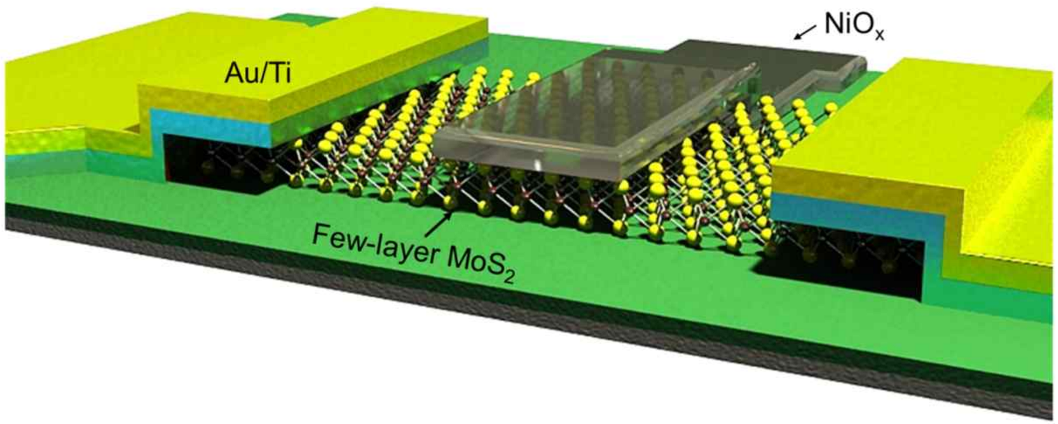


H.S. Lee et al. *ACS Nano,* **9**, 8312, (2015)

Structure of MoS_2 MESFET



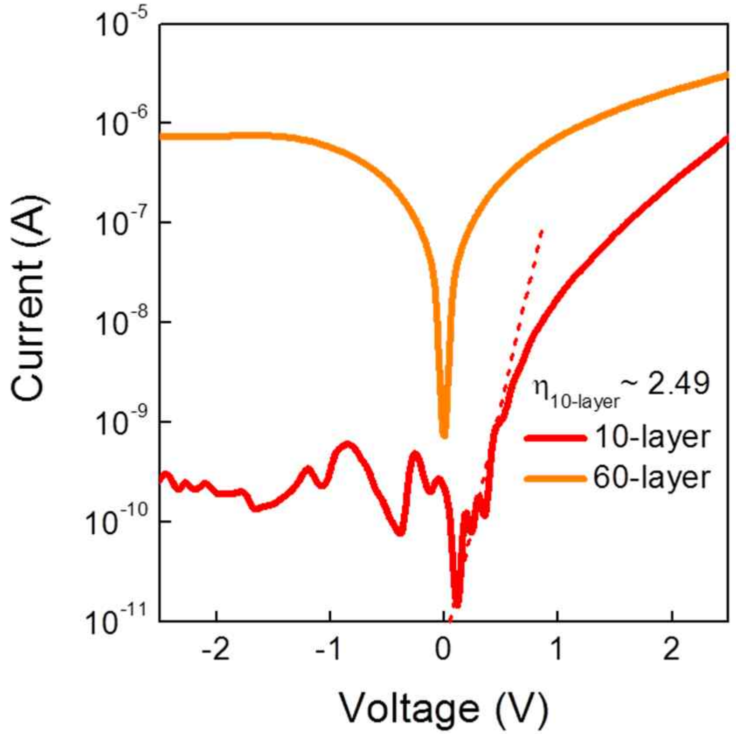




"Thermally evaporated **NiO_x** is known to have quite a **deep work function** of more than 5.1~5.2 eV as a Ni-rich **semi-transparent conducting oxide** (x~0.9)."

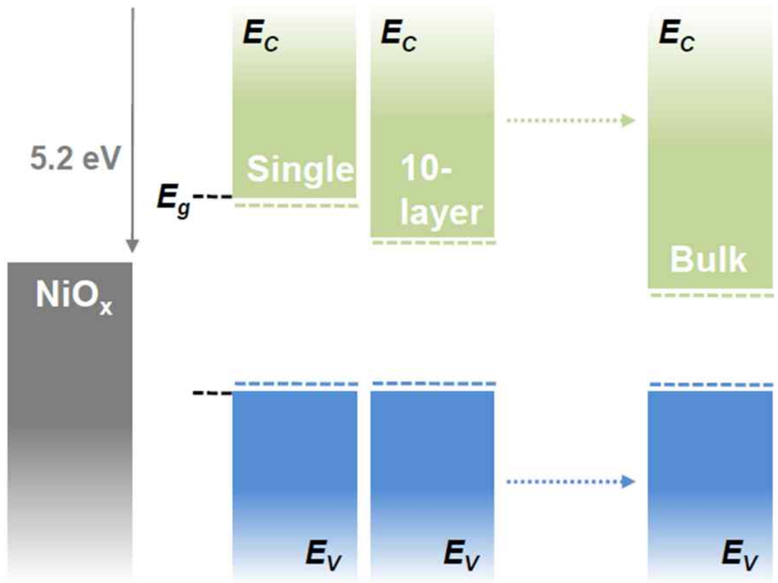
NiO_x van der Waals Schottky Interface

Schottky diode IV curves



- The better rectifying behavior for the thinner MoS_2

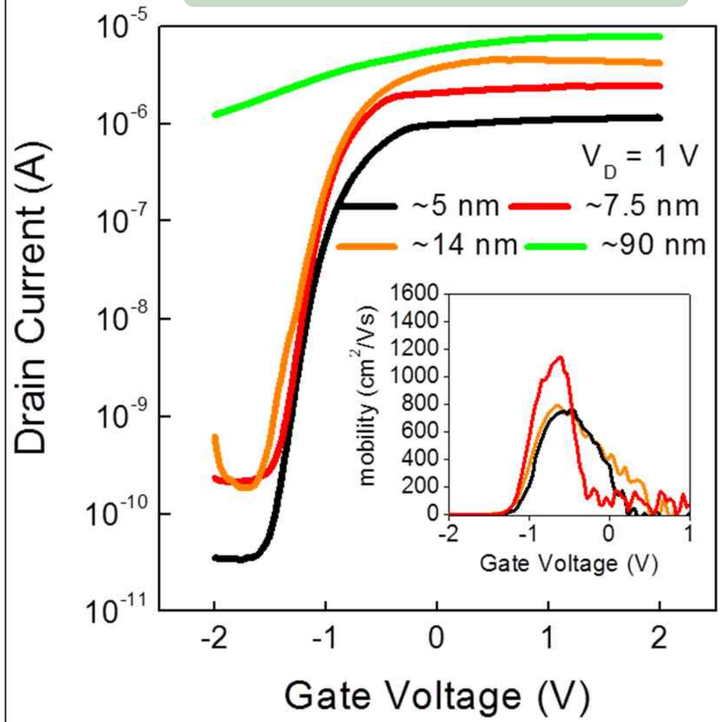
Energy band diagram



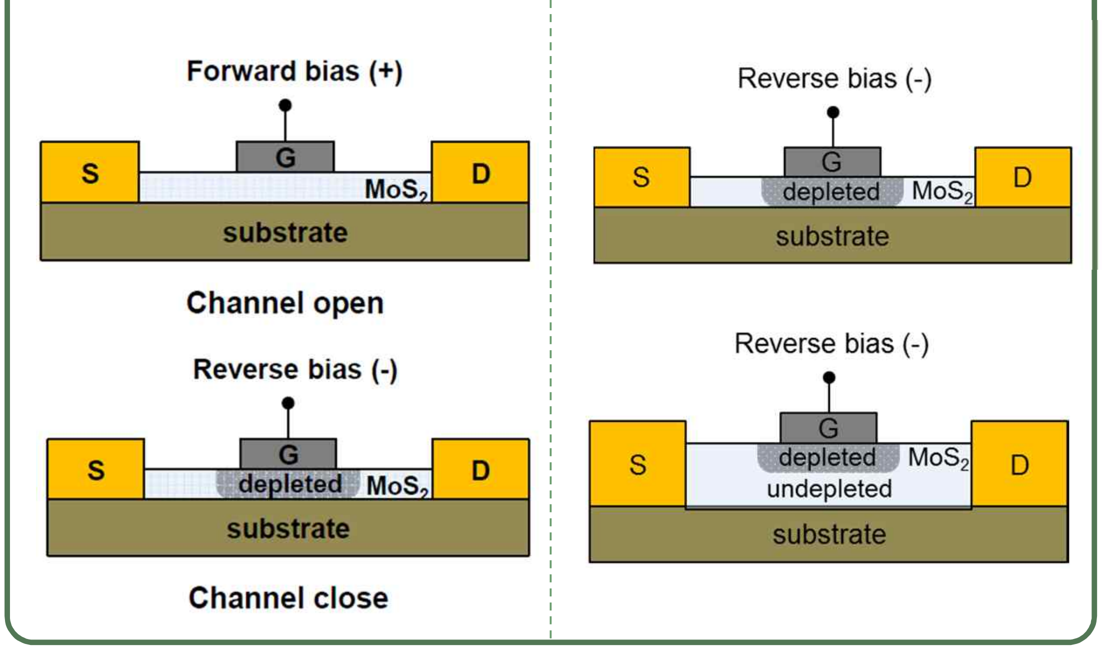
- The higher Schottky barrier height for the thinner MoS_2
- $q\emptyset_B = q\emptyset_{NiOx} - qX_{MoS2}$

MESFET : Channel Thickness Effects

MESFET Transfer Curve



MESFET switching | **Thickness dependency**



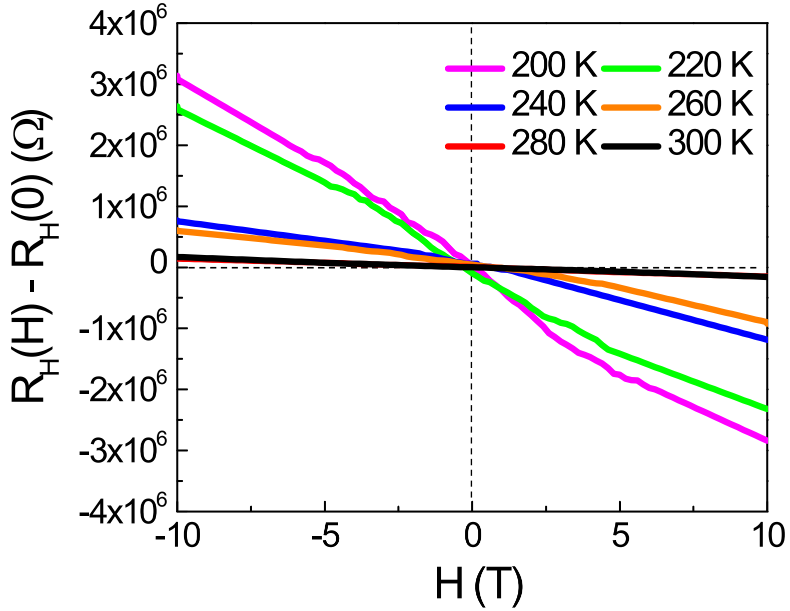
- NiO_x/MoS_2 van der Waals interface: 0.3 nm gap by calc. !

MESFET Mobility

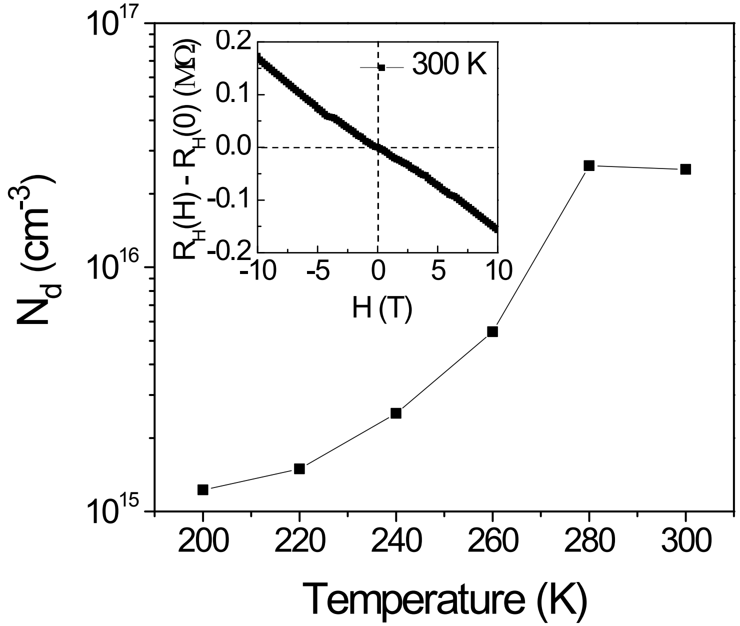
$$\mu = \frac{L g_{Max}}{q N_d t W} \quad \text{, where} \quad g_m = \frac{\partial I_D}{\partial V_G} = \frac{q N_d \mu t W}{L}$$

4-Probe Hall Measurement

MoS_2 Hall Coeff-H(T) Curve



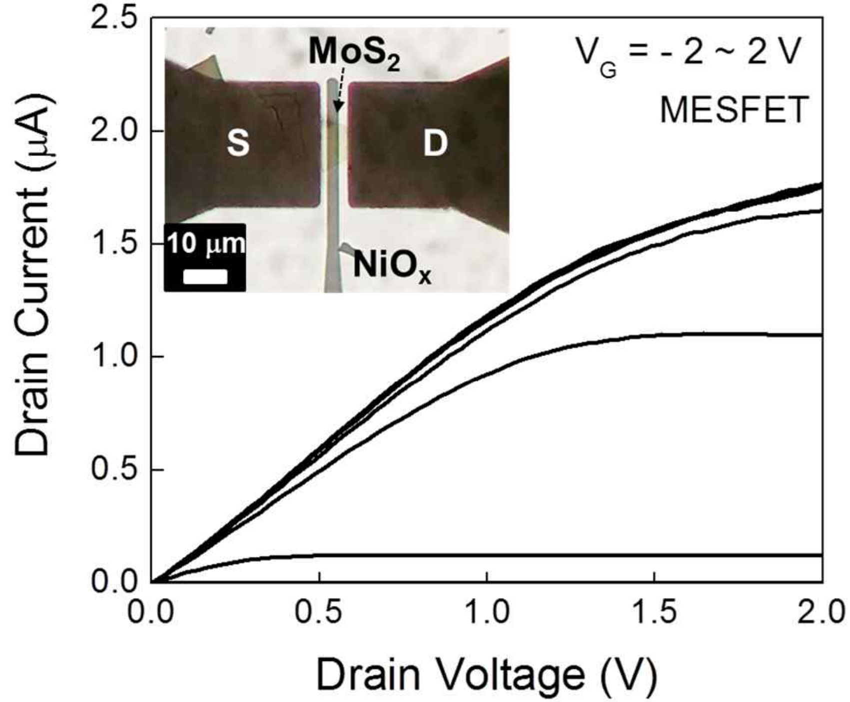
MoS_2 Nd conc. (T) plot

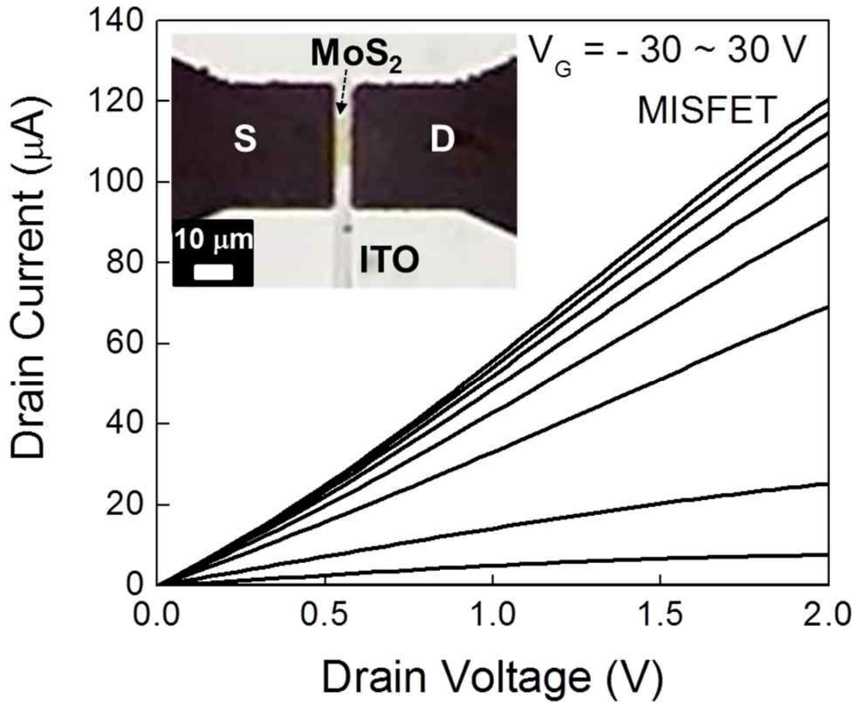


$$R_H = \frac{V_H}{I} = -\frac{H}{n_s q} \quad \rightarrow \quad n_s = -\frac{1}{q}\left(\frac{\partial R_H}{\partial H}\right)^{-1}$$

- n_s=4.03 x 10^{10} cm^{-2} (**2.52 x 10^{16} cm^{-3}**)
  for 16 nm-thick MoS_2 at 300 K
- Hall mobility of 16 nm-thick MoS_2 : ~200 cm^2/V s

MESFET vs. MISFET



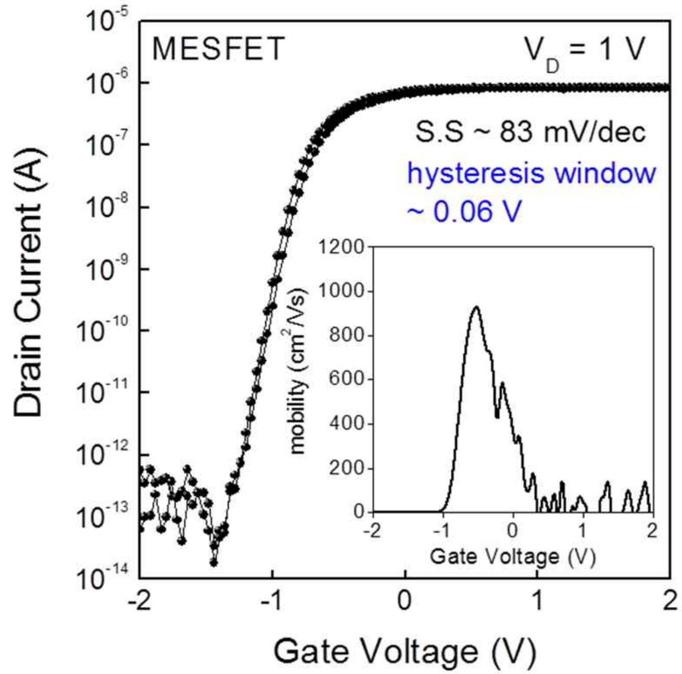


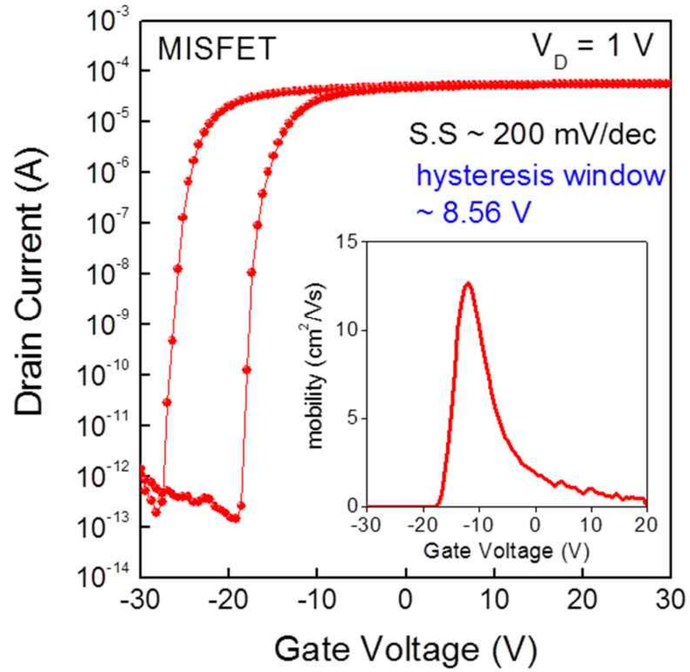
Saturation behavior in MESFET

: easier channel-depletion (pinch-off) in drain side

MESFET vs. MISFET

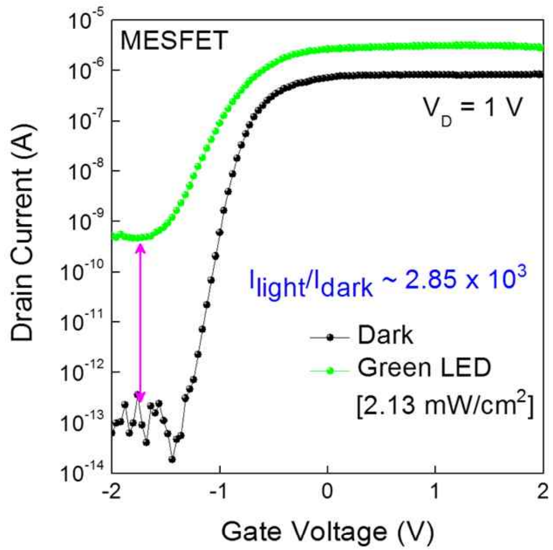
"The carrier transport in MESFET may hardly be interfered by insulator-semiconductor interface traps or an on-state gate field."

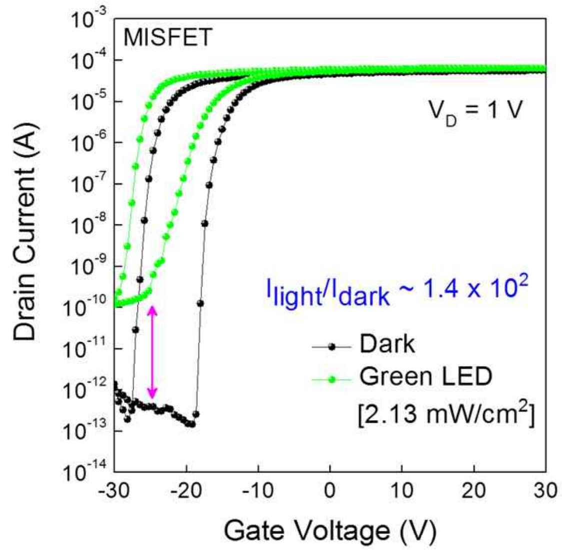


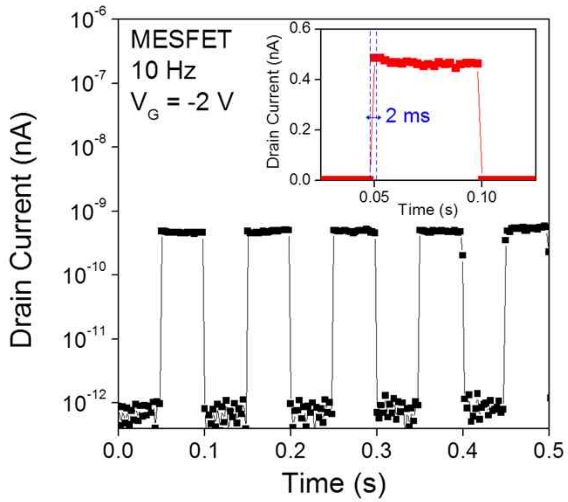


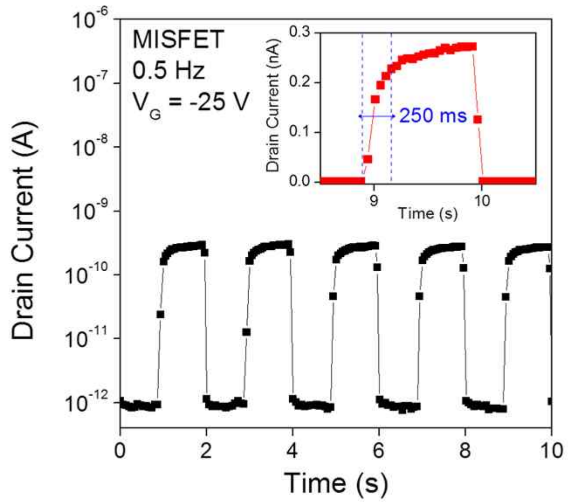
Parameters	MESFET	MISFET
Subthreshold swing	83 mV/dec	200 mV/dec
Mobility	950 $cm^2/V\,s$	13 $cm^2/V\,s$
Hysteresis	0.06 V	8.56 V
Threshold voltage	-1 V	-25 V

Photo-detecting properties & Dynamic









	MESFET	MISFET
Photo-to-dark current ratio	2.85×10^3	1.4×10^2
Responsivity (ON state)	5000 A/W	
Responsivity (OFF state)	1.1 A/W	
Delay	2 ms	250 ms

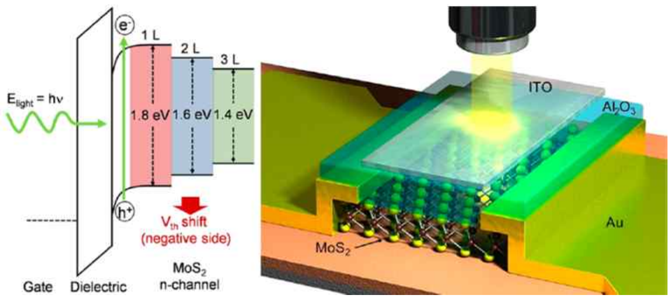
Summary

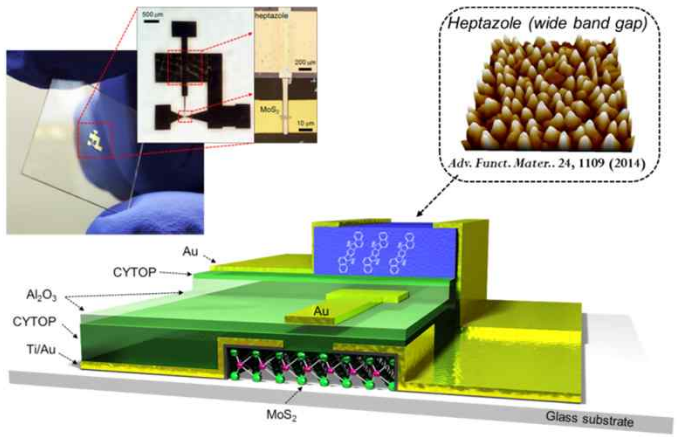
- **2D-FETs**
  analysis MoS_2 band gap, nonvolatile memory, p-n diode
- **Hybrid complimentary Inverter: nW power, high gain**
  2D-2D, 2D-1D, 2D-Organic
- **Black Phosphorous Dual Gate FETs: High current, NOR gate**
  TG BG bipolar transition voltage shifts, OLED switching
- **NiOx-MoS_2 van der Waals junction MESFET:**
  Intrinsic high mobility and photo-switching speed

IM's group activity on 2D Devices

FET

1. MoS_2 nanosheet phototransistors with thickness-modulated optical energy gap, ***Nano Letters***, **12**, 3695 (2012)
2. MoS_2 nanosheets for top-gate nonvolatile memory transistor channel, ***Small***, **20**, 3111 (2012)
3. Nanosheet thickness-modulated MoS_2 dielectric property evidenced by field-effect transistor performance, ***Nanoscale***, **5**, 548 (2013)
4. Direct imprint of MoS_2 flakes on the patterned gate for nanosheet transistors, ***Journal of Materials Chemistry C***, **1**, 7803, (2013)
5. Graphene versus ohmic metal as source-drain electrode for MoS_2 nanosheet transistor channel, ***Small***, **10**, 2356, (2014)
6. Trap density probing on top-gate MoS_2 nanosheet field-effect transistors by photo-excited charge collection spectroscopy ***Nanoscale***, **7**, 5617 (2015)
7. Metal Semiconductor Field-Effect Transistor with MoS2/Conducting NiOx van der Waals Schottky Interface for Intrinsic High Mobility and Photoswitching Speed, ***ACS Nano***, **9**, 8312, (2015)
8. Dual Gate Black Phosphorus Field Effect Transistors on Glass for NOR Logic and Organic Light Emitting Diode Switching, ***Nano letters,*** **15**, 5778, (2015)
9. High Performance Air Stable Top-gate p-channel WSe_2 Field Effect Transistor with Fluoropolymer Buffer Layer, ***Adv. Funct. Mater.,*** DOI: 10.1002/adfm.201502008, (2015)





Im’s group activity toward 2D semi.

Hybrid (Complimentary) Inverter

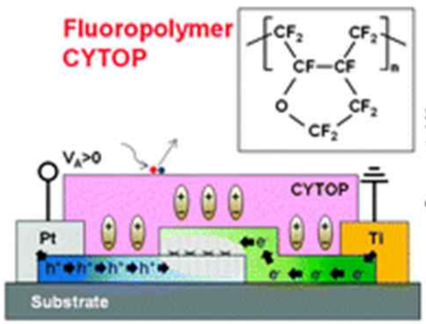
10. Molybdenum disulfide nanoflake-zinc oxide nanowire hybrid photoinverter, ***ACS Nano***, **8**, 5174 (2014)
11. Top and back gate molybdenum disulfide transistors coupled for logic and photo-inverter operation, ***Journal of Materials Chemistry C***, **2**, 6023, (2014)
12. High-gain subnanowatt power consumption hybrid complementary logic inverter with WSe_2 nanosheet and ZnO nanowire transistors on glass ***Advanced Materials***, **27**, 150 (2015)
13. Few layer MoS_2-organic thin film hybrid complementary inverter pixel fabricated on glass substrate ***Small***, **11**, 2132 (2015)
14. Low Power Consumption Complementary Inverters with n-MoS2 and p-WSe2 Dichalcogenide Nanosheets on Glass for Logic and Light-Emitting Diode Circuits, ***ACS Appl. Mater. Interfaces,*** DOI: 10.1021/acsami.5b06027, (2015)

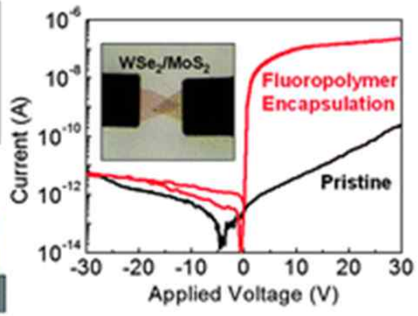
P-N and Schottky Diode

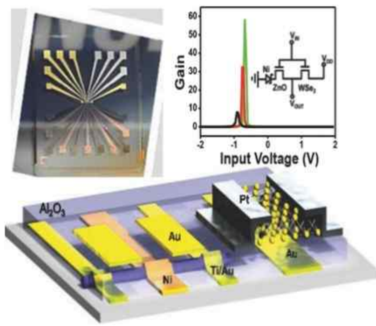
15. Multifunctional Schottky-diode circuit comprising palladium/molybdenum disulfide nanosheet, ***Small***, **10**, 23, (2014)
16. Enhanced device performances of WSe_2–MoS_2 van der Waals junction p–n diode by fluoropolymer encapsulation ***Journal of Materials Chemistry C***, **3**, 2751, (2015)

Memory FET

17. MoS_2 nanosheet channel and guanine DNA-base charge injection layer for high performance memory transistors ***Journal of Materials Chemistry C***, **2**, 5411, (2014)
18. Nonvolatile Ferroelectric Memory Circuit Using Black Phosphorous Nanosheet-based Field Effect Transistors with P (VDF-TrFE) Polymer, ***ACS Nano***, DOI: 10.1021/acsnano.5b04592, (2015)







Collaboration Groups & Acknowledgment

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- Brain Korea 21 plus

Collaboration Groups

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- Prof. Takhee Lee (Seoul National Univ. - Dept. of Physics and Astronomy)
- Prof. Myung Mo Sung (Hanyang Univ. - Dept. of Chemistry)
- Prof. Jae Hoon Kim, Hyoung Joon Choi, Yeonjin Yi (Yonsei Univ. - Dept. of Physics)
- Prof. Hyungjun Kim, Jong-Hyun Ahn (Yonsei Univ. - Dept. EE)

Thank you for listening

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