Supporting materials for

Quantum Capacitance Limited Vertical Scaling of Graphene Field Effect Transistor

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Part I: Procedure for retrieving κ and quantum capacitance

Denoting the total gate capacitances of two graphene devices respectively with C_{TG} and C_{TG}', their oxide capacitances with C_{OX} and C_{OX}' (given by $C_{OX} = \kappa\varepsilon_0 / t_{ox}$, with t_{ox} being the thickness of the Y_2O_3 film), we have the following set of two equations for the two unknown κ and C_Q

$$\begin{cases} C_{TG}^{-1}(V_{TG}) = C_Q^{-1}(V_{ch}) + \dfrac{t_{ox}}{\varepsilon_0\kappa} \\ C_{TG}^{'-1}(V_{TG}') = C_Q^{-1}(V_{ch}) + \dfrac{t_{ox}'}{\varepsilon_0\kappa} \end{cases} \tag{S1}$$

where ε_0 is the vacuum dielectric constant and κ is assumed to be independent of V_{TG}. The two unknowns can therefore be solved analytically to yield

$$\begin{cases} \kappa = \dfrac{t_{ox}' - t_{ox}}{\varepsilon_0[C_{TG}^{'-1}(V_{TG}') - C_{TG}^{-1}(V_{TG})]} \\ C_Q(V_{ch}) = \dfrac{t_{ox}' - t_{ox}}{t_{ox}' C_{TG}^{-1}(V_{TG}) - t_{ox} C_{TG}^{'-1}(V_{TG}')} \end{cases} . \tag{S2}$$

Now the unknown κ and $C_Q(V_{ch})$ are expressed in terms of the direct measurable parameters, *i.e.* t_{ox} from AFM measurement, and $C_{TG}(V_{TG})$ from CV measurement. The point to note here is that the same V_{ch} corresponds to the same charge Q in the graphene channel which can be obtained from experimental $C_{TG}(V_{TG})$ curves by integrating it. At any given V_{ch}, $C_{TG}(V_{TG})$

and $C_{TG}{}^{'}(V_{TG}{}^{'})$ can be determined as follows:

1. Obtaining charge Q as a function of the gate voltage for the two devices by integrating the C_{TG}-V_{TG} curves as shown in Figure 2d.
2. Obtaining V_{TG} and $V_{TG}{}^{'}$ for the same Q value as shown in Figure 2d.
3. Getting the corresponding C_{TG} and $C_{TG}{}^{'}$ values from the measured $C_{TG}(V_{TG})$ and $C_{TG}{}^{'}(V_{TG}{}^{'})$ curves as in Figure 2b, these obtained values of C_{TG} and $C_{TG}{}^{'}$ correspond to the same V_{ch} and charge Q and can be used to obtain V_{ch} independent κ using equation (S2).

It is worth noting that the quantum capacitance near the Dirac point varies from sample to sample owing to the fluctuations in the local density of state residue induced by charged impurities on graphene or in surroundings. Thus for real devices, equation (S2) will become invalid near the Dirac point. But we expect that equation (S2) gives a good description of graphene devices at relatively large gate voltage, where the gate effect largely dominants over the effect of residue charges.

Part II: Derivation of equation (5)

Now we will prove that $V_{TG,\,Dirac}$ linearly depend on V_{BG} following equation (5). Starting from the capacitive equivalent circuit (Figure 3b), [35] we can obtain the total charge Q_{ch} induced in the graphene channel by the top and bottom gates

$$Q_{ch} = -C_{OX}\left(V_{TG} - V_{ch}\right) - C_{BG}\left(V_{BG} - V_{ch}\right) \quad . \qquad \text{(S3)}$$

On the other hand, because of the charge neutrality condition, the same amount of charge (but with opposite sign) is also induced *via* the quantum capacitance

$$Q_{ch} = -C_Q V_{ch} \quad . \qquad \text{(S4)}$$

Due to the finite impurities in graphene channel, the Dirac point voltages for both the top and back gates are generally not equal to zero. In a general case we can define effective gate voltages V_{TG}^{*} and V_{BG}^{*} to replace V_{TG} and V_{BG} in equation (S3)

$$V_{TG}^{*} = V_{TG} - V_{TG,Dirac}^{0} \qquad \text{(S5)}$$

$$V_{BG}^{*} = V_{BG} - V_{BG,Dirac}^{0} \quad , \tag{S6}$$

where $V_{TG,Dirac}^{0}$ (or $V_{BG,Dirac}^{0}$) is the top (or back) gate voltage at the Dirac point under a certain fixed back (or top) gate voltage. At the Dirac point of the top gate, V_{ch} is equal to zero, and then Q_{ch} is also zero. Substituting equation (S5)–(S6) into (S3), we then obtain the V_{BG} dependent Dirac point voltage

$$V_{TG,Dirac}(V_{BG}) = V_{TG,Dirac}^{0} - \frac{C_{BG}}{C_{OX}}\left(V_{BG} - V_{BG,Dirac}^{0}\right), \tag{S7}$$

which is often rewritten as

$$C_{OX} / C_{BG} = -\Delta V_{BG} / \Delta V_{TG,Dirac} . \tag{S8}$$

Part III: Extracting mobility of Graphene FET

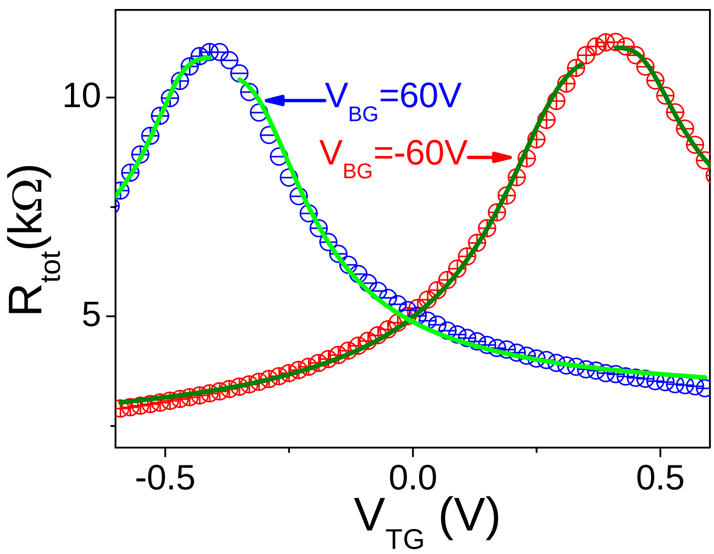

Figure S1: Total channel resistance R_{tot} *vs* V_{TG} for device 1 under various V_{BG}, the data were originated from Figure 3 (a). Circles represent experimental data, and lines indicate the fitting result.

The electron mobility μ_e and hole mobility μ_h of a graphene device were extracted according to a previously reported model, [11]

$$R_{total} = R_c + \frac{L}{W}\frac{1}{e\mu\sqrt{n_0^{\,2} + n^2}} \tag{S9}$$

where, $R_{total} = I_{ds} / V_{ds}$ is the total resistance of the graphene FET including the contact resistance R_c and the channel resistance, L is the length of the top gate and W is the width of the graphene channel covered by top gate, n and n_0 are the top gate modulated carrier density and the residual density respectively. The Fermi velocity was chosen as 1.15×10^6 m/s. The fitting results were shown in Figure S1 with the residual concentration $n_0=4.5\times10^{11}/cm^2$, and the mobility for electrons and holes were extracted to be about 1900 cm^2/Vs and 1800 cm^2/Vs respectively.