MOS-AK Asia-Pacific

SPICE Modeling of 2D-material based FETs with Schottky-barrier contacts

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Acknowledgements and Funding

Funding agencies

Where we are located!

Schottky Barrier 2D FET Model

Existing Models and Motivation

$$I_{ds} = \frac{2q}{h}\int_{-\infty}^{E_v} T(E)M_v(E)[f(E) - f(E - qV_{ds})]dE$$

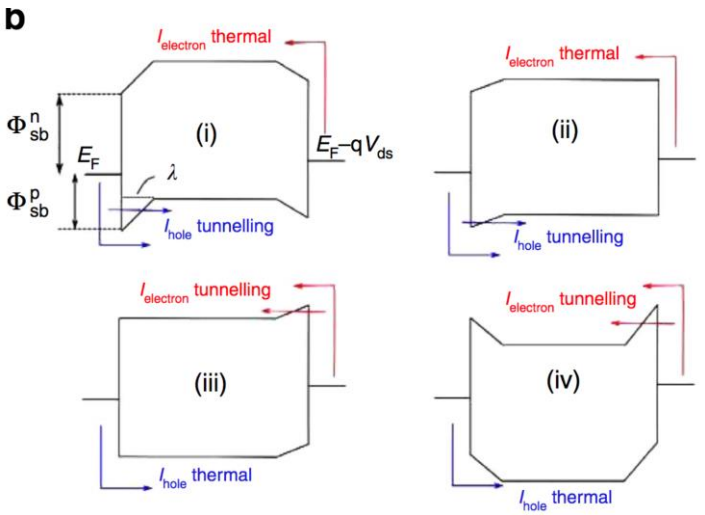
$$M_v(E) = \frac{g_v}{\pi\hbar}\sqrt{2m_h^*\left(E_v(V_g) - E\right)}$$

$$T_{wkb}(E) = exp\left(-\int_{x_m}^{x_0}\kappa(E)dx\right)$$

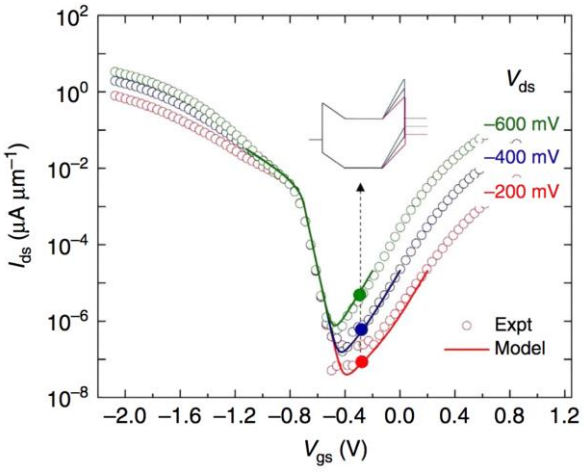
$$\kappa(E) = \frac{1}{\hbar}\sqrt{2m_h^*\left(E - E_v(x)\right)}$$

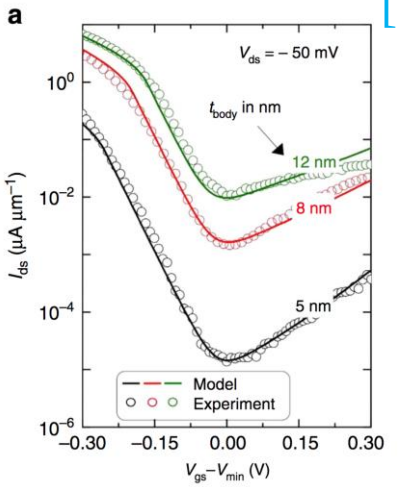
$$T = \frac{T_s T_d}{1 - (1 - T_s)(1 - T_d)}$$

Landauer Formalism



[1]





[1] Penumatcha *et al.*, *Nature Comm.*, **6 (8948),** [2015]

Off State Characteristics

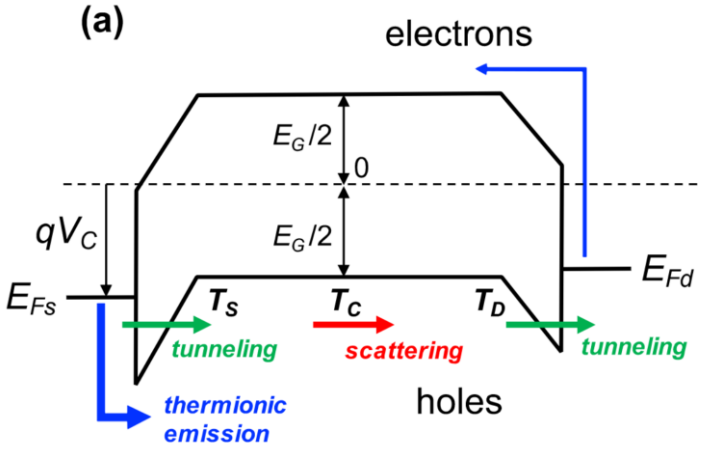
Existing Models and Motivation

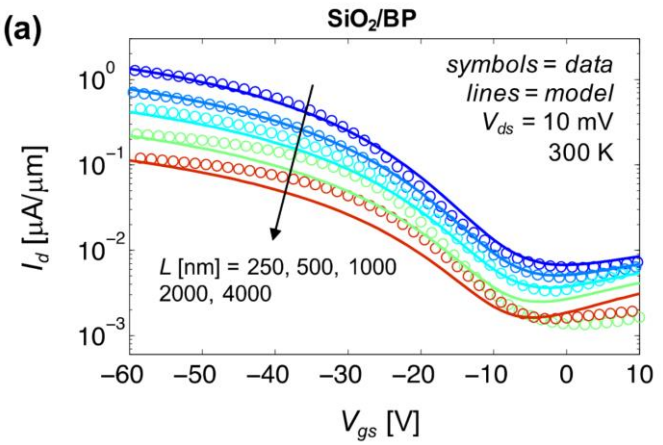
$$I_{ds} = \frac{2q}{h}\int_{-\infty}^{E_v} T(E)M_v(E)[f(E) - f(E - qV_{ds})]dE$$

$$T = \left[1 + \left(\frac{1 - T_s}{T_s}\right) + \left(\frac{1 - T_d}{T_d}\right) + \left(\frac{1 - T_c}{T_c}\right)\right]^{-1}$$

$$T_c = \frac{\lambda(E)}{\lambda(E) + L}$$

$$\lambda(E) = \lambda_0 \left[\frac{E_v - E}{k_B T}\right]^r$$

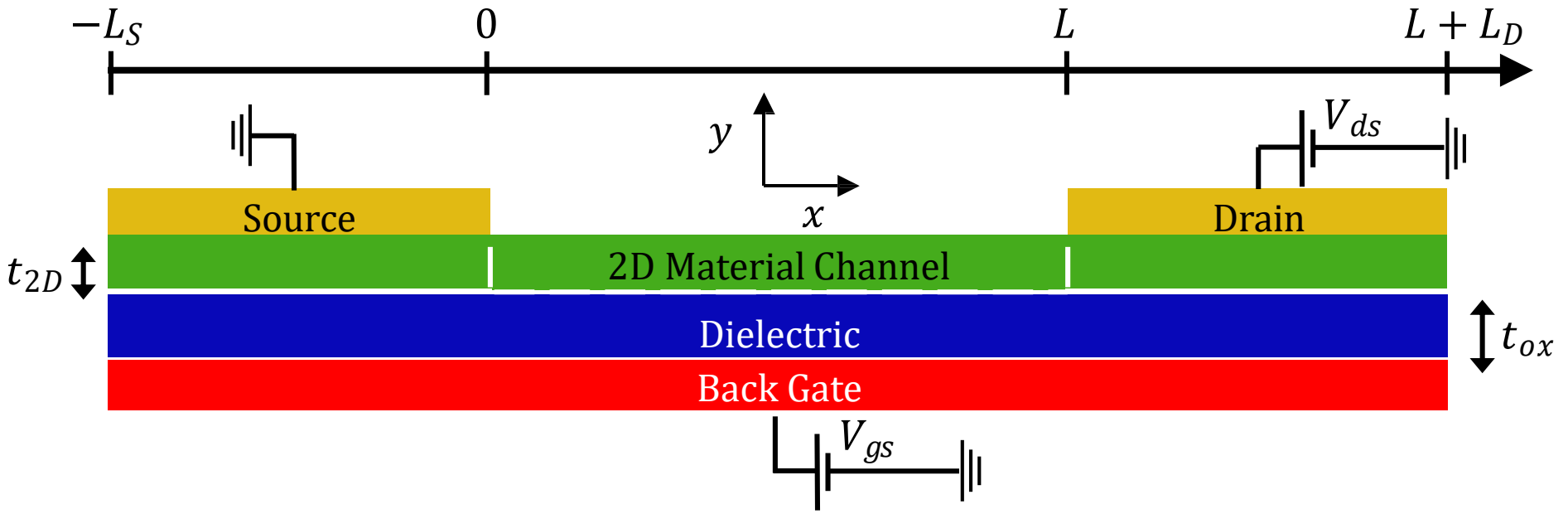




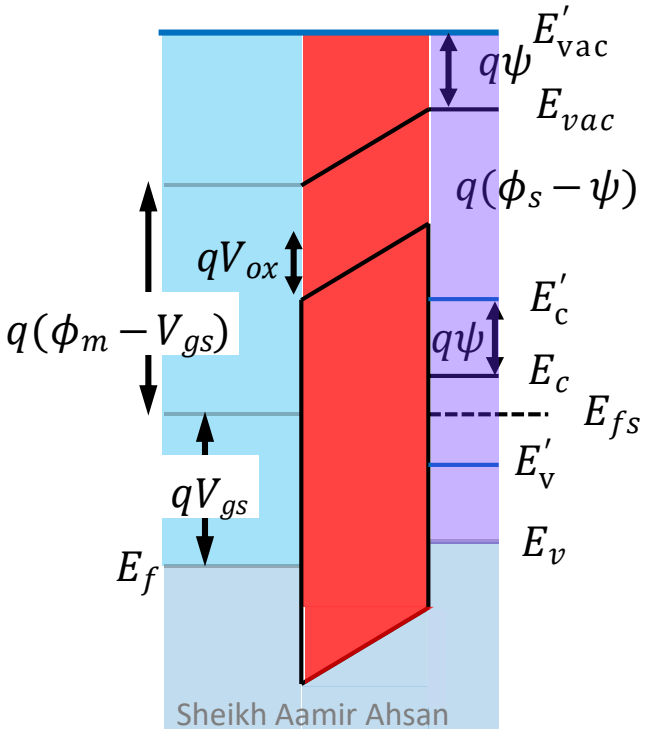
[1]

On-state but Near Equilibrium Characteristics

[1] Esqueda *et al.*, *IEEE Trans. Electron Devices*, **64 (12),** [2017]



Band Diagram



Model Description - Electrostatics

Potential Balance From Gate/Oxide/2DM $\longrightarrow$ $\phi_m - V_g + V_{ox} = \phi_s - {}^{(E_{vac} - E_{vac}^0)}/_q$

Using $E_{vac} - E_{vac}^0 = E_c - E_c^0 = q\psi$ and rearranging the terms:

$$Q = Q_e - Q_h = C_{ox}(V_g - \phi_{ms} - \psi) \qquad \text{with} \qquad C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

Using Fermi-Dirac Statistics:

$$\frac{Q}{qkT} = \underbrace{D_e \ln\left[1 + \exp\left(\frac{-\phi_e + q(\psi - V)}{kT}\right)\right]}_{Electrons} - \underbrace{D_h \ln\left[1 + \exp\left(\frac{-\phi_h - q(\psi - V)}{kT}\right)\right]}_{Holes}$$

where $D_e = \frac{m_e^*}{\pi\hbar^2}$; $D_h = \frac{m_h^*}{\pi\hbar^2}$

Surface-potential – Explicit

$$\psi(x) = V_{gs} - \phi_{ms} - \frac{qkTD_e}{C_{ox}} \ln\left[1 + \exp\left(\frac{-\phi_e + q\left(\psi(x) - V(x)\right)}{kT}\right)\right] + \frac{qkTD_h}{C_{ox}} \ln\left[1 + \exp\left(\frac{-\phi_h - q\left(\psi(x) - V(x)\right)}{kT}\right)\right]$$

$$y = ze^z$$

$$z = W(y)$$

Lambert-W Function

$$\psi_0 = V_{gs} - \phi_{ms} - \phi_{\mathrm{th}} W\left(\frac{q^2 D_{\mathrm{e}}}{C_{ox}} \exp\left(\frac{V_{gs} - \phi_{\mathrm{ms}} - \phi_{\mathrm{e}} - V}{\phi_{\mathrm{th}}}\right)\right) + \phi_{\mathrm{th}} W\left(\frac{q^2 D_{\mathrm{h}}}{C_{ox}} \exp\left(\frac{-V_{gs} + \phi_{\mathrm{ms}} - \phi_{\mathrm{h}} + V}{\phi_{\mathrm{th}}}\right)\right)$$

Halley's Correction

$$\psi = \psi_0 + \Delta$$

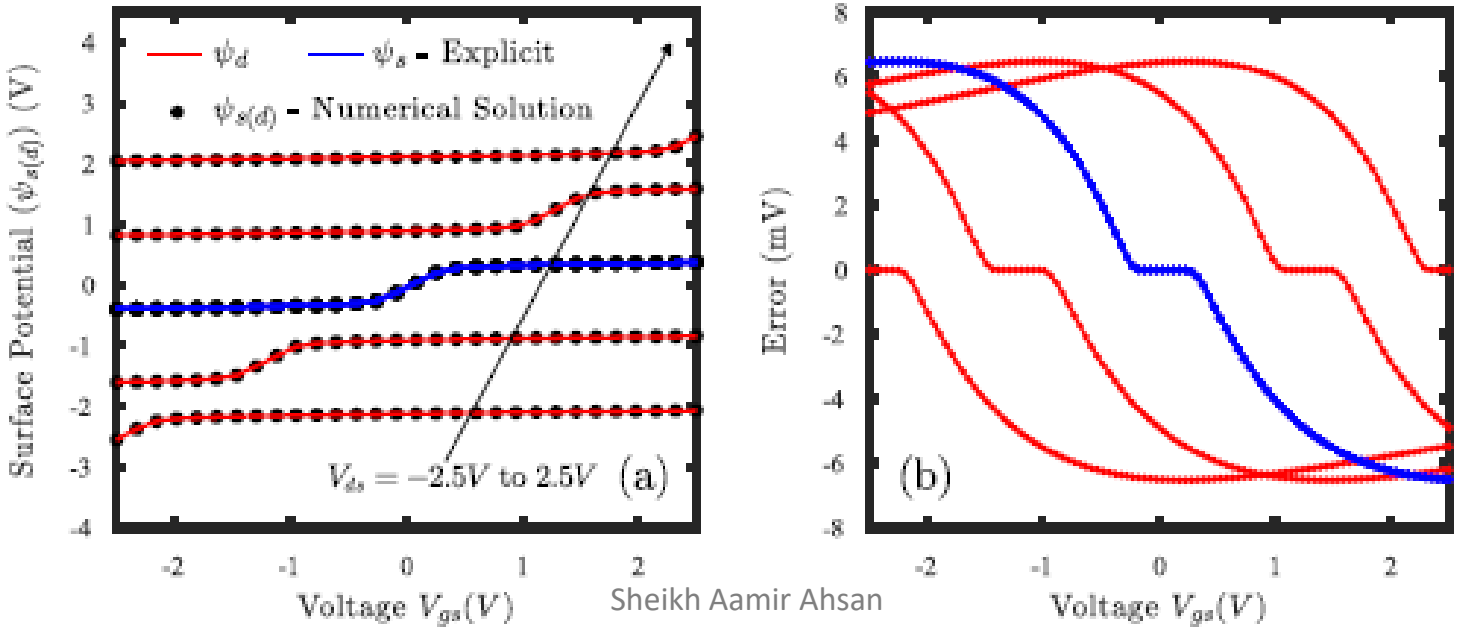
$$\Delta = -\frac{r}{r'}\left(1 + \frac{0.5rr''}{r'^2}\right)$$

$$r = C_{ox}\left(V_{gs} - \phi_{ms} - \psi_0\right) - qD_e kT \ln\left[1 + e^{\left(\frac{-\phi_e + (\psi_0 - V)}{\phi_{\mathrm{th}}}\right)}\right] + qD_h kT \ln\left[1 + e^{\left(\frac{-\phi_h - (\psi_0 - V)}{\phi_{\mathrm{th}}}\right)}\right.$$

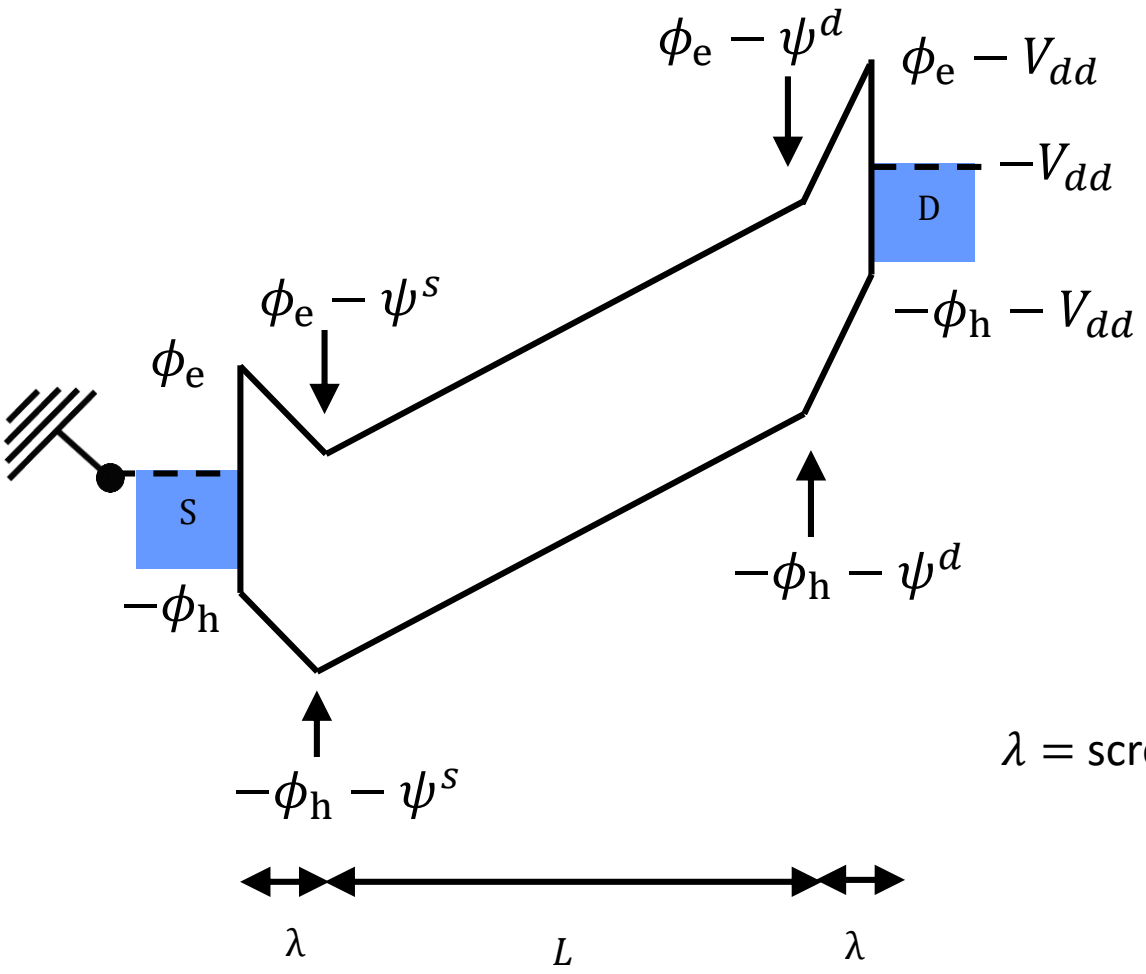
Surface-potential – Source & Drain

$$\psi^s = V_{gs} - \phi_{ms} - \frac{qkTD_e}{C_{ox}} \ln\left[1 + \exp\left(\frac{-q\phi_e + q\psi^s}{kT}\right)\right] + \frac{qkTD_h}{C_{ox}} \ln\left[1 + \exp\left(\frac{-q\phi_h - q\psi^s}{kT}\right)\right]$$

$$\psi^d = V_{gs} - \phi_{ms} - \frac{qkTD_e}{C_{ox}} \ln\left[1 + \exp\left(\frac{-q\phi_e + q\left(\psi^d - V_{ds}\right)}{kT}\right)\right] + \frac{qkTD_h}{C_{ox}} \ln\left[1 + \exp\left(\frac{-q\phi_h - q\left(\psi^d - V_{ds}\right)}{kT}\right)\right]$$

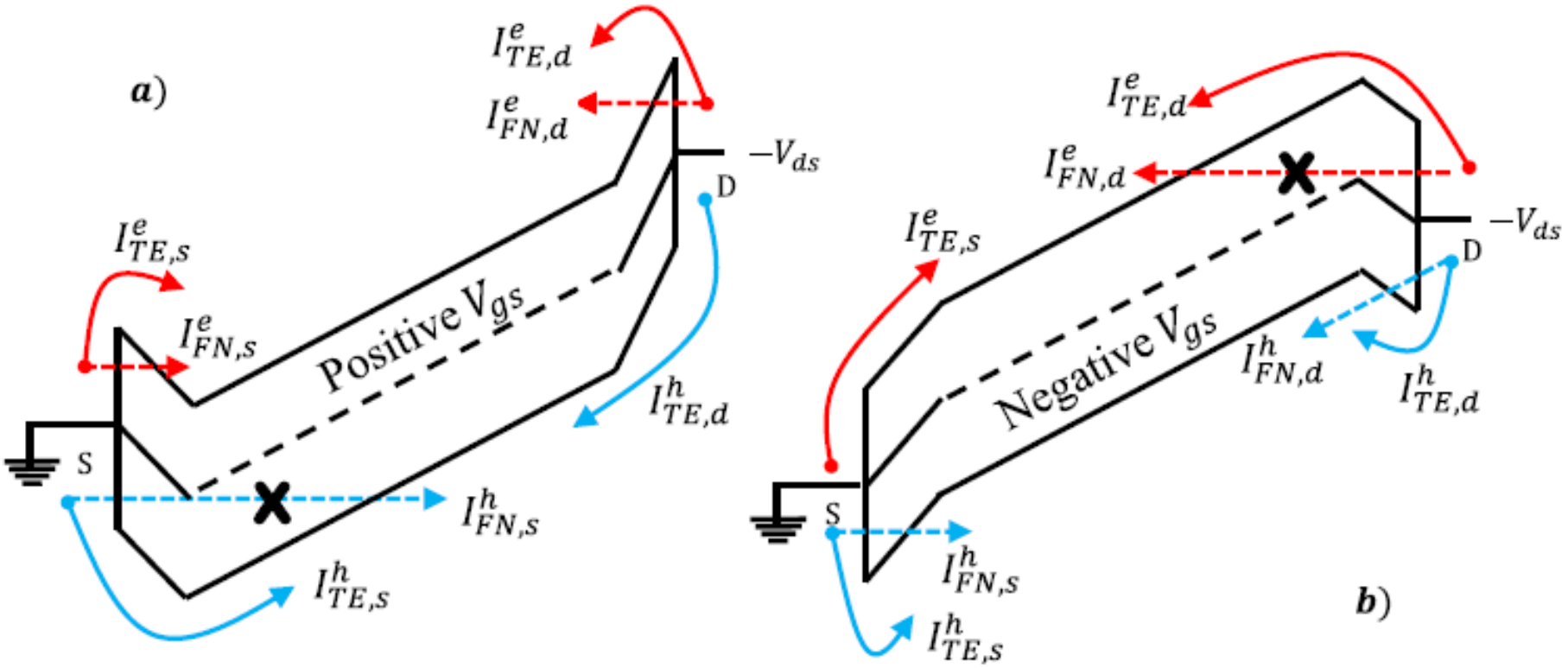


Band Diagram – Potential Points



λ = screening length

Band Diagram – Bias dependent



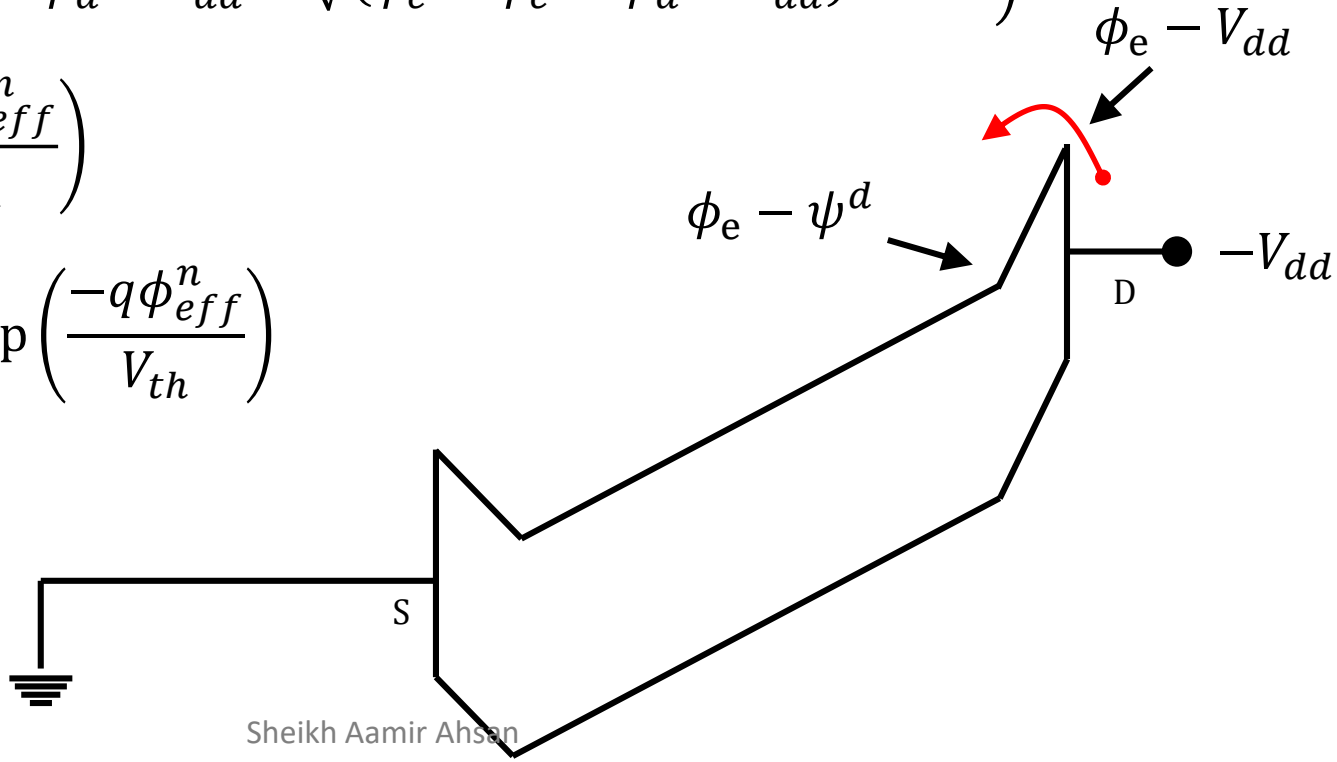
Electron TE Current at drain

Effective barrier height wrt drain terminal = maximum of ϕ_e and $\phi_e - \psi_d + V_{dd}$

$$\phi_{eff}^n = {}^1/_2\left(\phi_e + \phi_e - \psi_d + V_{dd} + \sqrt{(\phi_e - \phi_e + \psi_d - V_{dd})^2 + \delta^2}\right)$$

$$J_{TE}^n = A_R^n T^2 \exp\left(\frac{-q\phi_{eff}^n}{V_{th}}\right)$$

$$I_{TE,d}^n = W L_{con} A_R^n T^2 \exp\left(\frac{-q\phi_{eff}^n}{V_{th}}\right)$$



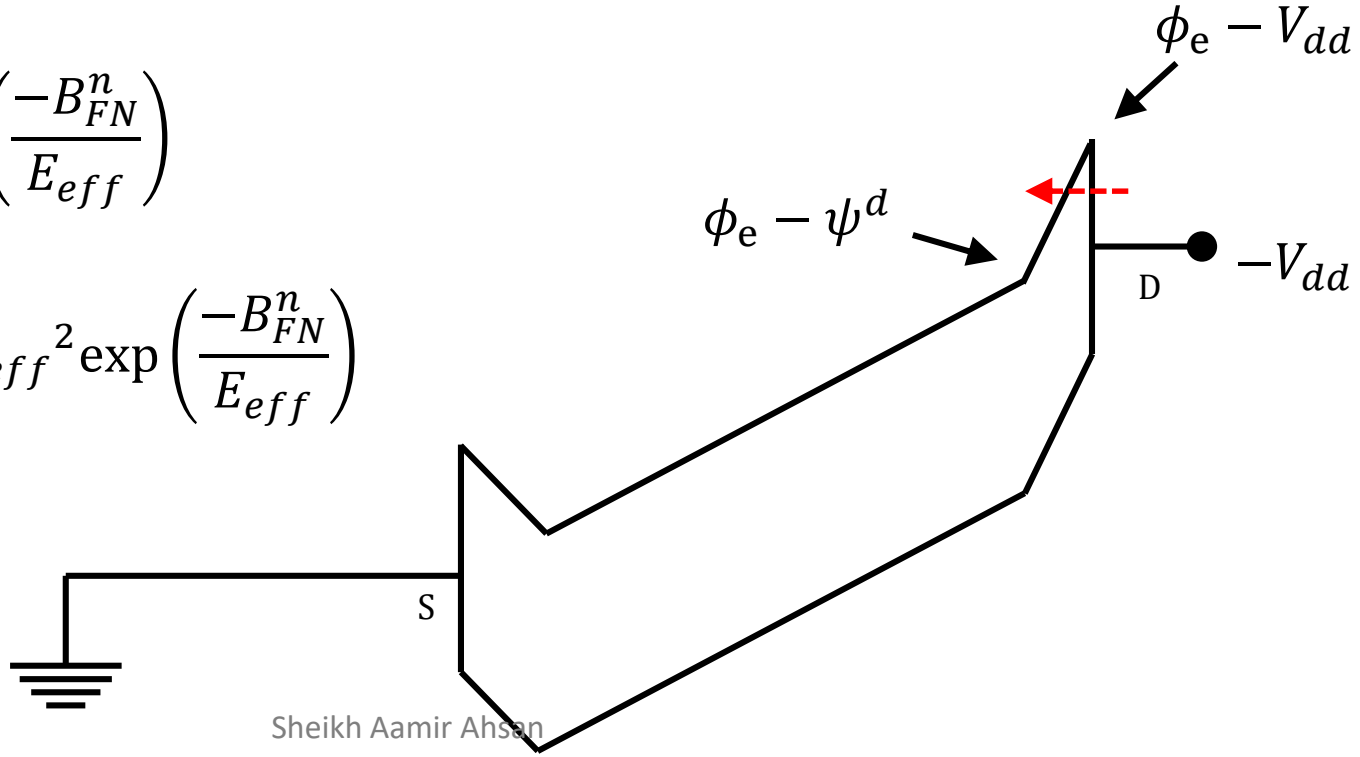
Electron FN Current at drain

Electric field at the drain end = $E' = \frac{(\phi_e - V_{dd}) - (\phi_e - \psi_d)}{\lambda} = \psi_d - V_{dd}$

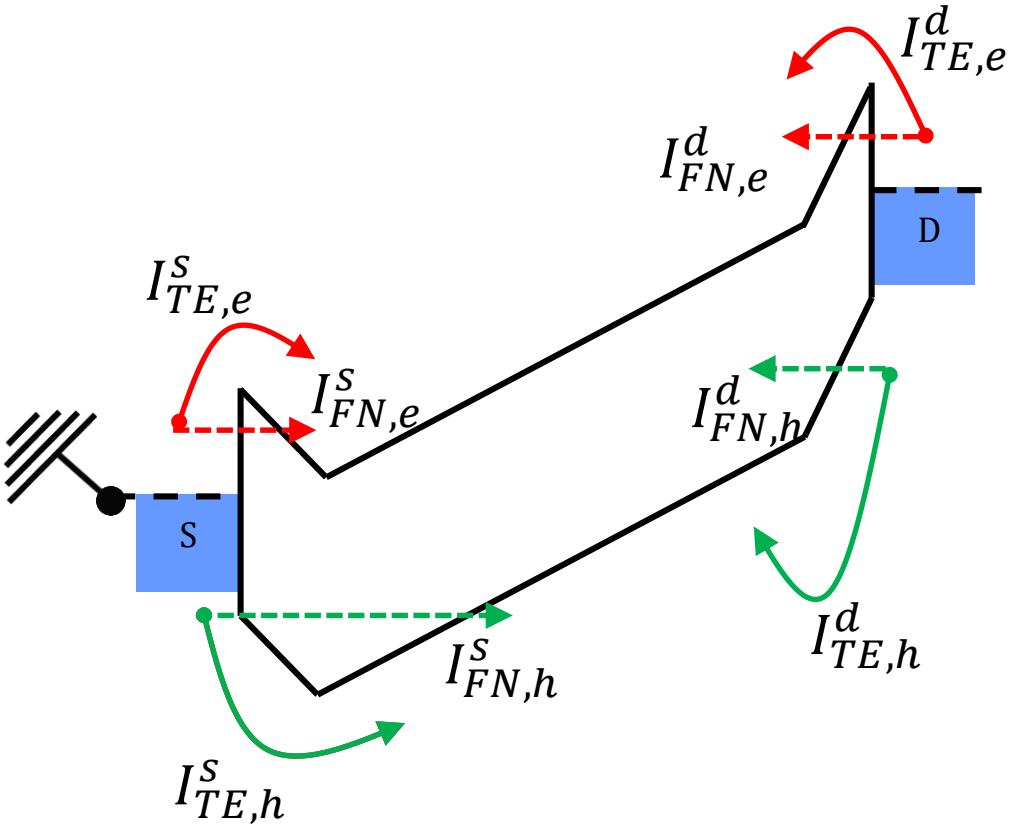
$$E_{eff} = {}^{1}/_{2}\left(E' + \sqrt{(E')^2 + \delta^2}\right)$$

$$J_{FN}^{n} = A_{FN}^{n} {E_{eff}}^{2} \exp\left(\frac{-B_{FN}^{n}}{E_{eff}}\right)$$

$$I_{FN,d}^{n} = W L_{con} A_{FN}^{n} {E_{eff}}^{2} \exp\left(\frac{-B_{FN}^{n}}{E_{eff}}\right)$$

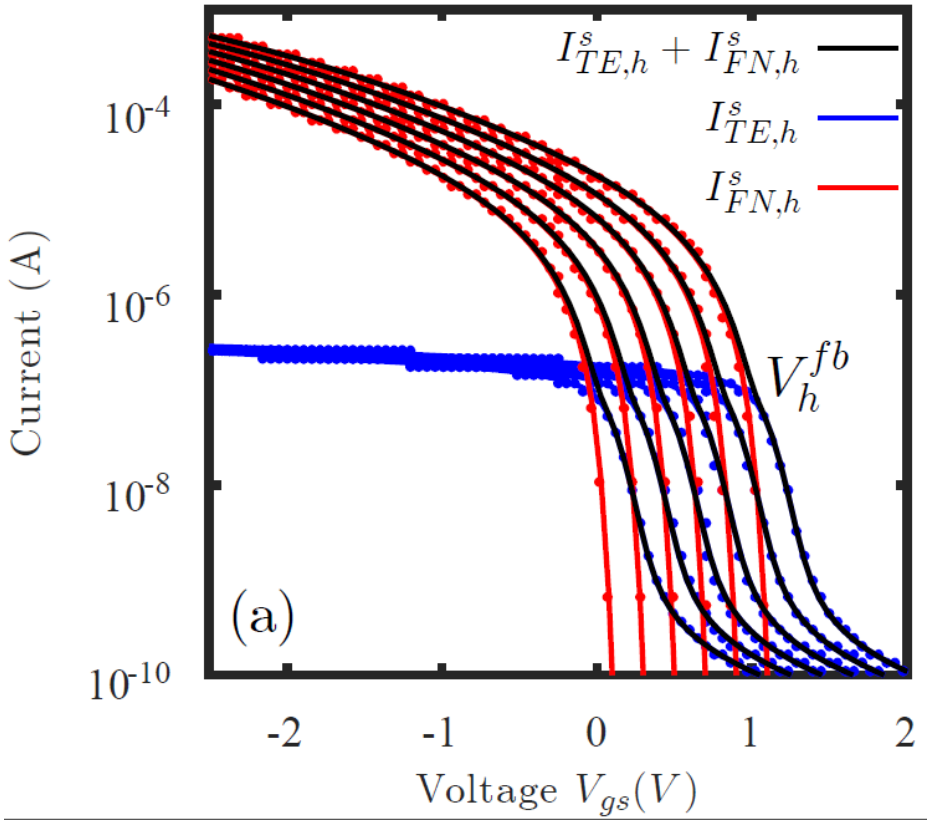


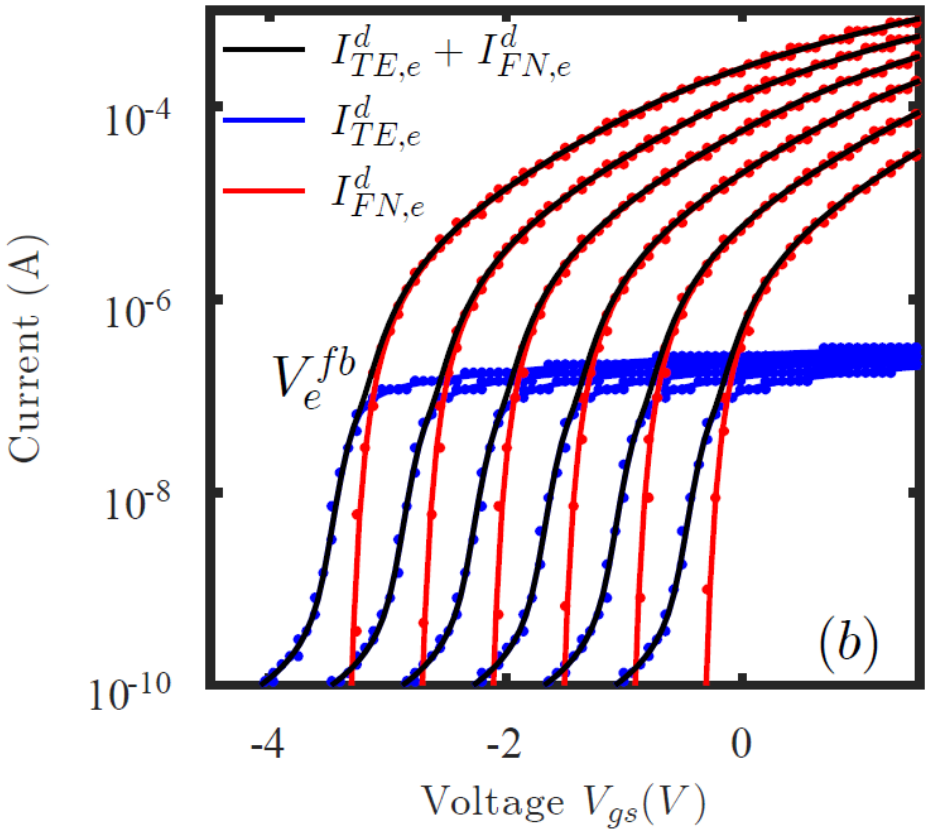
Overall Schottky Barrier Current



$$I_{ds} = I^s_{TE,e} + I^s_{FN,e} + I^d_{TE,h} + I^d_{FN,h} - I^d_{TE,e} - I^d_{FN,e} - I^s_{TE,h} - I^s_{FN,h}$$

Electron and Hole current components

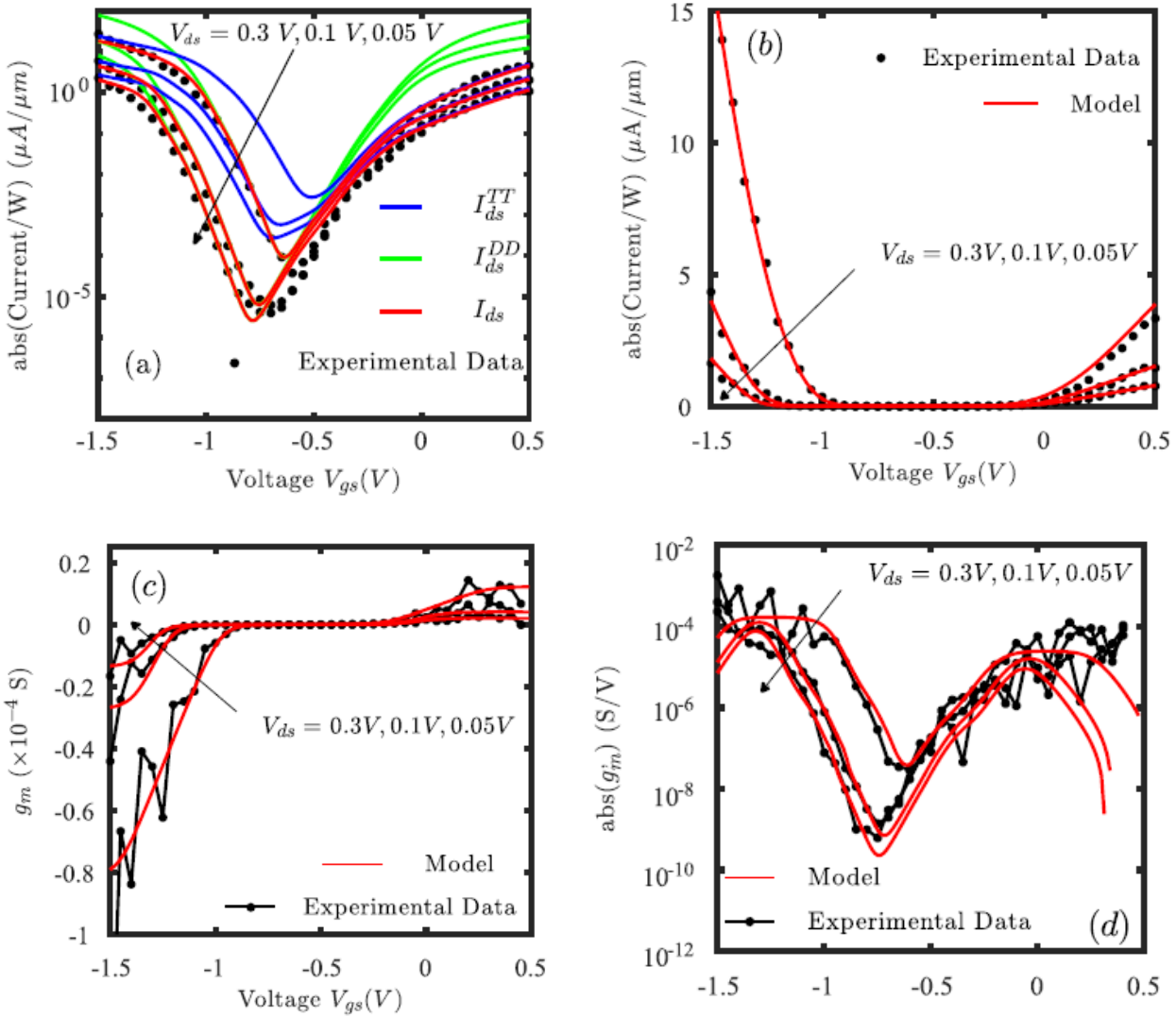




Hole current injected from source SB

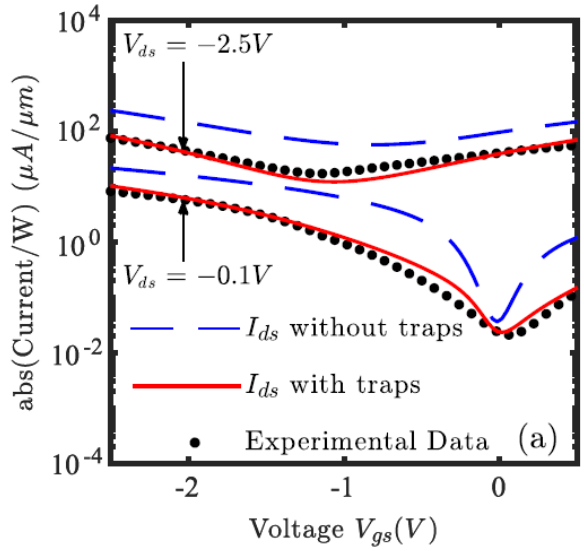
Electron current injected from drain SB

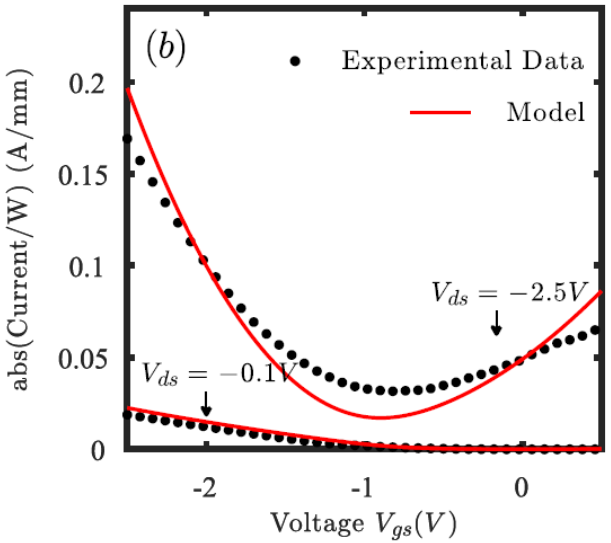
Validation – MoTe2

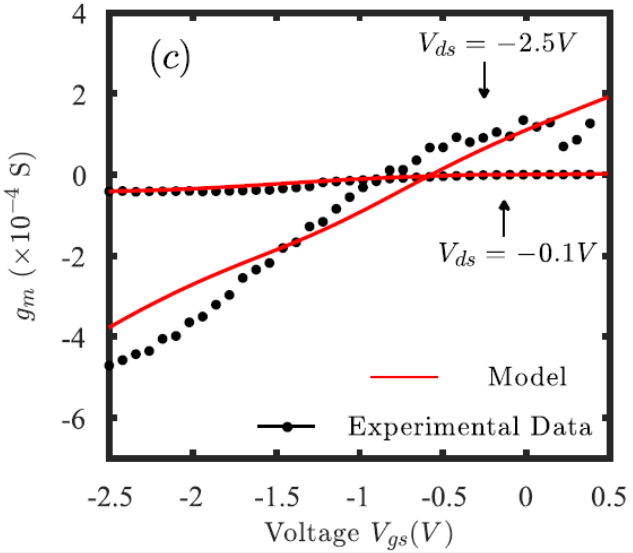


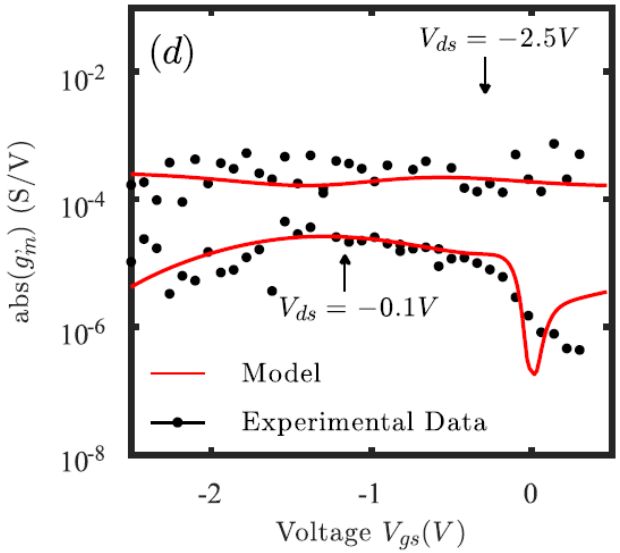
[1] S. A. Ahsan *et al.*, *IEEE Trans. Electron Devices*, **67 (11)**, [2020]

Validation – Black phosphorus



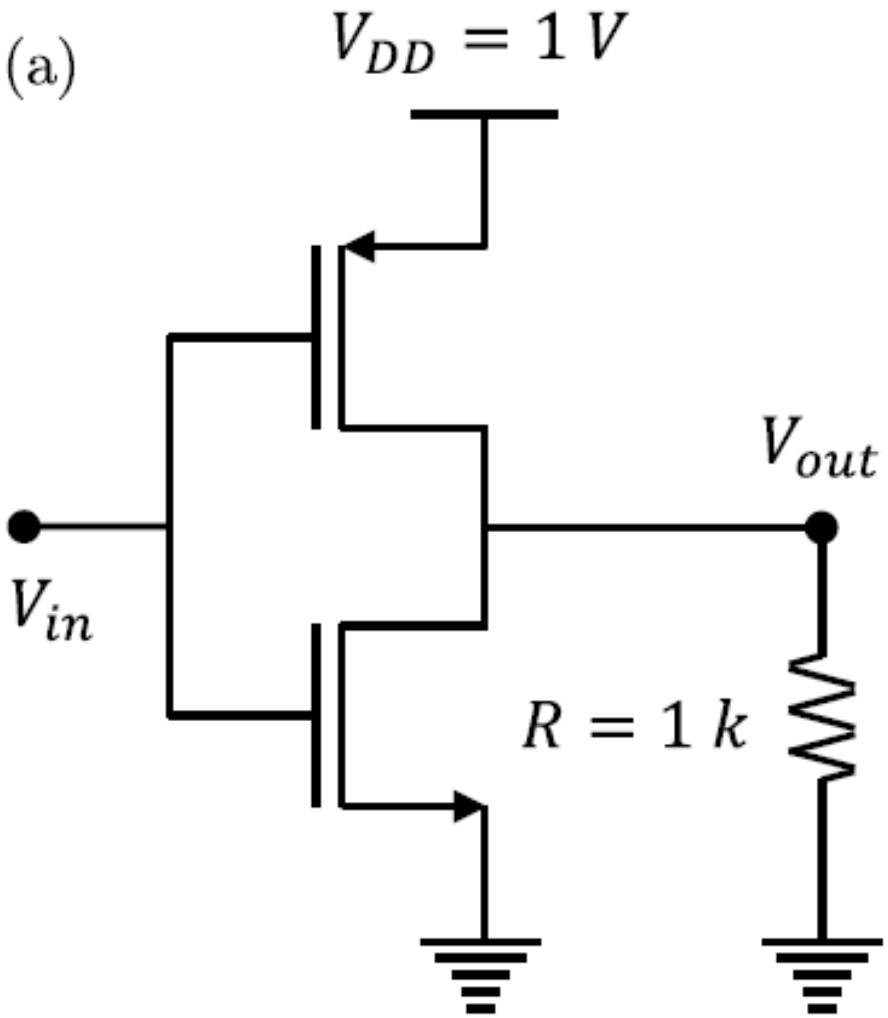


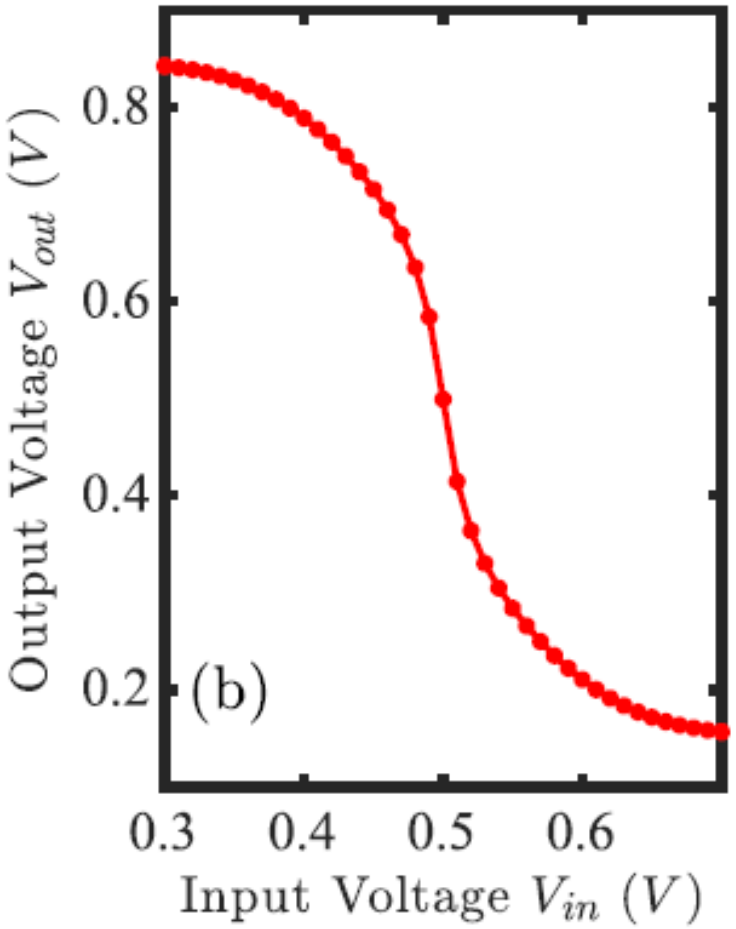




[1] S. A. Ahsan *et al.*, *IEEE Trans. Electron Devices*, **67 (11)**, [2020]

Circuit Simulation in SPICE





[1] S. A. Ahsan *et al.*, *IEEE Trans. Electron Devices*, **67 (11)**, [2020]

Conclusion

- A physics-based compact model for 2D Material FETs with Schottky-barrier contacts was presented
- Model is surface potential based & explicit – Lambert W
- Includes the essential physics of carrier emission and tunneling, as observed in Schottky Barrier FETs
- Takes into consideration Fermi-Dirac Statistics, ambipolarity, unlike prior models
- Fits different 2D material FET technologies and is SPICE compatible

Thank You!