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

—Supplementary Information

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This file includes:

1. The electrical results of the graphene transistor
2. The electrical results of the MoS2 transistor
3. The electrical results of the FESBT
4. The device model of the FESBT
1. The electrical results of the graphene transistor

![Graphene Resistance vs. Gate Voltage Figure](image)

**Figure S1.** The graphene resistance vs. gate voltage at $V_{\text{bias}}=0.6$ V. The contact resistance in our devices is $\sim 2$ kΩ. The mobility is as high as $1835.4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ after subtracting the contact resistance.
Figure S2. The current vs. bias voltage characteristics of the graphene transistor at various fixed V\textsubscript{gate} values. V\textsubscript{gate} 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

![Graph showing current vs. gate voltage characteristics](image)

**Figure S3.** The current vs. gate voltage characteristics of the MoS$_2$ and GMH transistor at $V_{\text{bias}}=1$ V.
Figure S4. The current vs. bias voltage characteristics of the MoS$_2$ transistor at various fixed $V_{\text{gate}}$ values. $V_{\text{gate}}$ 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 $V_{\text{gate}}$. The black
arrow indicates the direction of increasing $V_{\text{gate}}$. (c) The current vs. gate voltage characteristics of GMH at various $V_{\text{bias}}$. The black arrow indicates the direction of increasing $V_{\text{bias}}$. (d) The forward bias current as a function of $V_{\text{gate}}$. 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 $V_{\text{gate}}$. The black arrow indicates the direction of increasing $V_{\text{gate}}$. (c) The current vs. gate voltage characteristics of GMH at various $V_{\text{bias}}$. The black arrow indicates the direction of
increasing $V_{\text{bias}}$. (d) The forward bias current as a function of $V_{\text{gate}}$. 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,

\[ \begin{array}{c}
\text{\includegraphics{circuit_diagram}} \\
\text{Figure S8. Series-capacitors model of the device}
\end{array} \]

Where the silicon oxide and MoS$_2$ layers are presented by parallel plate capacitors,
and graphene is expressed by a quantum capacitor [1],

\[ C_Q = \frac{2q^2kT_{s\text{GR}}}{\pi(h\nu)^2} \ln \left[ 2 \left( 1 + \cosh \frac{qV_{ch}}{kT} \right) \right] \]

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

\[ F_{\text{oxide}} \cdot t_{\text{oxide}} + F_{\text{MoS}_2} \cdot t_{\text{MoS}_2} = W_{\text{MoS}_2} \left( V_g \right) - W_{\text{electrode}} \left( V_g \right) \]

Where \( F \) is the electric field, \( t \) is the thickness of silicon oxide and \( \text{MoS}_2 \), and \( W \) is the work function which is modulated by gate voltage. Also electric field is consistent at the interface between oxide and \( \text{MoS}_2 \),

\[ F_{\text{oxide}} \cdot \varepsilon_{\text{oxide}} = F_{\text{MoS}_2} \cdot \varepsilon_{\text{MoS}_2} \]

Where \( \varepsilon \) is the relative dielectric constant. Note that for \( \text{MoS}_2 \) material, \( \varepsilon \) equals to 3.3 [2]. As electric field penetrates into graphene, it couples free charges, so we obtain

\[ -\varepsilon_{\text{MoS}_2} \cdot F_{\text{MoS}_2} = en_{2D} \]

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]

\[ \rho(E) = \frac{g_s g_v}{2\pi(2\hbar \nu)^2} |E| \]

Where \( \nu_F \sim 10^8 \text{ cm/s} \) 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,

\[ f(E) = \frac{1}{1 + e^{(E-E_p)/kT}} \]

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

The current flow through graphene-MoS\(_2\) heterojunction is evaluated by Schottky theory,

\[ I = S \cdot A^* T^2 e^{-\phi_B (V_s)/\eta kT} \]

Where \( S \) is the effective area of the junction, \( T \) is the absolute temperature, \( \phi_B \) is the Schottky barrier modulated by gate voltage, \( \eta \) is the ideality factor that was extracted from experiments, and \( A^* \) is the Richardson constant, which is expressed by

\[ A^* = \frac{4 \pi e K^2}{h^3} \sqrt{m_x m_y} \]

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

