Novel Field-Effect Schottky Barrier Transistors Based on Graphene-MoS2 Heterojunctions

—Supplementary Information

He Tian,[1,2,†] Zhen Tan,[1,2,†] Can Wu,[1,2,†], Xiaomu Wang[1,2,†], Mohammad Ali Mohammad,[1,2]
Dan Xie,[1,2] Yi Yang,[1,2] Jing Wang,[1,2] Lain-Jong Li, [3,*] Jun Xu, [1,2,*] Tian-Ling Ren,[1,2,*]

[1]Institute of Microelectronics, Tsinghua University, Beijing 100084, China
[2]Tsinghua National Laboratory for Information Science and Technology (TNList),
Tsinghua University, Beijing 100084, China
[3]Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei 11529, Taiwan

[†] These authors contributed equally to this work

*Corresponding Author E-mail:

RenTL@tsinghua.edu.cn, JunXu@Tsinghua.edu.cn, lanceli@gate.sinica.edu.tw

This file includes:

1. The electrical results of the graphene transistor
2. The electrical results of the MoS_2 transistor
3. The electrical results of the FESBT
4. The device model of the FESBT

1. The electrical results of the graphene transistor

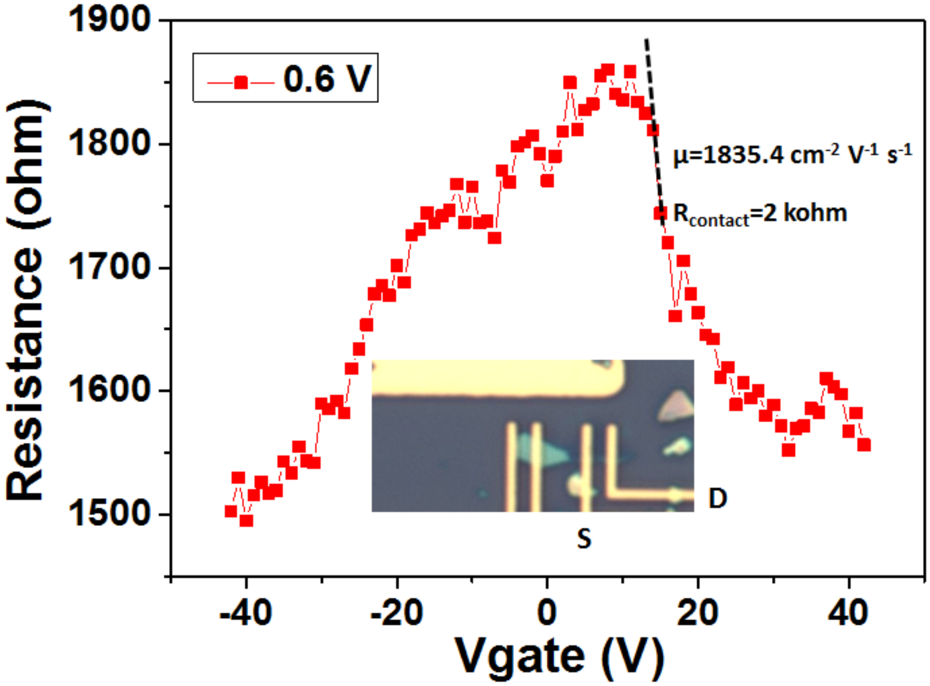

Figure S1. The graphene resistance vs. gate voltage at V_{bias}=0.6 V. The contact resistance in our devices is~2 kΩ. The mobility is as high as 1835.4 $cm^2V^{-1}s^{-1}$ after subtracting the contact resistance.

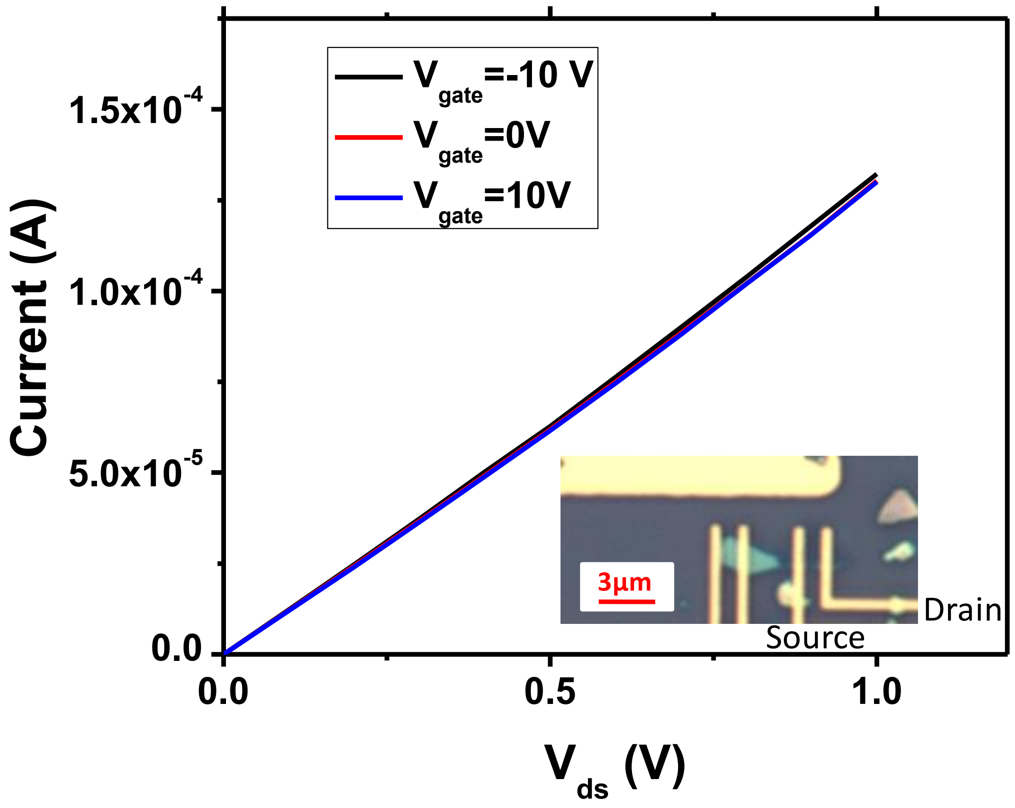

Figure S2. The current vs. bias voltage characteristics of the graphene transistor at various fixed Vgate values. Vgate varies in the range -10 to 10 V, with a step size of 10 V for each curve.

2. The electrical results of the MoS_2 transistor

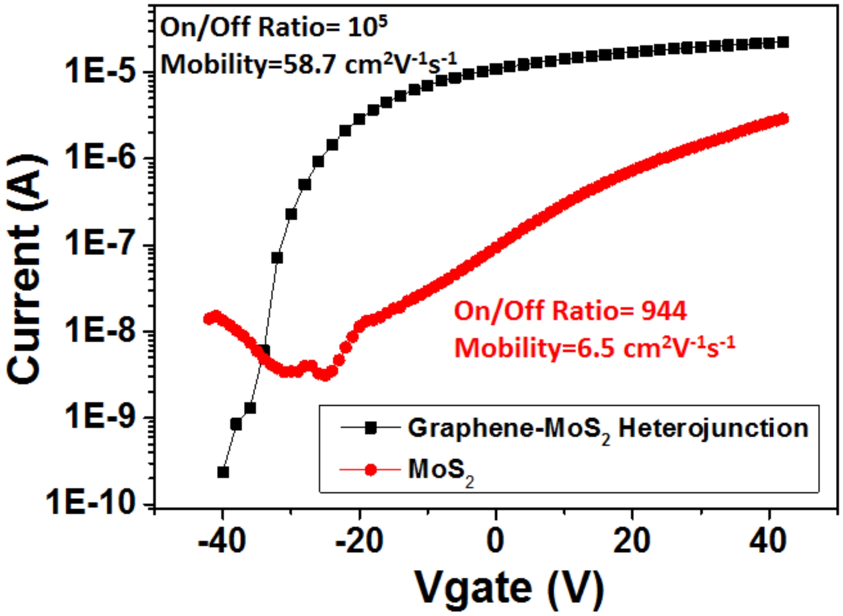

Figure S3. The currentvs. gate voltage characteristics of the MoS_2 and GMH transistor at V_{bias}=1 V.

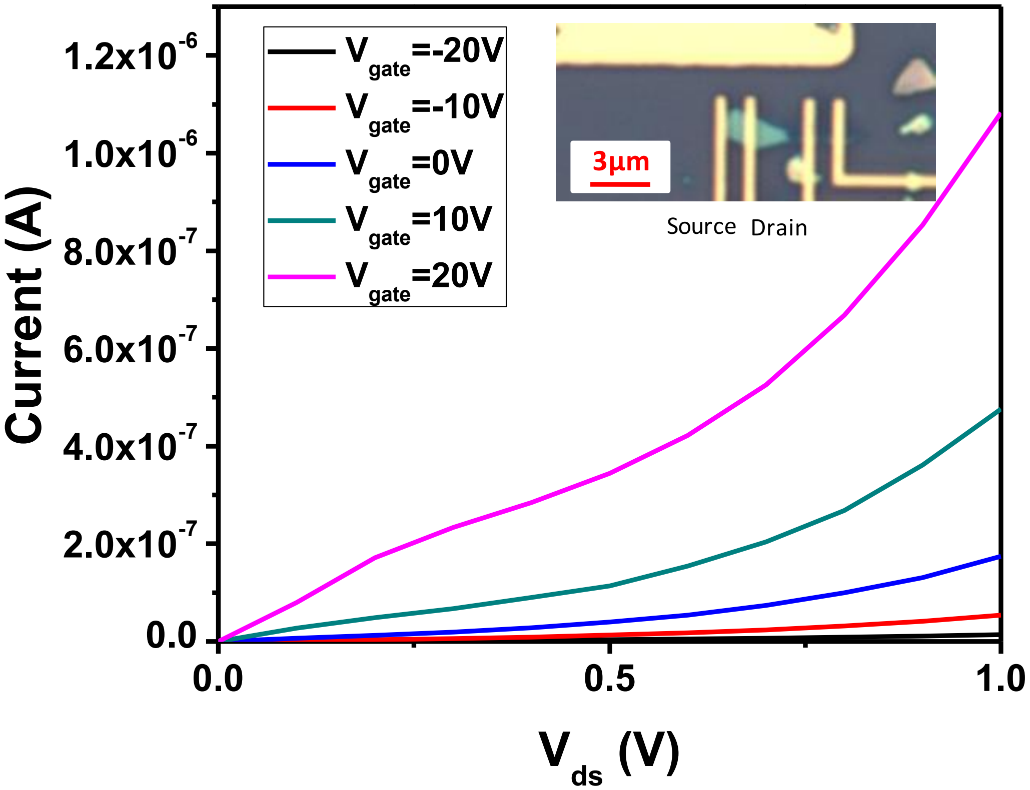

Figure S4. The current vs. bias voltage characteristics of the MoS_2 transistor at various fixed V_{gate} values. V_{gate} varies in the range -20 to 20 V, with a step size of 10 V for each curve.

3. The electrical results of the FESBT

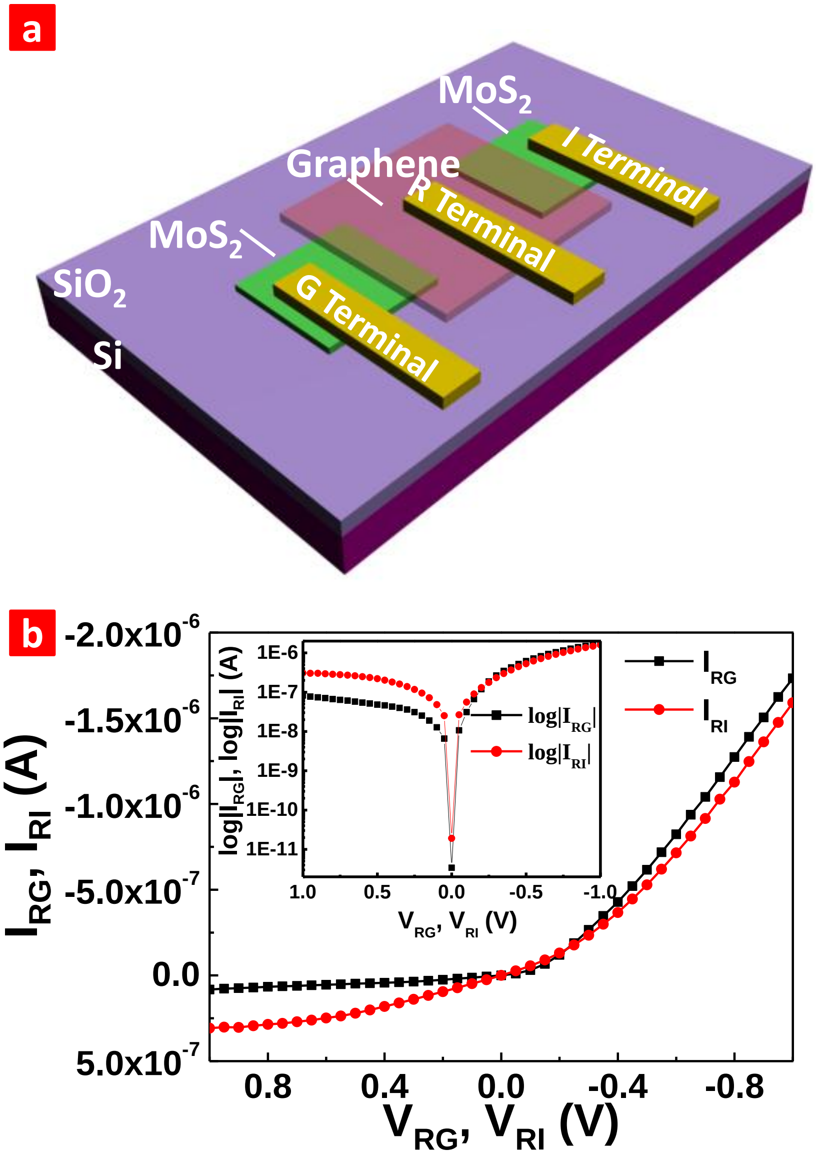

Figure S5. (a) Schematic structure of the two GMHs. (b) Heterojunction diodes characteristics of the R-I junction and R-G junction of the two GMHs.

.

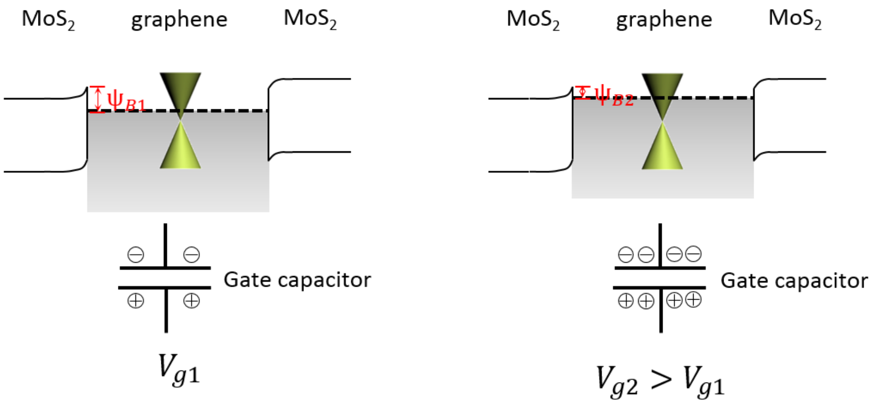

Figure S6. The energy band diagrams for MGM. When higher gate voltage is applied, it induces more charges in graphene, of which the Fermi level rises. Thus the energy barrier between graphene and MoS2 decreases and the conductance increases. In this way, the current flow is modulated by gate voltage.

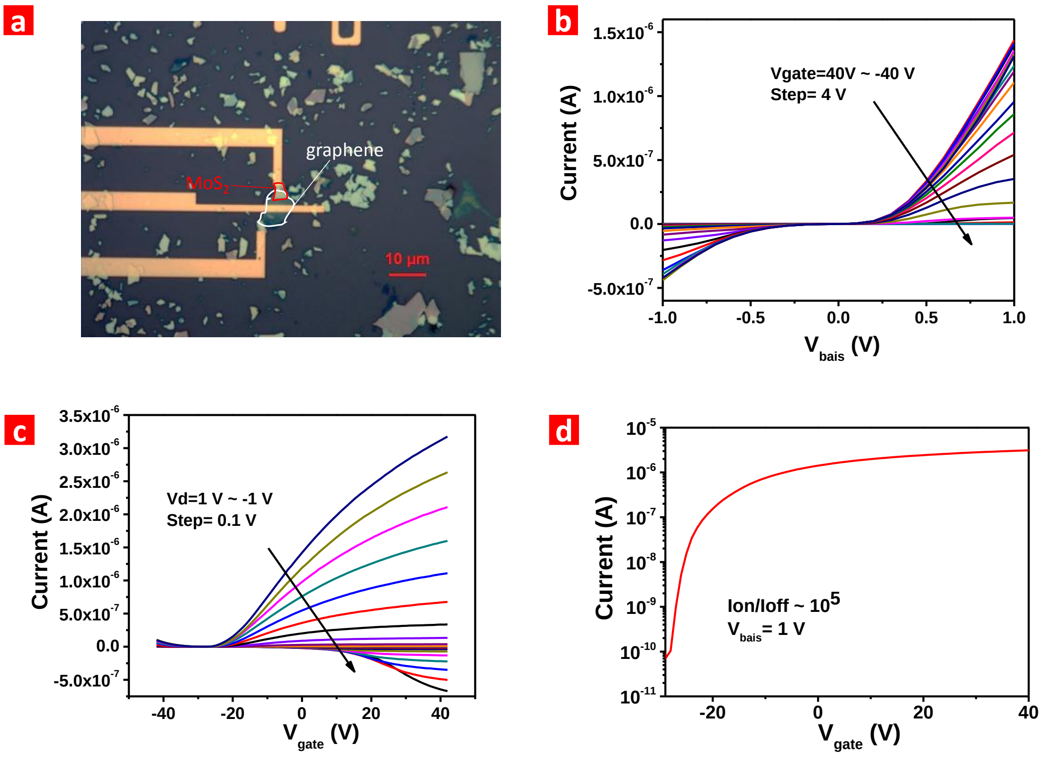

Figure S7. More experimental results of the FESBT. (a) The optical image of the second FESBT. (b) The current vs. bias voltage characteristics of GMH at various V_{gate}. The black arrow indicates the direction of increasing V_{gate}. (c) The current vs. gate voltage characteristics of GMH at various V_{bias}. The black arrow indicates the direction of increasing V_{bias}. (d) The forward bias current as a function of V_{gate}. Unipolar control of forward current with the ratio of 10^5 is obtained.

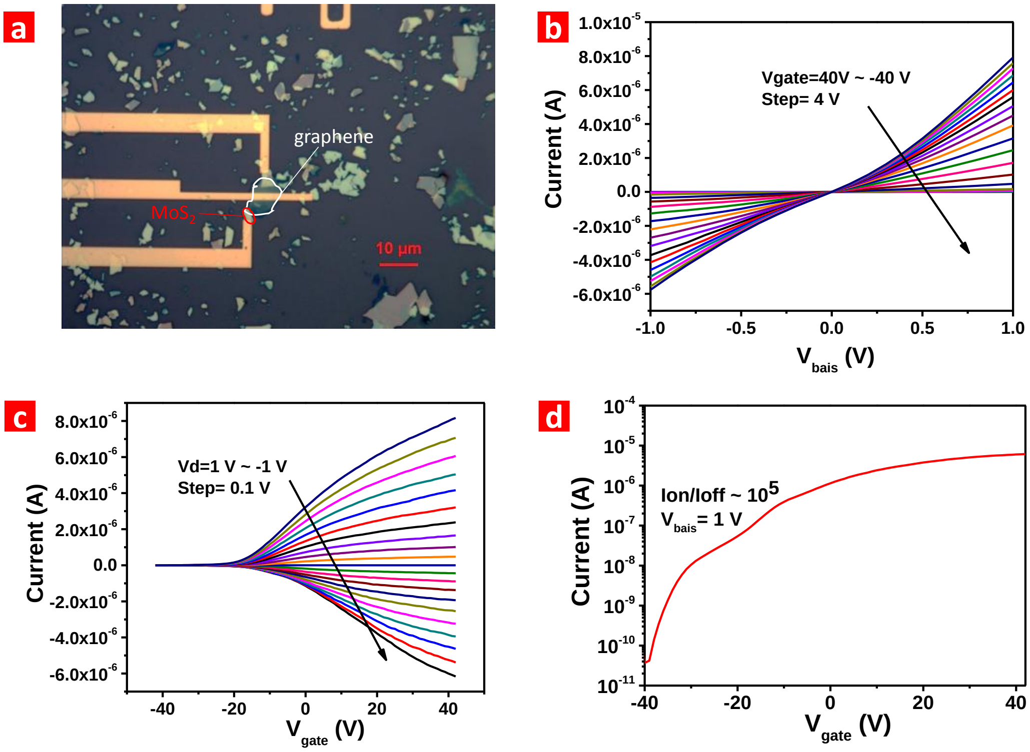

Figure S8. More experimental results of the FESBT. (a) The optical image of the third FESBT. (b) The current vs. bias voltage characteristics of GMH at various V_{gate}. The black arrow indicates the direction of increasing V_{gate}. (c) The current vs. gate voltage characteristics of GMH at various V_{bias}. The black arrow indicates the direction of increasing V_{bias}. (d) The forward bias current as a function of V_{gate}. Unipolar control of forward current with the ratio of 10^5 is obtained.

4. The device model of the FESBT

In order to quantitatively understand this device, we model this device with four elements: back gate dielectric, graphene-MoS_2 heterojunction, and two series resistors of graphene and MoS_2.

When applying gate voltage, electric field penetrates into oxide dielectric, inducing charges in MoS_2 and graphene layer. As a result, the Fermi level in graphene is modulated, thus the energy barrier between MoS_2 and graphene is controlled by gate voltage, as shown in **Figure 4**.

Here we consider MoS_2 as an extremely thin bulk material with the thickness of 8 nm, thus electric field is assumed constant throughout MoS_2. As a result, the junction of MoS_2 and graphene with gate could be modeled as three series capacitors, as shown in Figure S5,

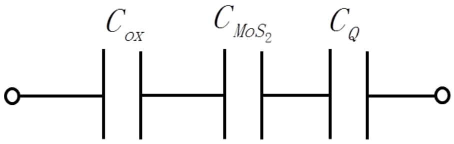

Figure S8. Series-capacitors model of the device

Where the silicon oxide and MoS_2 layers are presented by parallel plate capacitors, and graphene is expressed by a quantum capacitor [1],

$$C_Q = \frac{2\mathrm{q}^2 kTS_{GR}}{\pi(\hbar v_F)^2} \ln\left[2\left(1 + \cosh\frac{qV_{ch}}{kT}\right)\right]$$

Since graphene only has several layers, the drop of electric potential in graphene is ignored,

$$F_{\mathrm{oxide}} \cdot t_{oxide} + F_{MoS_2} \cdot t_{MoS_2} = W_{MoS_2}\left(V_g\right) - W_{electrode}\left(V_g\right)$$

Where F is the electric field, t is the thickness of silicon oxide and MoS_2, and W is the work function which is modulated by gate voltage. Also electric field is consistent at the interface between oxide and MoS_2,

$$F_{\mathrm{oxide}} \cdot \varepsilon_{oxide} = F_{MoS_2} \cdot \varepsilon_{MoS_2}$$

Where ε is the relative dielectric constant. Note that for MoS_2 material, ε equals to 3.3 [2].As electric field penetrates into graphene, it couples free charges, so we obtain

$$-\varepsilon_{MoS_2} \cdot F_{MoS_2} = \mathrm{e}n_{2D}$$

Where e is the electron charge and n_{2D} is the two-dimensional carrier density in graphene.

As a zero-bandgap semiconductor, graphene has a linear density of states (DOS) which is given by [2]

$$\rho\left(E\right) = \frac{g_s g_v}{2\pi\left(2\hbar v_F\right)^2}\left|E\right|$$

Where $v_F \sim 10^8 cm/s$ is the Fermi velocity [3], $g_s = 2$ is the spin degenerate, and $g_v = 2$ presented that there are two valleys in the first Brillouin zone. So the density of electrons in graphene is expressed by

$$n=\int_{0}^{\infty}\rho(E)\,f(E)\,dE$$

Where $f(E)$ is the equilibrium Fermi-Dirac distribution function,

$$f(E)=\frac{1}{1+e^{(E-E_F)/KT}}$$

Combined with capacitors model and density function in graphene, we obtain the Schottky barrier height vs. gate voltage, as shown in **Figure 3**b.

The current flow through graphene-MoS$_2$ heterojunction is evaluated by Schottky theory,

$$I=S\cdot A^{*}T^{2}e^{-e\phi_B(V_g)/\eta KT}$$

Where S is the effective area of the junction, T is the absolute temperature, φ_B is the Schottky barrier modulated by gate voltage, η is the ideality factor that was extracted from experiments, and A^{*} is the Richardson constant, which is expressed by

$$A^{*}=\frac{4\pi eK^{2}}{h^{3}}\sqrt{m_x m_y}$$

Where h is the Plank constant, m_x and m_y are the effective masses of electrons perpendicular to transport direction. Note that two series resistors of MoS$_2$ and graphene adjusted by field effect are also included in our model.

Supplementary References

[1] Fang, Tian, et al. "Carrier statistics and quantum capacitance of graphene sheets and ribbons." Applied Physics Letters 91.9 (2007): 092109-092109.

[2] Yoon, Youngki, Kartik Ganapathi, and Sayeef Salahuddin. "How good can monolayer MoS2 transistors be?." Nano letters 11.9 (2011): 3768-3773.

[3] Trauzettel, Björn, et al. "Spin qubits in graphene quantum dots." Nature Physics 3.3 (2007): 192-196.