Room Temperature Gate-tunable Negative Differential Resistance in MoS_2 / hBN / WSe_2 Heterostructures

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TEXAS

Theme/Task: 2400.001

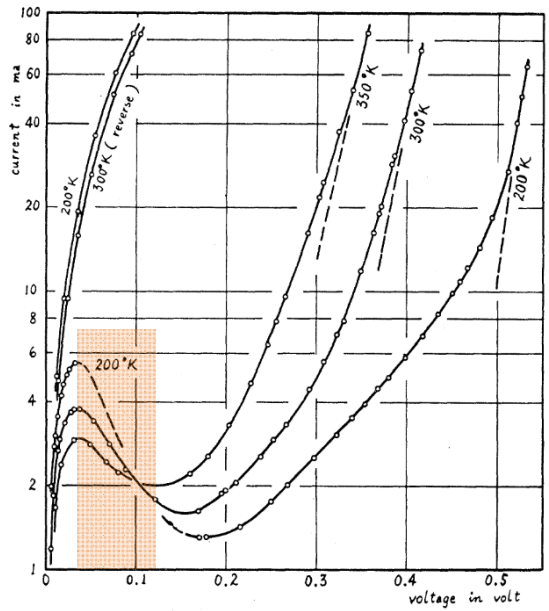
Tech Transfer

- Industry Interactions
  - Dr. Luigi Colombo – Texas Instruments
  - Dr. Ravi Pillarisetty – Intel
- Publications/presentations
  - Room Temperature Gate-tunable Negative Differential Resistance in MoS_2/hBN/WSe_2 Heterostructures, *74th Device Research Conference* 2016

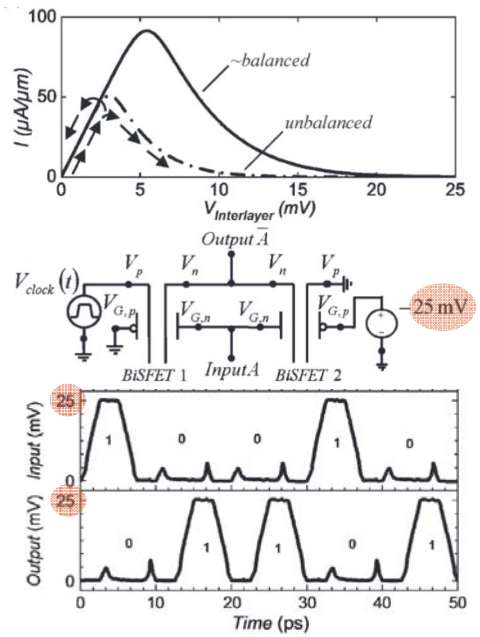
Motivation :
Negative Differential Resistance (NDR)

- Portion in the I-V characteristics where $dV/dI < 0$

Esaki Diode[1]



BiSFET[2]

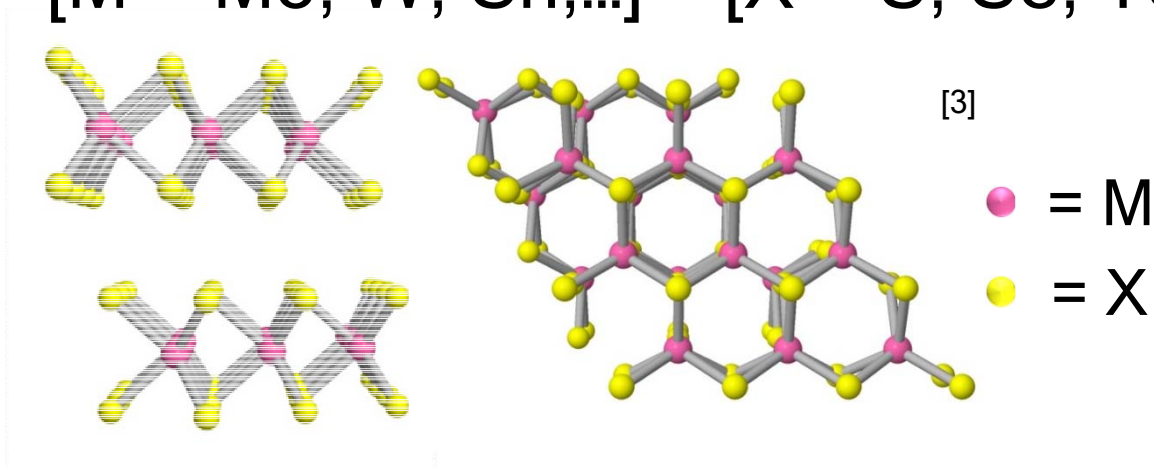


Post-CMOS logic, memory using NDR devices!

[1] L. Esaki, *Phys. Rev.*, vol. 109, p. 603 (1957)
[2] S. K. Banerjee *et al.*, *IEEE Elec. Dev. Lett.*, vol. 30, p. 158 (2009)

Motivation :
Transition Metal Dichalcogenides (TMDs)

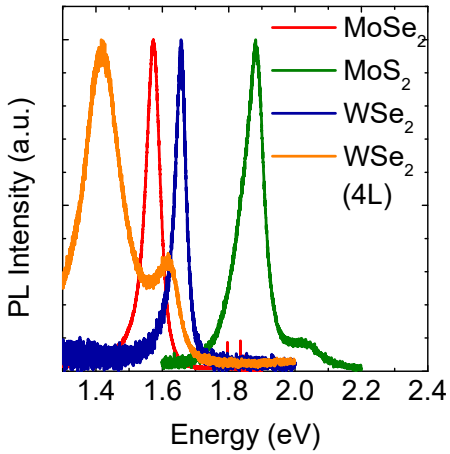
- MX_2 [M = Mo, W, Sn,...] [X = S, Se, Te]

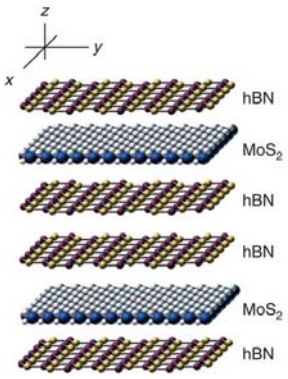


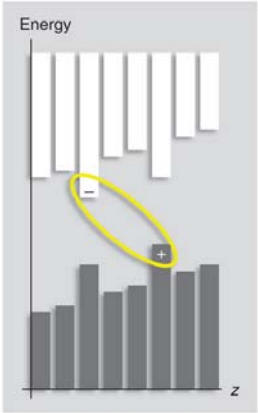
[3]

[4]

- Why TMDs?
  - Sharp interfaces
  - Hetero-assembly
  - *Excitonics* : BiSFET



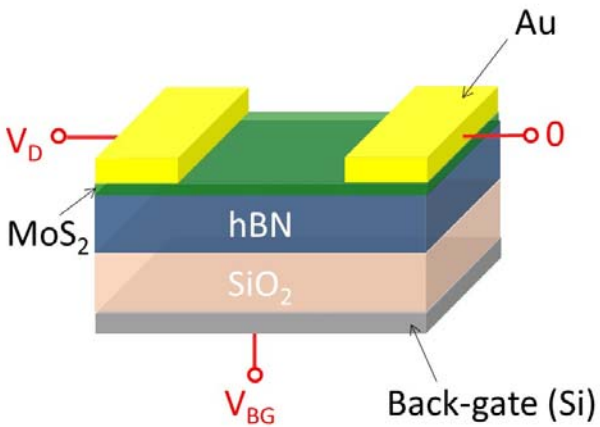


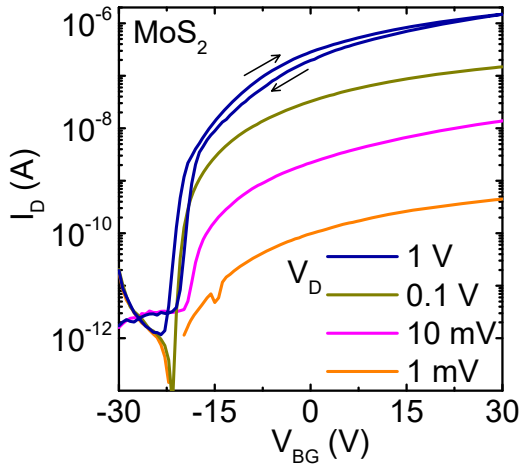


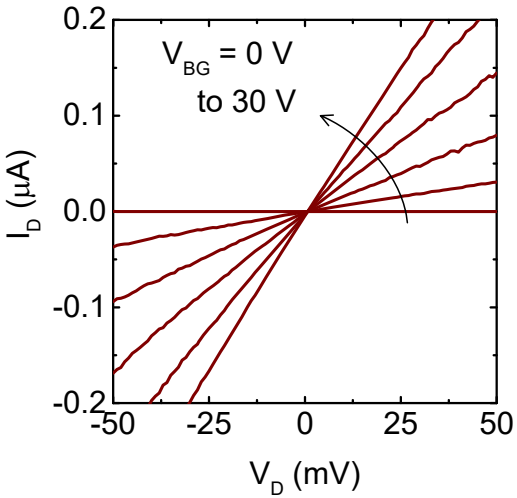
[3] Jmol: an open-source Java viewer for chemical structures in 3D. http://www.jmol.org/
[4] M. M. Fogler *et al.*, *Nat Commun.,* vol. 5, p. 4555 (2014)

MoS_2 and WSe_2 : Contacts

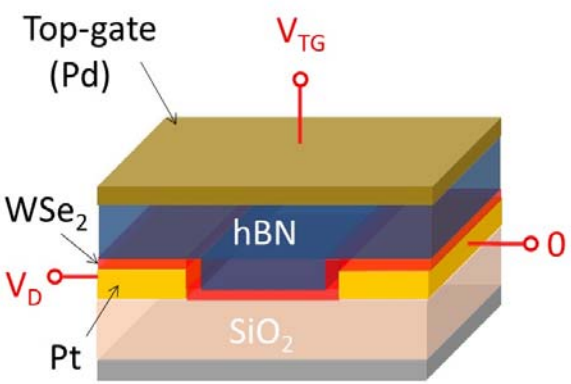
- MoS_2 : top Au *n*-contacts

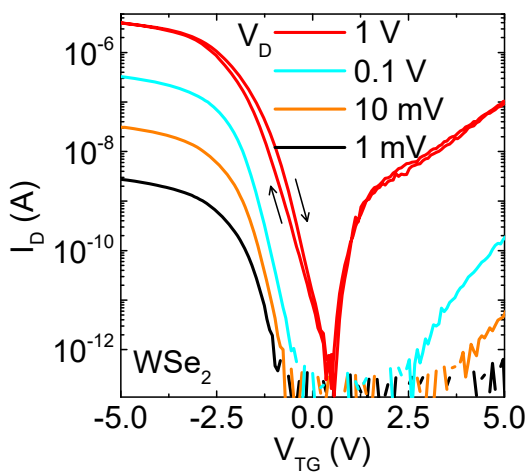


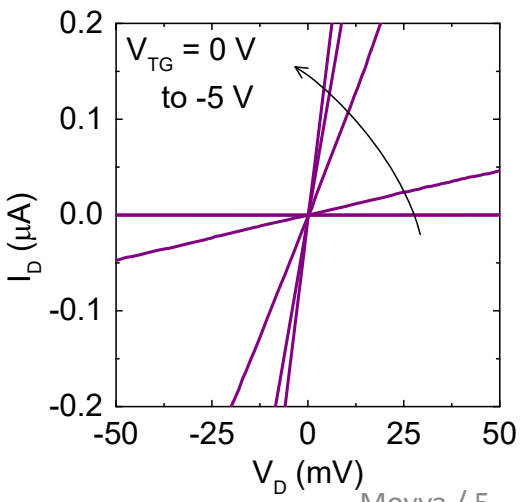




- WSe_2 : bottom Pt *p*-contacts

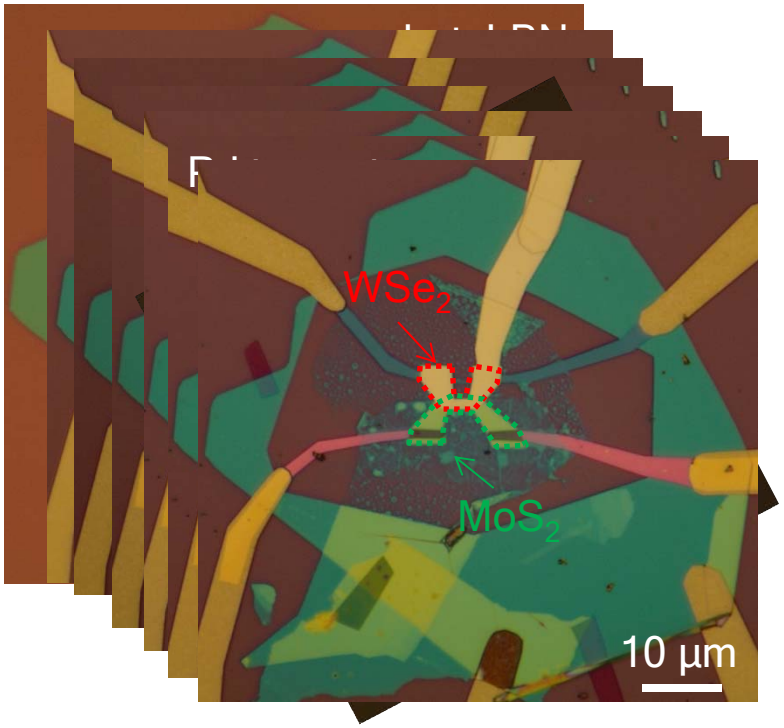


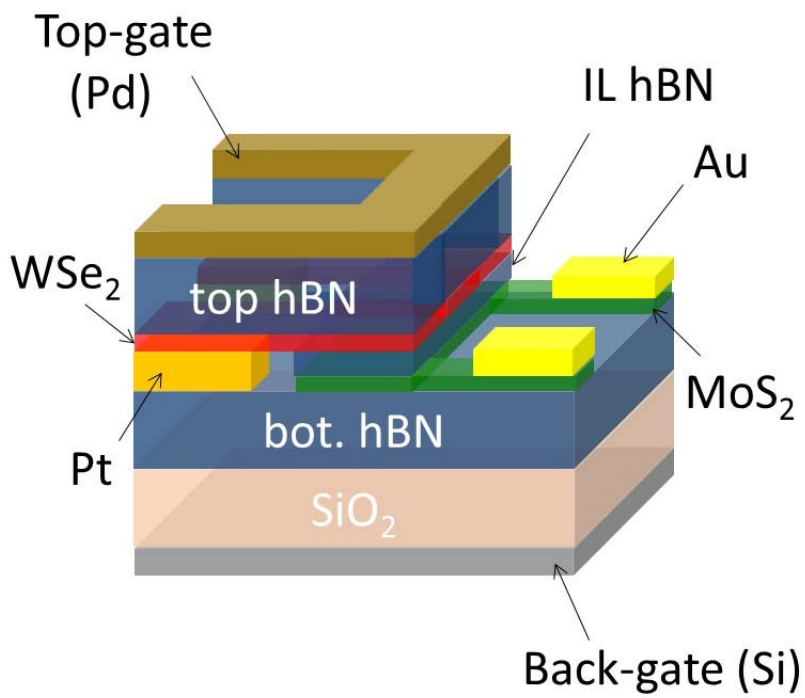




Heterostructure Fabrication Process

- Layer-by-layer assembly using exfoliated flakes

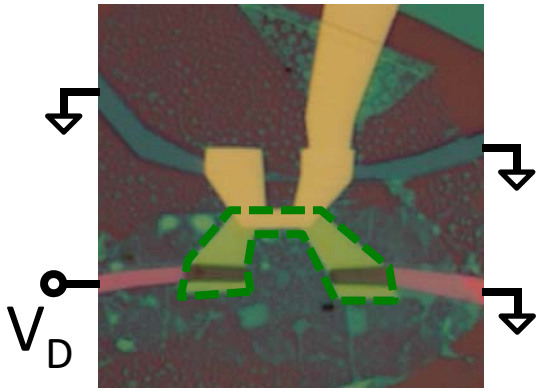


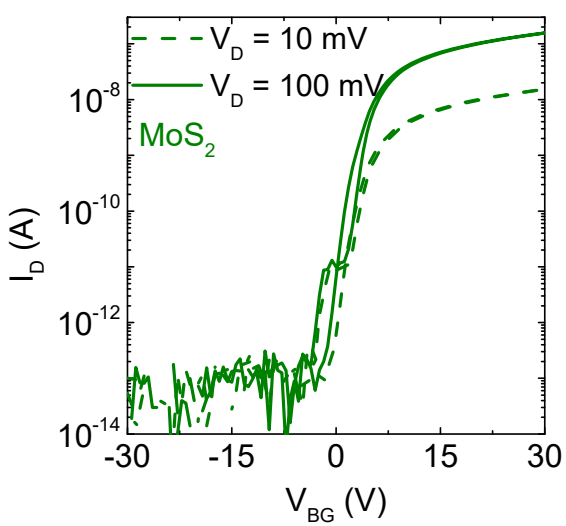


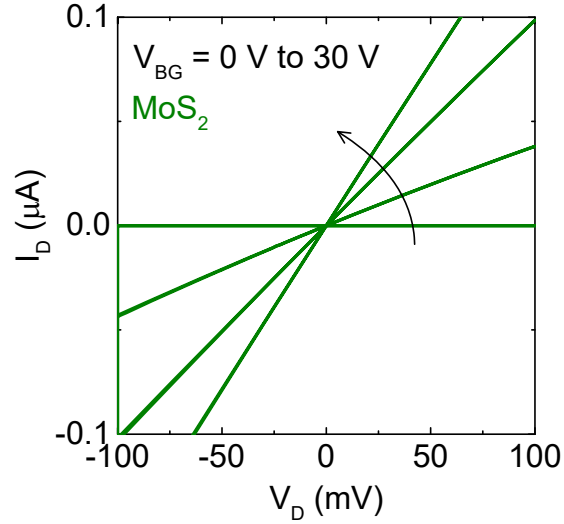
1. Bottom hBN on Si/SiO_2
2. Pt back-contacts for WSe_2
3. Transfer MoS_2
4. Au top-contacts for MoS_2
5. Assemble top hBN / WSe_2 / IL hBN
6. Transfer top hBN/WSe_2/IL hBN
7. Pattern local Pd top-gate
8. Etch device active area

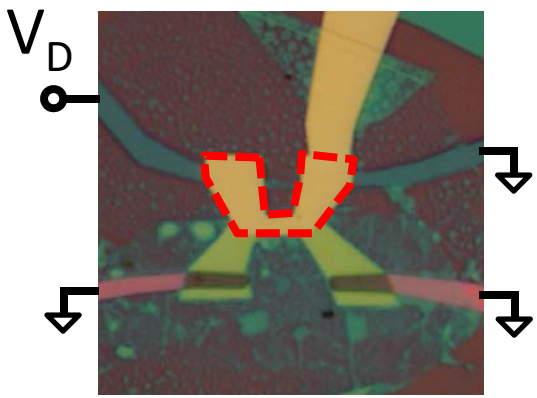
Individual Layer Characteristics

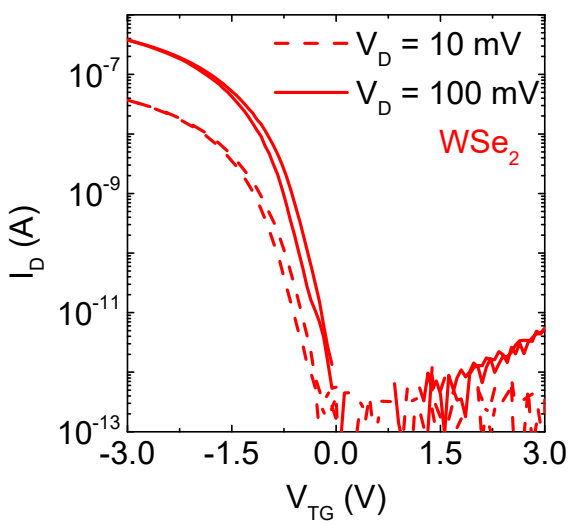
- Individual layer control by the corresponding gate

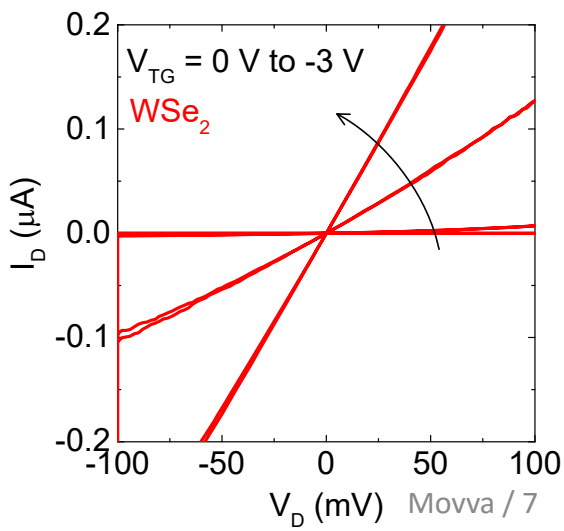






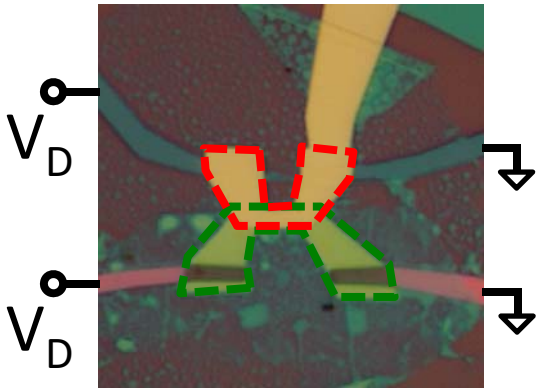


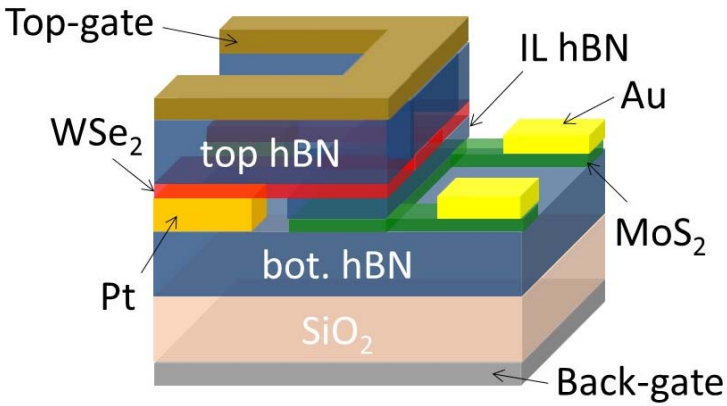


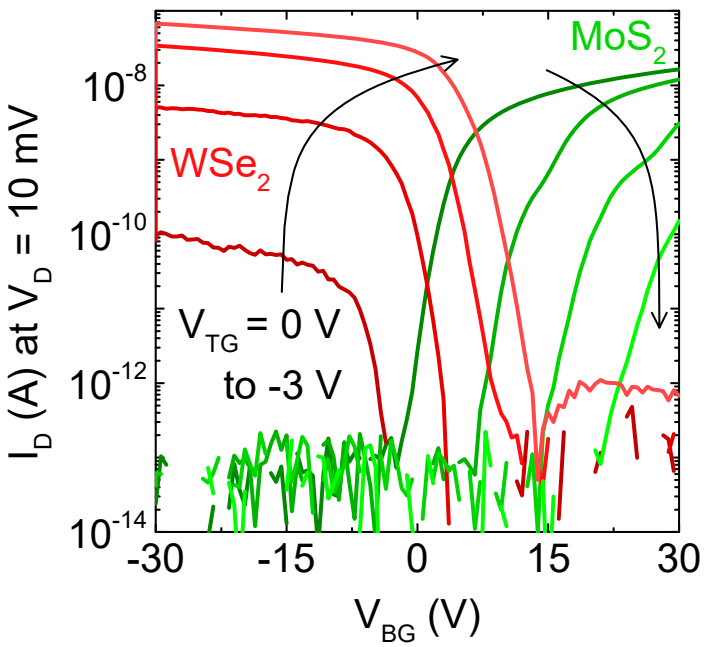


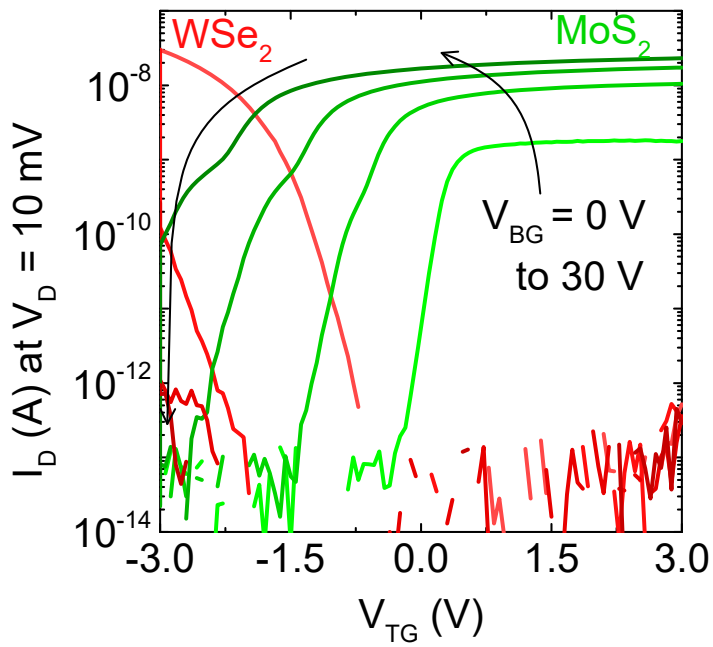
Dual Gated MoS_2 / hBN / WSe_2

- Partial screening by both the MoS_2 and WSe_2



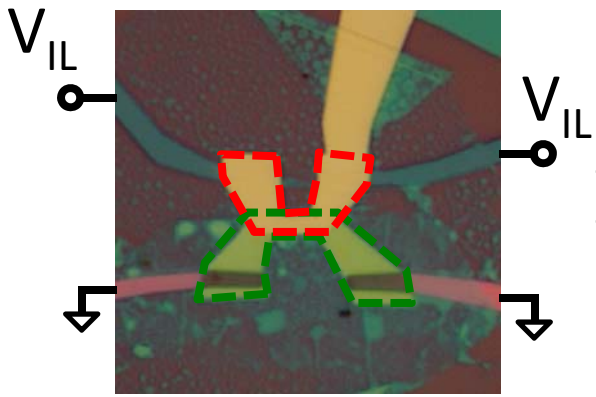


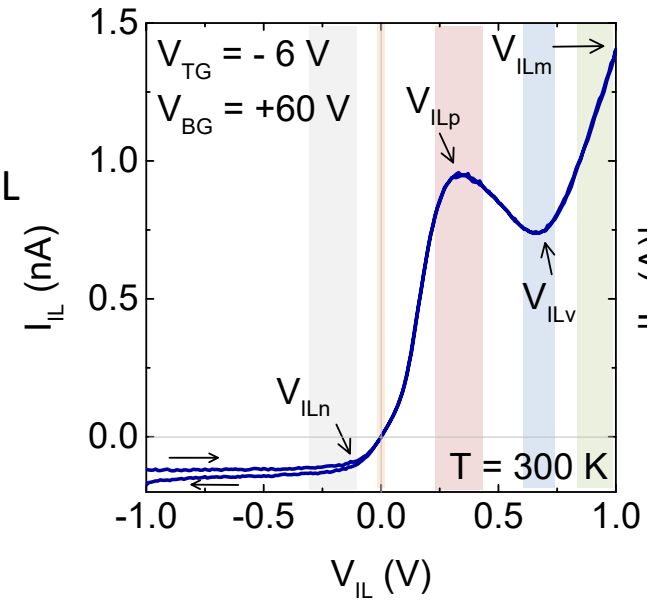


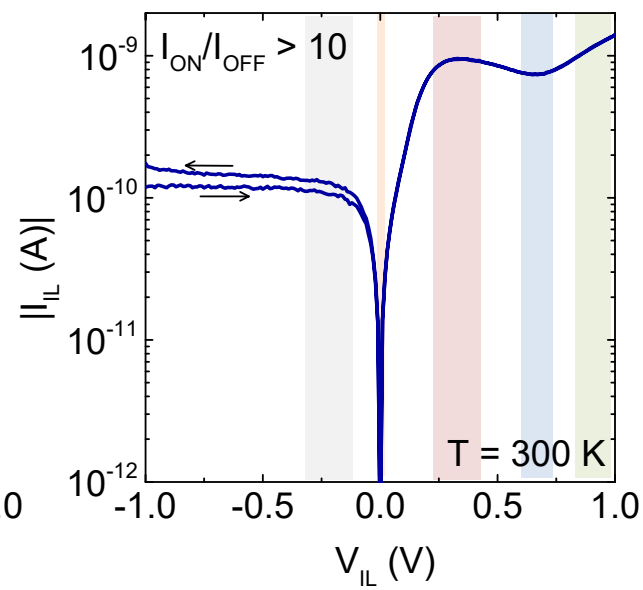


Interlayer I-V : Room Temperature NDR

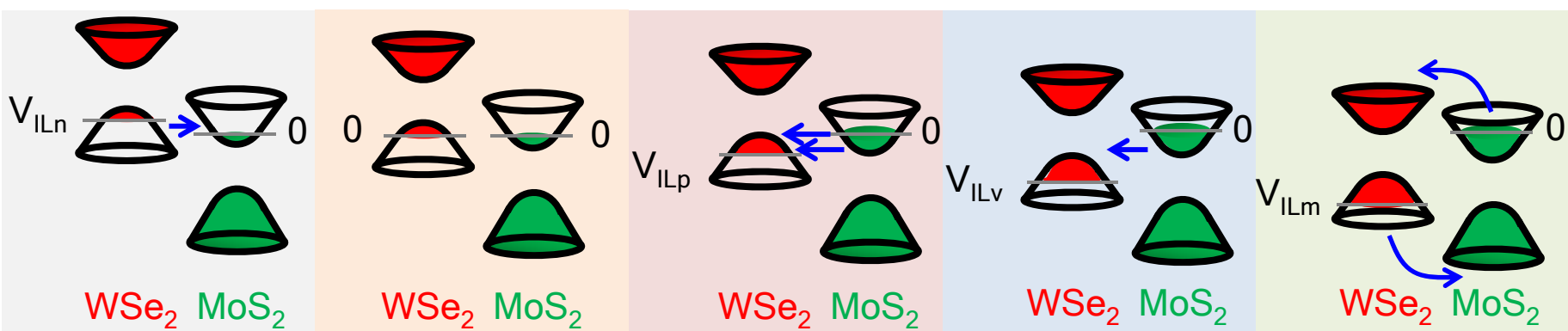
- NDR when MoS_2 (WSe_2) accumulated with *e* (*h*)





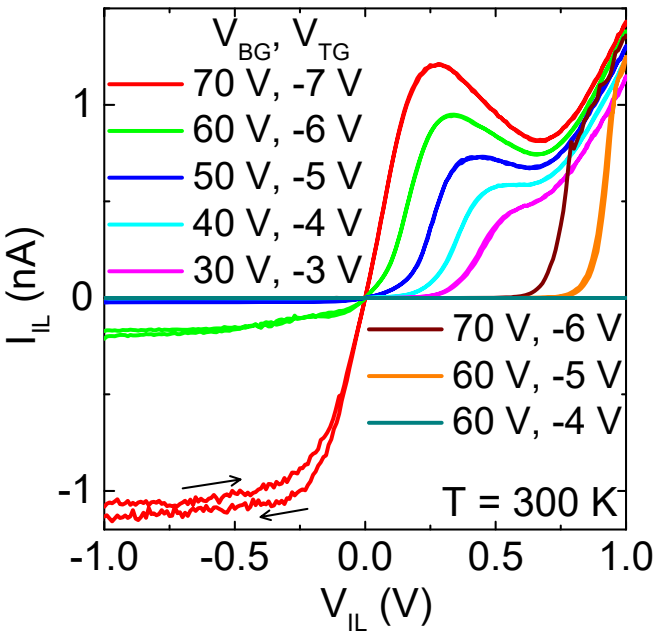


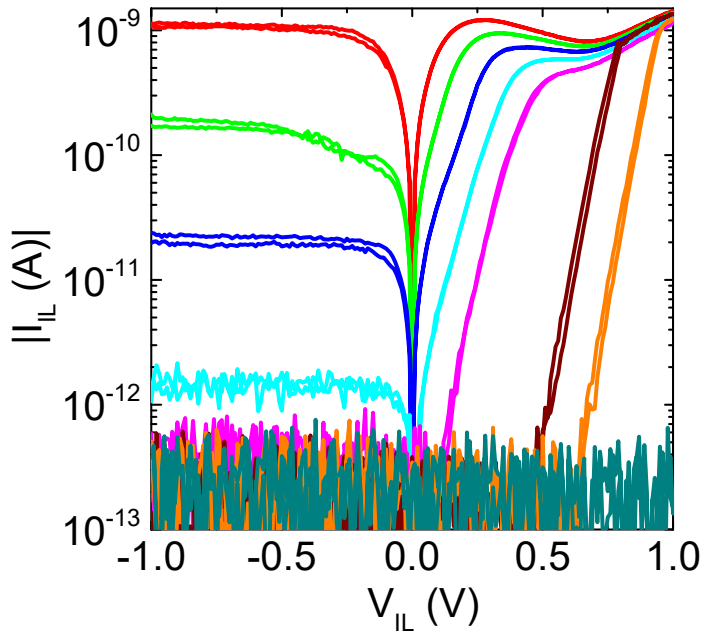
- Esaki NDR



Interlayer I-V : Gate-tunable NDR

- Tunability of the NDR by changing V_{BG} and V_{TG}

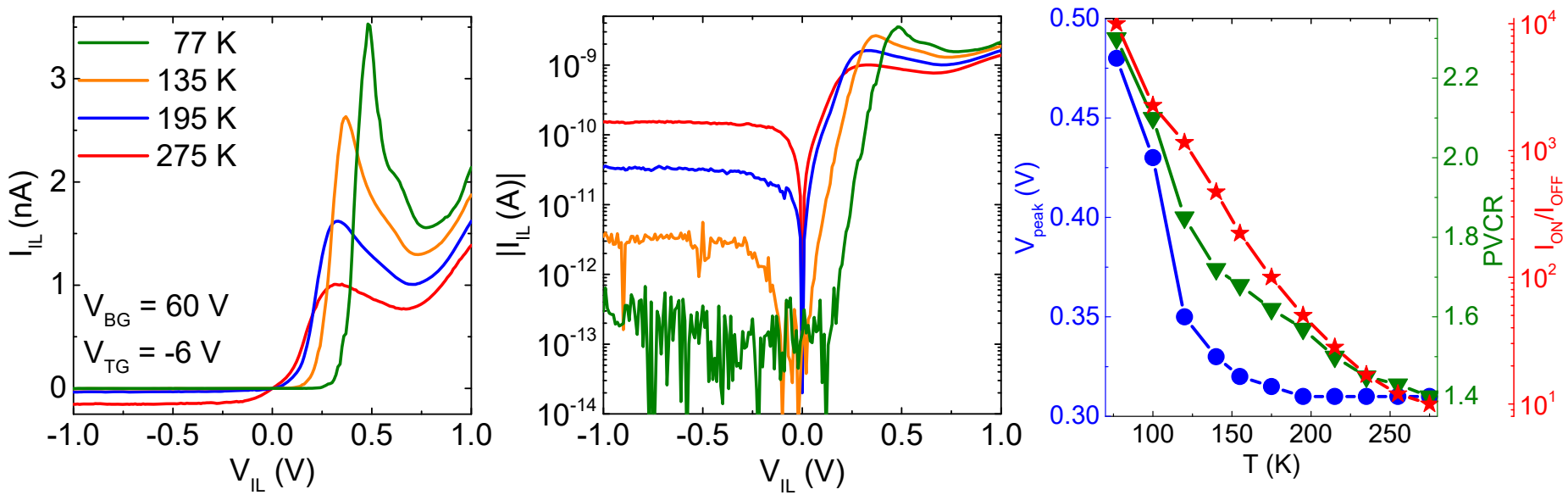




- Both position and amplitude of NDR are tunable
- Decreasing n, $p \Rightarrow$ NDR, I_{peak}, I_{OFF} decrease
- NDR disappears for certain values of V_{BG} and V_{TG}

Interlayer I-V : Temperature Dependence

- NDR becomes stronger at lower temperatures

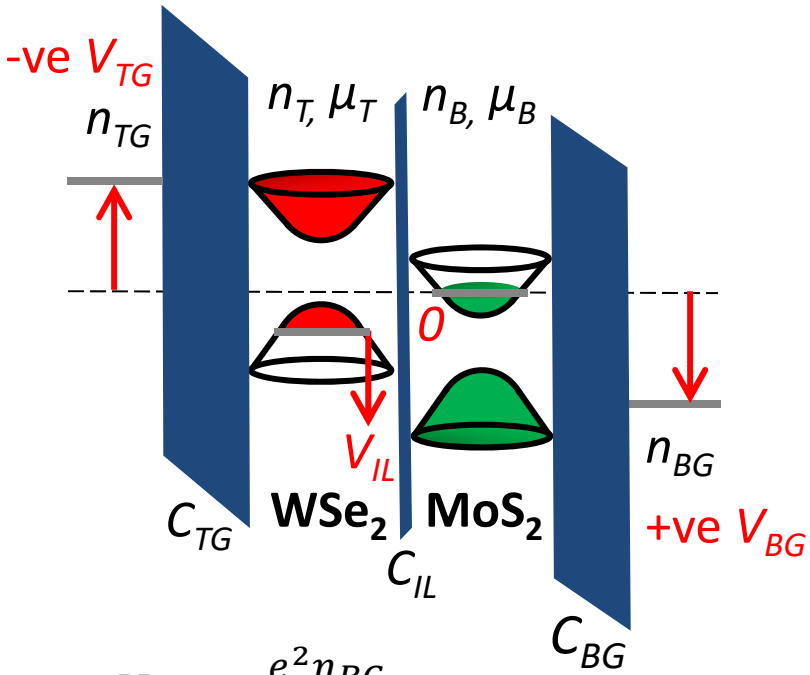


- T-dependence indicates a tunneling mechanism
- I_{OFF} ↓ due to Schottky contacts at low *n* (*p*) and T
- Fine features at 77 K due to "phonon offsets"? [5]

[5] L. Esaki, *Rev. Mod. Phys.*, vol. 46, p. 237 (1974)

MoS_2 / hBN / WSe_2 : Electrostatics

- Self-consistent Poisson and 2D carrier statistics

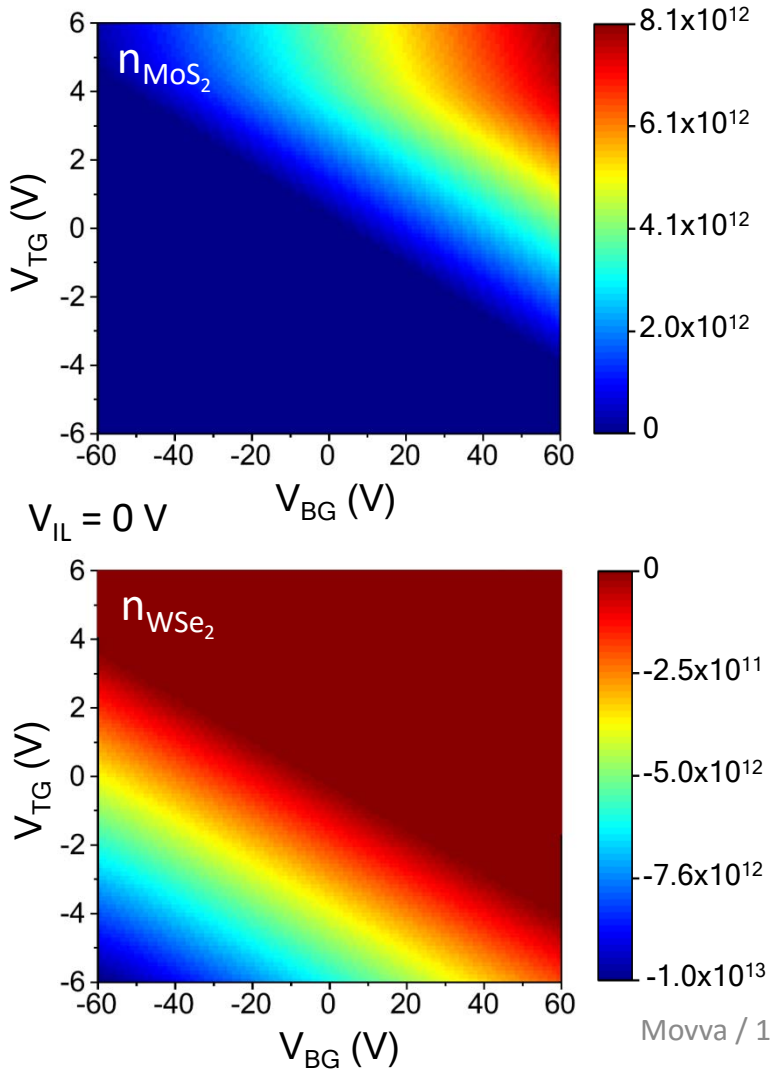


$$eV_{BG} = \frac{e^2 n_{BG}}{C_{BG}} + \mu_B$$

$$eV_{TG} = \frac{e^2 n_{TG}}{C_{TG}} + \mu_T + eV_{IL}$$

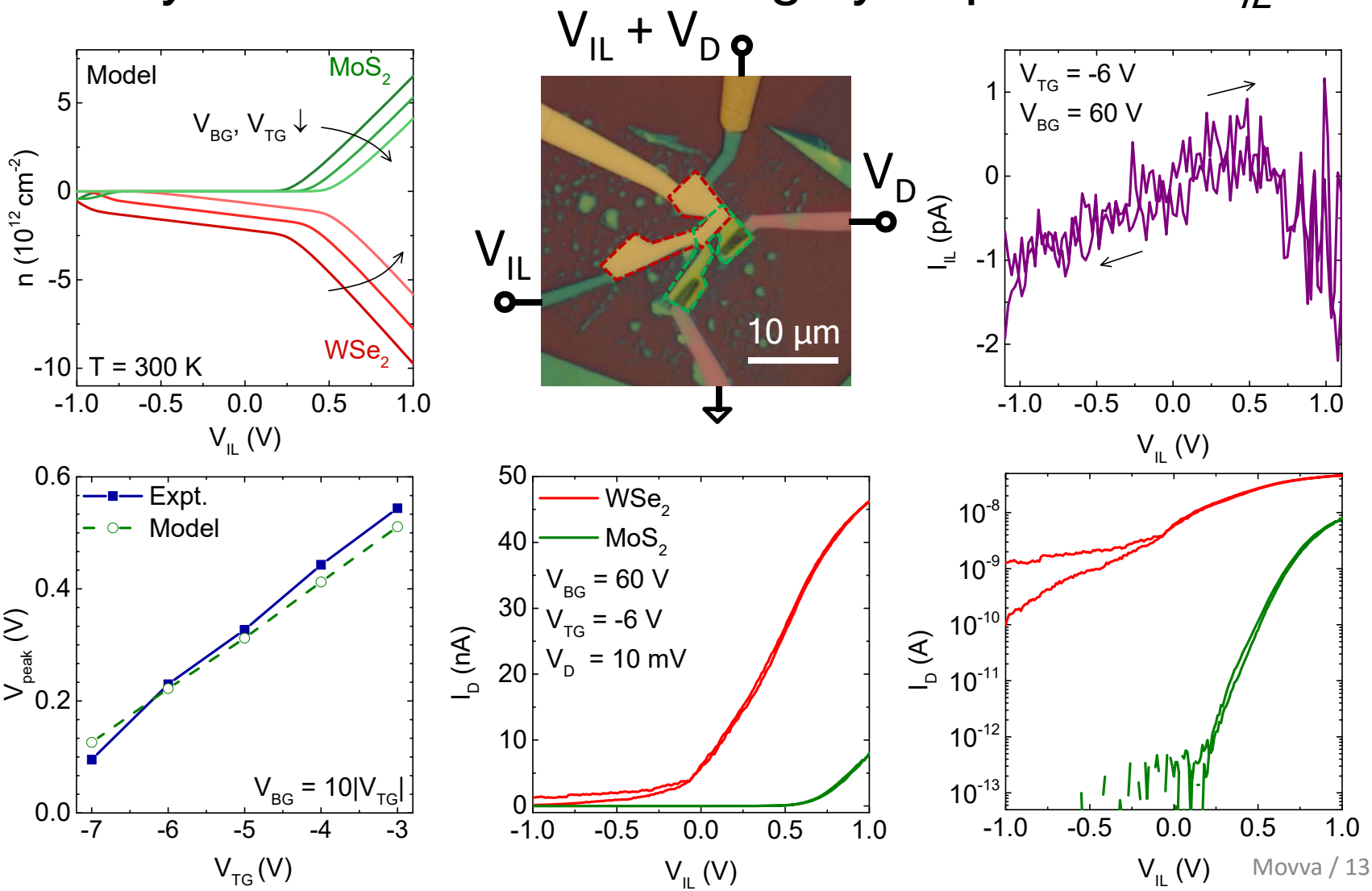
$$eV_{IL} = \frac{e^2 (n_T + n_{TG})}{C_{IL}} + \mu_B - \mu_T$$

$$n_{T(B)} = f\left(\mu_{T(B)}\right)$$



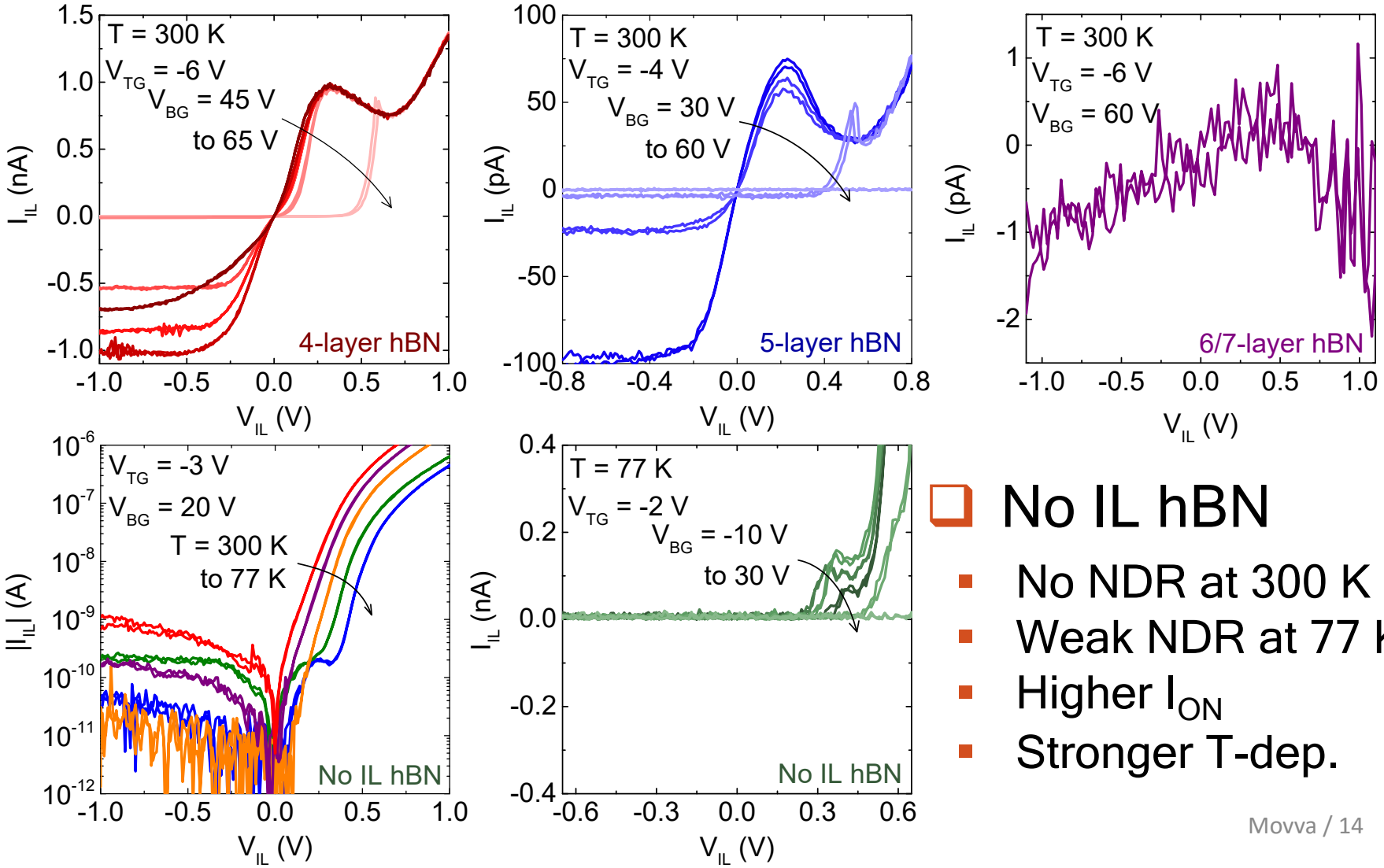
MoS_2 / hBN / WSe_2 : Interlayer Voltage

- Layer carrier densities largely depend on V_{IL}



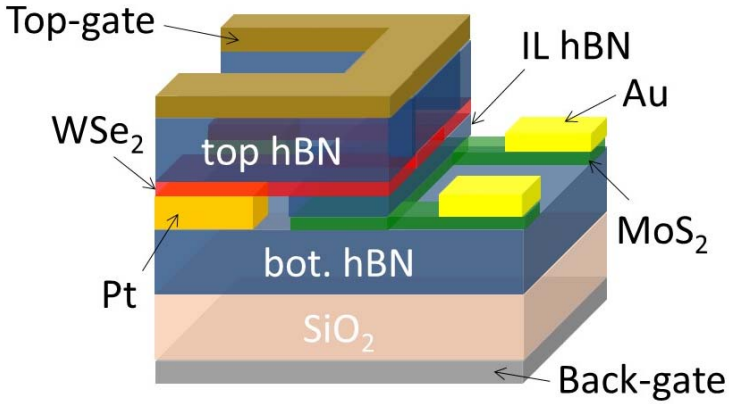
Effect of interlayer hBN thickness

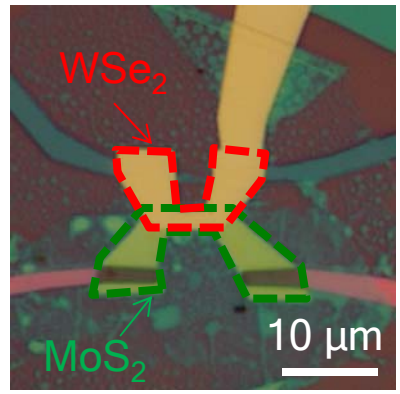
- I_{IL} decreases with increasing IL hBN thickness

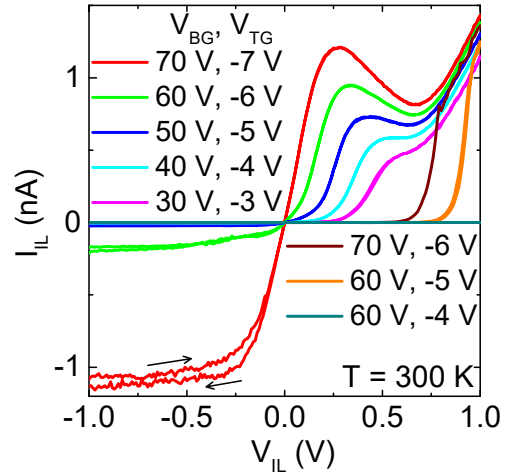


- No IL hBN
  - No NDR at 300 K
  - Weak NDR at 77 K
  - Higher I_{ON}
  - Stronger T-dep.

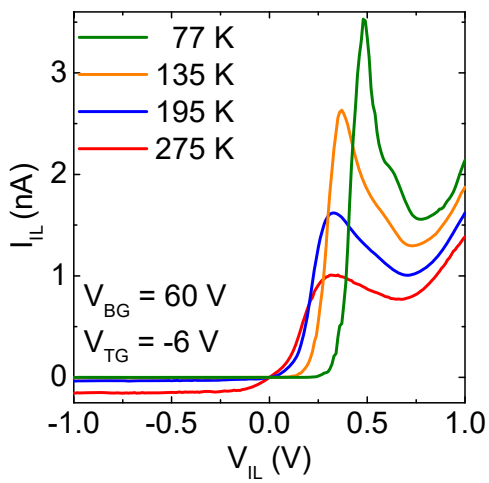
Summary

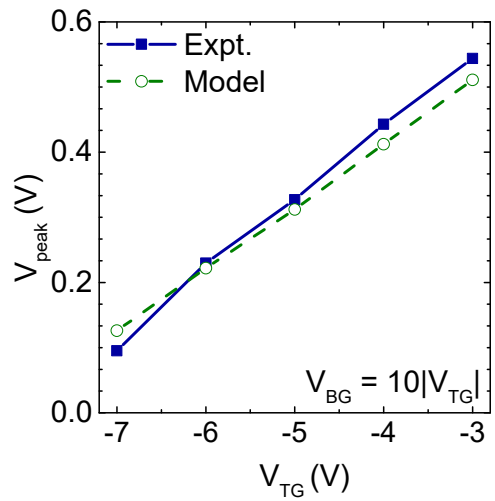


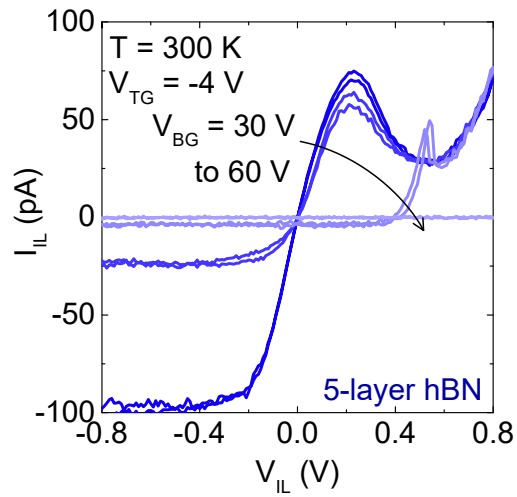




- Dual-gated MoS_2 / hBN / WSe_2 devices
- Esaki NDR

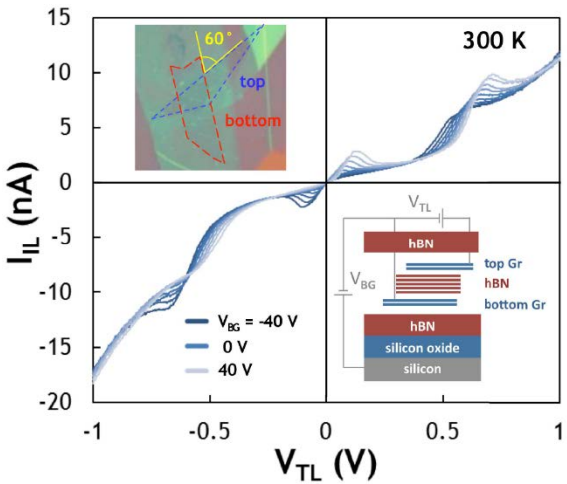




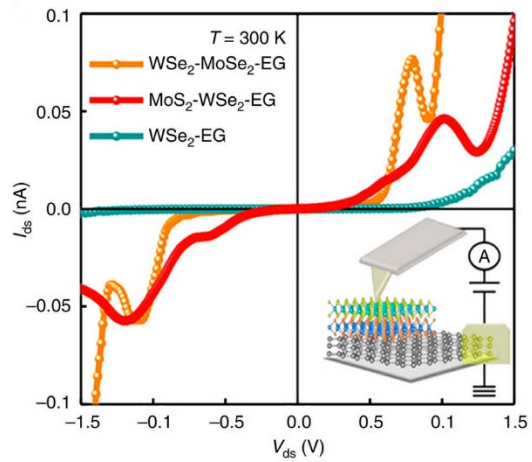


- NDR ↑ with ↓ T
- Electrostatics model
- Effect of IL hBN

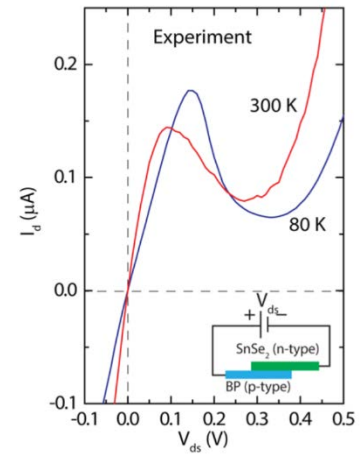
NDR in 2D Heterostructures



Gr / hBN / Gr [6]

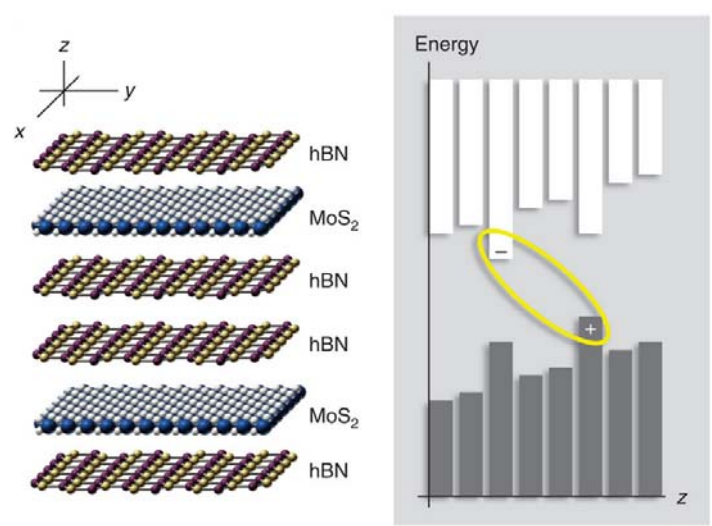


MoS_2 / WSe_2 [7]



$SnSe_2$ / black-P [8]

- Building block for TFETs
- Low-power logic
- High-T superfluidity ?

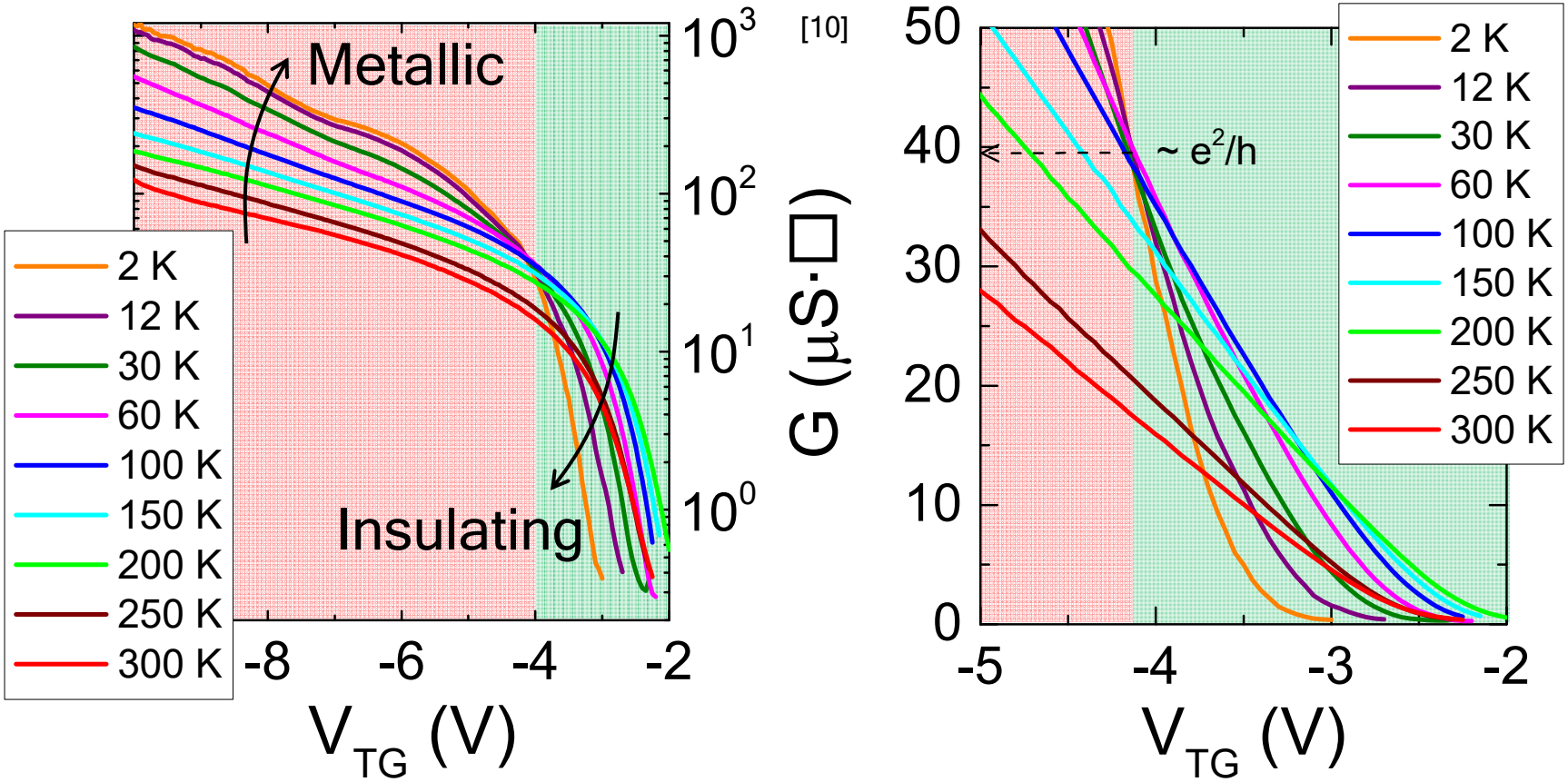


[9]

[6] S. Kang *et al.*, *IEEE Elec. Dev. Lett.*, vol. 36, p. 405 (2015)
[7] Y. -C. Lin *et al.*, *Nat Commun.,* vol. 6, p. 7311 (2015)
[9] R. Yan *et al.*, *Nano Lett.,* vol. 15, p. 5791 (2015)
[9] M. M. Fogler *et al.*, *Nat Commun.,* vol. 5, p. 4555 (2014)

Metal Insulator Transition

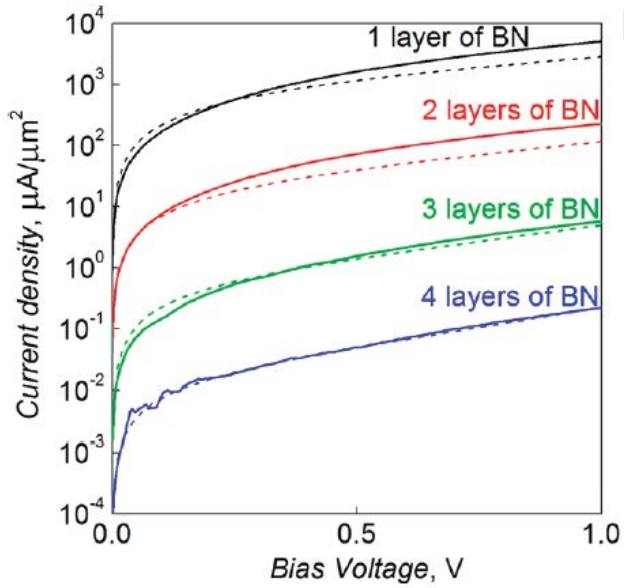
- Metal-Insulator Transition at $V_{TG} \sim -4.2$ V
- MIT conductivity $\simeq e^2/h$



[10] H. C. P. Movva *et al.*, *ACS Nano*, vol. 9, p. 10402 (2015)

Tunneling through hBN

- $I_{IL} \downarrow$ by one order for every extra hBN layer



[11]

[11] L. Britnell *et al.*, *Nano Lett.*, vol. 12, p. 1707 (2012)