Supporting Information for

Evidence of electric field tunable tunneling probability in graphene and metal contact

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I. Deriving the eq 3 in the main text

Here, we derive the eq 3 in the main text step by step.

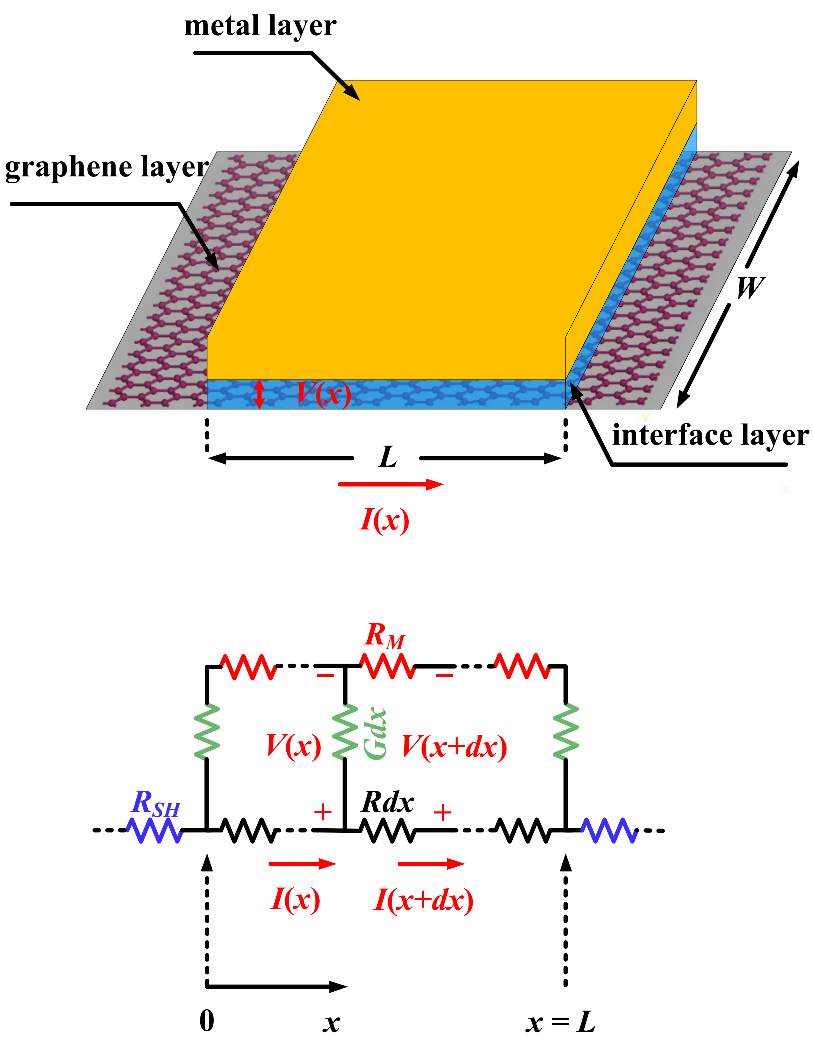

Figure S1 Diagram of the metal/graphene contact region and the corresponding transmission line contact model

Figure S1 shows the diagram of the metal/graphene contact region and the corresponding transmission line contact model. The contact between contact metal and graphene layer can be described as the resistive network, which is obtained by slicing the structure into small sections with length dx. The resistance of the graphene layer under contact corresponds to the series resistance R of the transmission line, and the interface resistance is the counterpart of the parallel conductance G. They are given by:

$$R = \frac{R_{SK}}{W}, \tag{S1}$$

$$G = \frac{W}{\rho_c}, \tag{S2}$$

where R_{SK} is the sheet resistance of graphene under contact with units of Ω/□, which is different from R_{SH} at the outside contact region, ρ_c is the specific contact resistivity with units of Ωcm^2 and W is the width of the contact. In addition, the resistance of metal layer R_M can be neglected because it is much smaller than the other resistances.

Using Kirchoff's laws, we can obtain the following relationships between the voltages and currents at x and $x + dx$.

$$V(x+dx) - V(x) = -I(x+dx)Rdx \tag{S3}$$

$$I(x+dx) - I(x) = -V(x)Gdx \tag{S4}$$

When dx approaches zero, we get the following differential equations for the current, $I(x)$, and voltage, $V(x)$:

$$\frac{dV(x)}{dx} = -I(x)R \tag{S5}$$

$$\frac{dI(x)}{dx} = -V(x)G \tag{S6}$$

Equations S5 and S6 then can be combined into the following equation:

$$\frac{d^2V(x)}{dx^2} + \alpha^2 V(x) = 0 \ , \tag{S7}$$

where $\alpha = \sqrt{\rho_c / R_{SK}}$.

The general solution of eq S7 can be written as:

$$V(x) = A_1 e^{\alpha x} + A_2 e^{-\alpha x} \tag{S8}$$

Substituting eq S8 back into eq S5, we obtain the corresponding solution for the current as follows:

$$I(x) = -\frac{1}{Z_0}(A_1 e^{\alpha x} - A_2 e^{-\alpha x}) \ , \tag{S9}$$

where $Z_0 = \sqrt{R_{SK}\rho_c} / W$.

Considering the boundary conditions, $I(x = 0) = I$ and $I(x = L) = 0$, the final solution for voltage can be expressed as:

$$V(x)=\frac{IZ_0\cosh\alpha(L-x)}{\sinh\alpha L}=\frac{I\sqrt{R_{SK}\rho_C}}{W}\frac{\cosh\left[(L-x)/L_T\right]}{\sinh(L/L_T)}\ . \tag{S10}$$

The voltage is highest at the contact edge x = 0 and drops exponentially with distance. The distance over which the voltage drops to 1/e of $V(0)$ is defined as the transfer length L_T:

$$L_T=1/\alpha=\sqrt{\rho_c/R_{SK}} \tag{S11}$$

By making use of properly designed test structures, two unique measurements of the metal/graphene contact can be made. One is the contact front resistance, R_{CF}, defined as the voltage drop across the interface layer at the edge of the contact where the current density is highest, $V(x = 0)$, to the total current flowing into the contact, $I(x = 0)$. The other is the contact end resistance, R_{CE}, defined as the ratio of the voltage drop across the interface layer at the edge of the contact where the current density is least, $V(x = L)$, to the total current flowing into the contact, $I(x = 0)$. According to eq S10, the R_{CF} and R_{CE} can be expressed as:

$$R_{CF}=\frac{V(x=0)}{I(x=0)}=\frac{\sqrt{R_{SK}\rho_C}}{W}\coth(L/L_T)=\frac{\rho_C}{WL_T}\coth(L/L_T) \tag{S12}$$

$$R_{CE}=\frac{V(x=L)}{I(x=0)}=\frac{\sqrt{R_{SK}\rho_C}}{W}\frac{1}{\sinh(L/L_T)}=\frac{\rho_C}{WL_T}\frac{1}{\sinh(L/L_T)} \tag{S13}$$

Then, equations S12 and S13 can be combined into the eq 3 in the main text.

II. Measurement processes of R_{CF} and R_{CE}

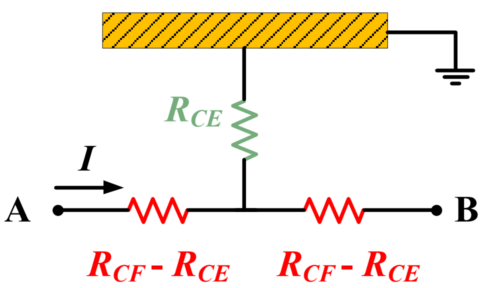

Figure S2 Equivalent circuit of a single contact showing the contact front and end resistances.

Figure S2 shows the simple equivalent circuit under the contact suggested by equations S12 and S13. When current I flows into the contact, the resistance between A and ground is R_{CF} and that between B and ground is R_{CE} (Here, I at $x = L$ is assumed to be very small and can be omitted compared to I at $x = 0$. The assumption is correct in our measurement due to $L > L_T$.).

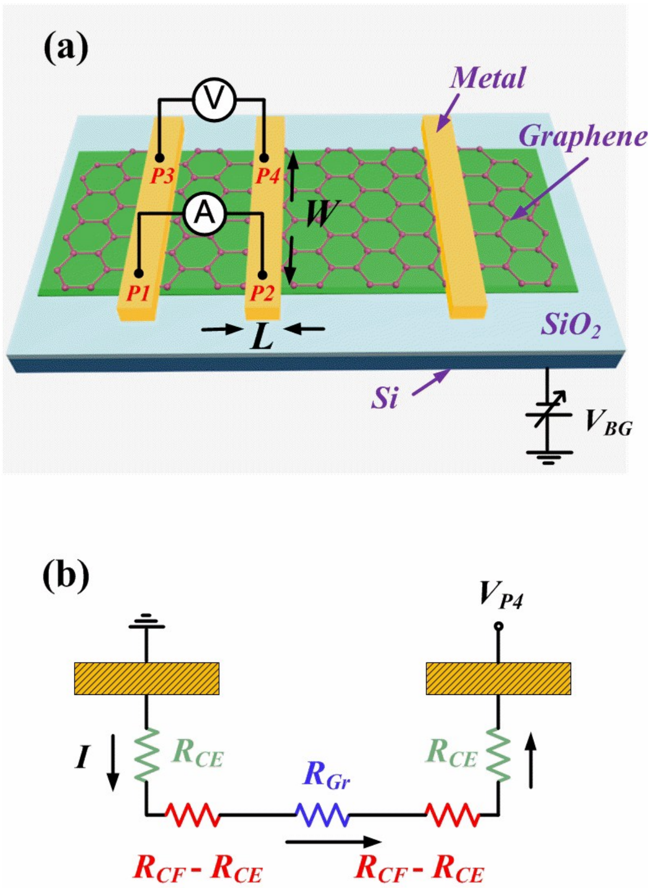

Figure S3 **(a)** Schematic of test structure for achieving R_{CF}. **(b)** The corresponding equivalent circuit.

The measurements for R_{CF} and R_{CE} are carried out in vacuum at room temperature through B1500 semiconductor parameter analyzer using four probes: *P1*, *P2*, *P3* and *P4*. The silicon substrate was used as back gate. To obtain R_{CF} in TLM test structures, the voltage and current at same contacts are measured, as shown in Figure S3a. *P1* and *P2* are set to a voltage mode, which are used for providing current. *P1* is grounded and *P2* is with various voltages from -1 V to 1 V by a step of 0.01 V. *P3* and *P4* are set to a current mode, which are used for detecting voltage. The current flowing into *P3* and *P4* are set to zero. The voltage between the two contacts V_T is equal to V_{P4}- V_{P3}. Based on the equivalent circuit of the test structure for R_{CF} measurement shown in Figure S3b, the measured total resistance (R_T) consists of two components:

$$R_T = -\frac{V_{P4}}{I} = 2R_{CF} + R_{Gr} \tag{S14}$$

where R_{Gr} is the resistance of graphene in channel, which can be expressed as :

$$R_{Gr} = R_{SH}\frac{L_X}{W} \tag{S15}$$

As a result, the measured total resistance between two contacts is given by:

$$R_T = 2R_{CF} + R_{SH}\frac{L_X}{W} \tag{S16}$$

We measured the total resistances between two contacts with four different spacings (L_X) and the total resistance is linearly dependent on the spacing (shown in Figure 1c of main text). When the spacing approaches zero, the y-intercept would be just twice the contact front resistance.

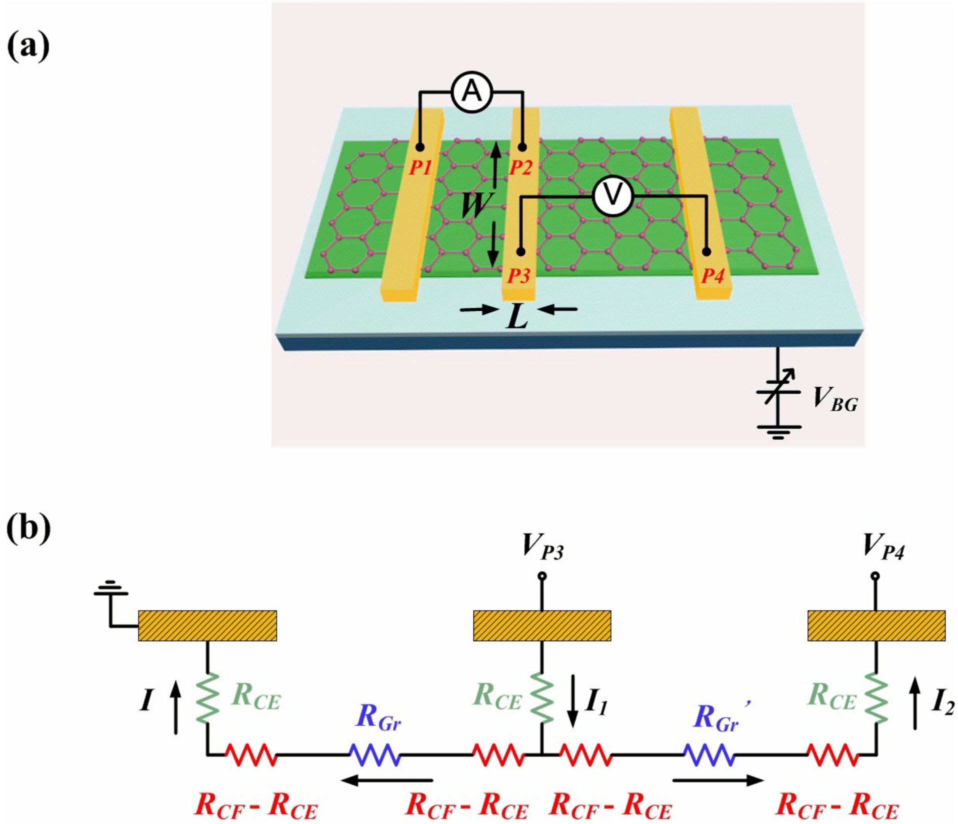

Figure S4 **(a)** Schematic of test structure for achieving R_{CE}. **(b)** The corresponding equivalent circuit.

To achieve R_{CE}, the voltage is measured between two contacts along with current flowing across the other two contacts beside them (shown in Figure S4a). *P1* and *P2* are set to a voltage mode, which are used for providing current. *P1* is grounded and *P2* is with various voltages from -1 V to 1 V by a step of 0.01 V. *P3* and *P4* are set to a current mode, which are used for detecting voltage. The current flowing into *P3* and *P4* are set to zero. The voltage between the two contacts V_T is equal to V_{P4}- V_{P3}. Based on the corresponding equivalent circuit of the test structure for R_{CE} (shown in Figure S4b), V_{P3} and V_{P4} can be given by:

$$V_{P3} = I(R_{CE} + R_{CF} - R_{CE} + R_{Gr} + R_{CF} - R_{CE}) + I_1 R_{CE} \tag{S17}$$

$$V_{P4} = I(R_{CE} + R_{CF} - R_{CE} + R_{Gr} + R_{CF} - R_{CE}) \\ + I_2(R_{CF} - R_{CE} + R_{Gr}{}' + R_{CF} - R_{CE} + R_{CE}) \tag{S18}$$

and thus

$$-\frac{V_{P4} - V_{P3}}{I} = -\frac{I_2(R_{CF} - R_{CE} + R_{Gr}{}' + R_{CF} - R_{CE} + R_{CE}) - I_1 R_{CE}}{I} \tag{S19}$$

Since the current drops nearly exponentially with contact distance, I_2 is much smaller than I_1. Thus, I_1 is almost equal to I and eq S19 is then expressed as:

$$-\frac{V_{P4} - V_{P3}}{I} = -\frac{-I_1 R_{CE}}{I} = R_{CE} \tag{S20}$$

III. Calculating processes of λ and λ_m

According to Xia's study, the transfer length (L_T) and tunneling probability (T) can be expressed as the following equations[1]:

$$L_T = \sqrt{\lambda \lambda_m}, \tag{S21}$$

$$T = \sqrt{\lambda / (\lambda + \lambda_m)}, \tag{S22}$$

Where λ is the scattering mean free path and λ_m is effective coupling length. Based on eq S21, λ_m can be given by:

$$\lambda_m = L_T{}^2 / \lambda, \tag{S23}$$

Substituting eq S23 back into eq S22, we obtain the expression of λ as follows:

$$\lambda = L_T T / \sqrt{1 - T^2}, \tag{S24}$$

Then, substituting eq S24 into eq S23, the expression of λ_m is given as follows:

$$\lambda_m = \left(L_T \sqrt{1 - T^2}\right) / T, \tag{S25}$$

The values of L_T at different V_{BG} are given in Fig. 2b in the main manuscript (the red line). The values of T at different V_{BG} are given in Fig. 4a in the main manuscript (the blue line). Based on eq S24 and eq S25, the values of λ and λ_m at different V_{BG} can be finally obtained.

Reference:

1. F. N. Xia, V. Perebeinos, Y. M. Lin, Y. Q. Wu, and P. Avouris, Nat Nanotechol. 2011. 6, 179-184.