Coulomb blockade in monolayer MoS_2 single electron transistor: Supplementary information

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METHODS

Monolayer and few layered MoS_2 were exfoliated from commercially available molybdenum disulfide crystal (SPI Supplies). The conductance of MoS_2 single electron transistors at 6K was measured in a cryogen-free closed cycle cryogenic probe station (CRX-4K, LakeShore).

Optical images of exfoliated MoS_2 flakes

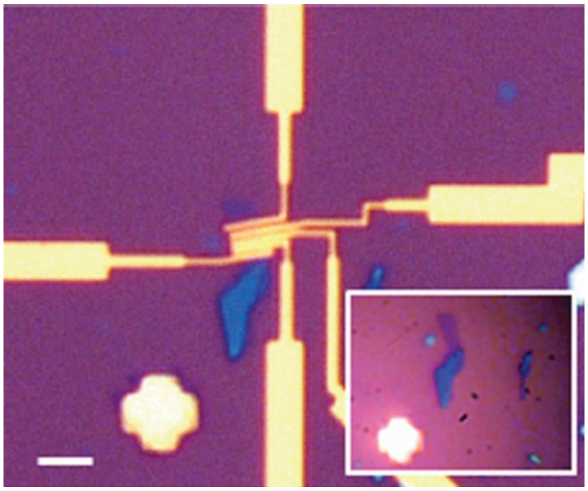

FIG. S1. Optical image of MoS_2 single electron transistor. (Inset) Optical image of exfoliated MoS_2 flakes.

I-V characteristics of monolayer 300nm channel length MoS_2 device with SiO_2

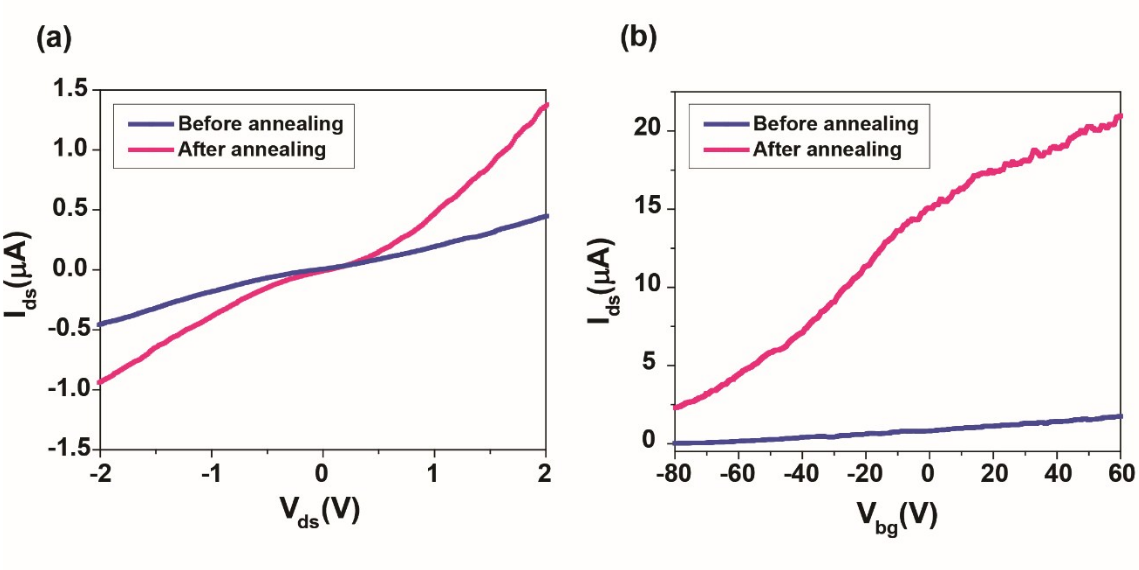

FIG. S2. (a) Room temperature *I-V* characteristics of monolayer MoS_2 transistor with L = 300 nm, W = 1.2 μm. This device was made from same monolayer MoS_2 flake, from which *I-V* characteristics on 200 nm channel length device was shown in Fig. 1. (b) Transfer characteristics before and after thermal annealing process. V_{ds} = 10 mV.

I-V characteristics of monolayer MoS_2 device with Al_2O_3 as the gate dielectrics

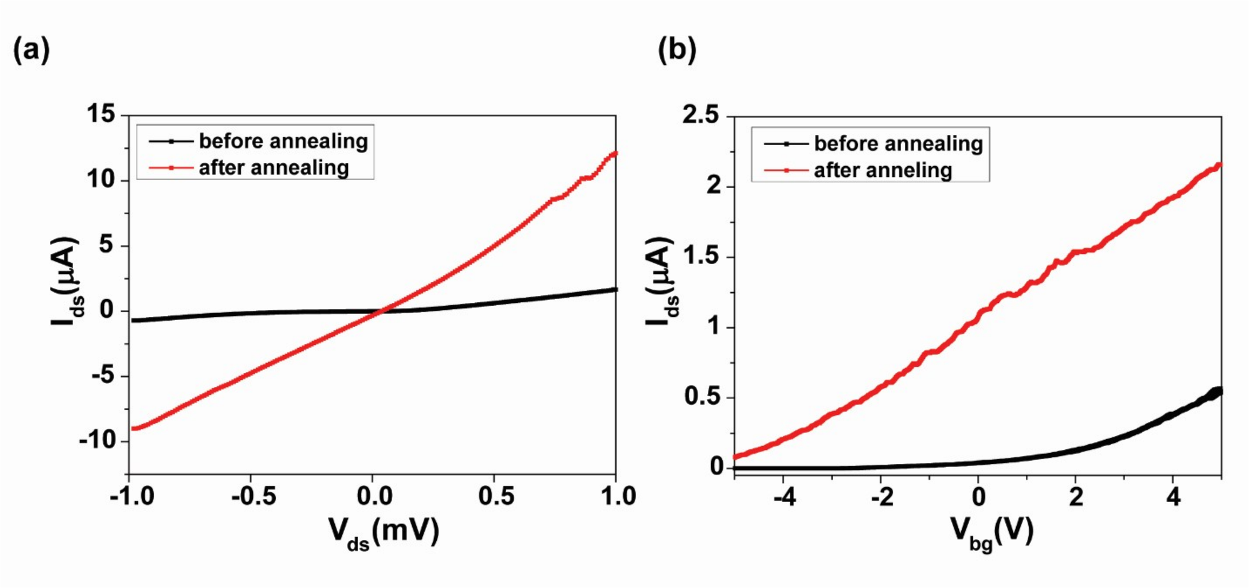

FIG. S3. (a) Room temperature *I-V* characteristics of monolayer MoS_2 transistor with 70 nm Al_2O_3 as the back-gate dielectrics. (b) Transfer characteristics before and after thermal annealing process. V_{ds} = 100 mV.

Electrostatic simulation of fringing field screening effect

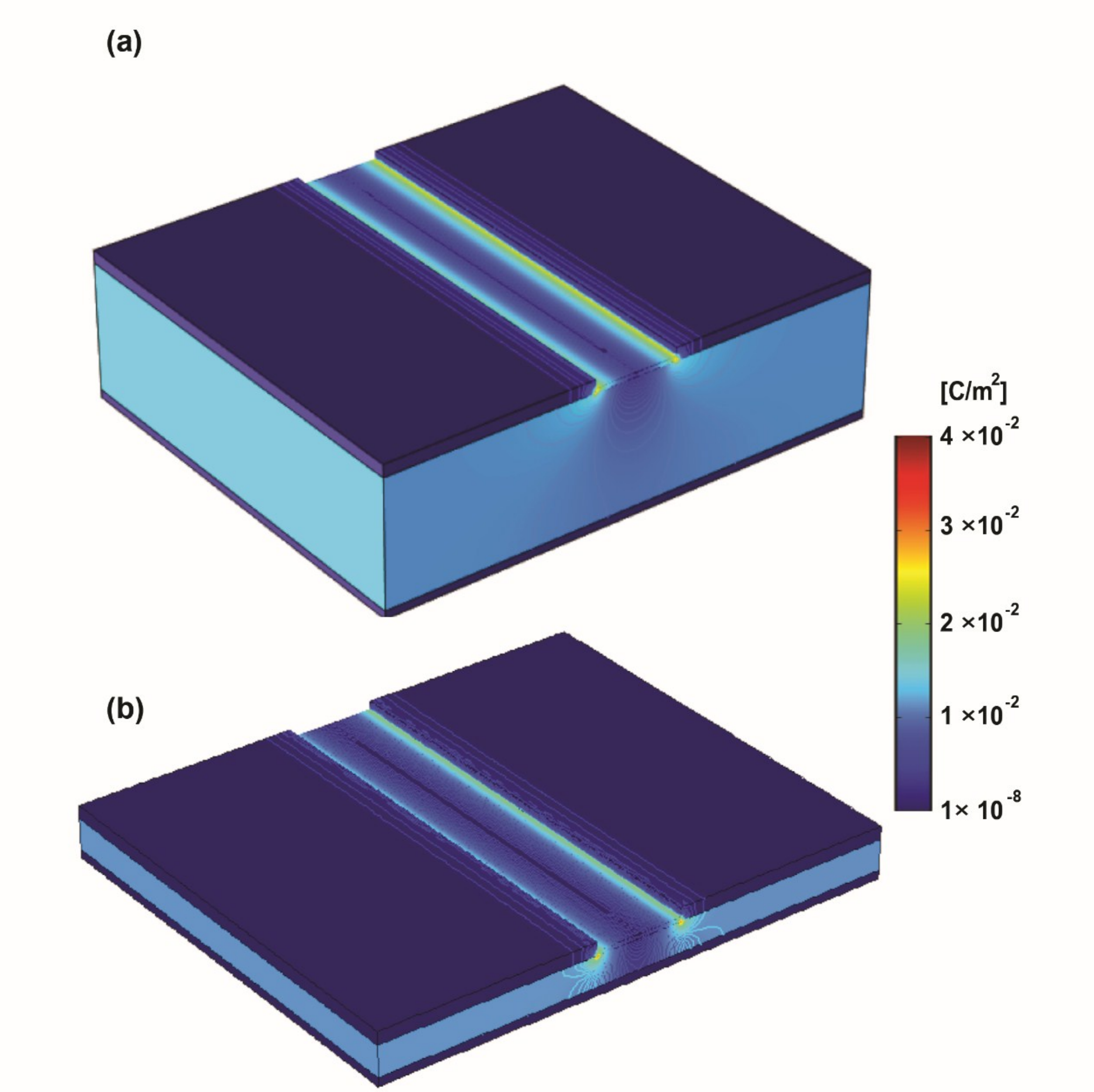

FIG. S4. The electric displacement field distribution (with contour) on the MoS2 layer with (a) 280nm SiO_2 as a gate dielectric layer, and (b) 70nm Al_2O_3 as a gate dielectric layer for the device geometry of W = 1μm, L = 200nm. Herein, (a) V_{bg} = 50V, V_{ds} = 100mV, (b) V_{bg} = 6.25V, V_{ds} = 100mV in consideration of $\varepsilon_{SiO2}=3.9$, and $\varepsilon_{Al2O3}=7.8$. This result indicates that only small portion of MoS_2 channel can contribute to the back gate capacitance due to fringing field screening effect due to contact electrodes.

Coulomb blockade in monolayer and multilayer MoS_2 SET

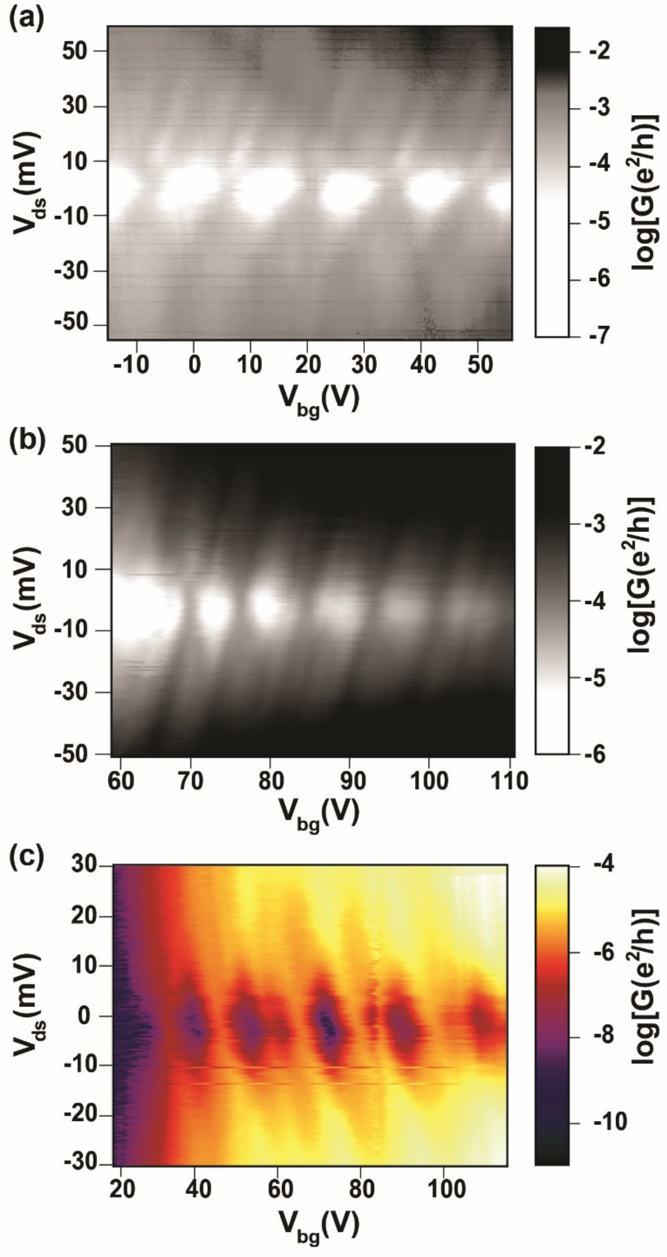

FIG. S5. The Coulomb diamonds observed in monolayer MoS_2 SETs from the devices with dimension of (a) *L* = 300 nm, *W* = 1.2 μm (Room temperature I-V characteristics was shown in FIG. S2), and (b) *L* = 200 nm, *W* = 1.5 μm. (c) The Coulomb diamonds in a multilayer MoS_2 (flake thickness ~ 4nm, corresponding to 5 layers) SET with *L* = 250 nm and *W* = 700 nm.

Line-shape of Coulomb oscillations in the MoS_2 SET

There are two different temperature regimes for Coulomb blockade.

(i) $\Delta E << k_B T << e^2/C$, the *classical or metallic Coulomb blockade regime*, where many excited levels are present due to thermal fluctuation.

(ii) $k_B T << \Delta E << e^2/C$, *quantum Coulomb blockade regime,* where only one or a few levels are excited in transport.

The line-shape of the coulomb-blockade oscillations can be fitted to the conductance expression[1]:

In the quantum Coulomb blockade regime,

$$\frac{G}{Gmax} = cosh^{-2}(\frac{ea|V - V_{peak}|}{2k_B T})$$

Equation B- 1

And in the classical or metallic Coulomb blockade regime.

$$\frac{G}{Gmax} = cosh^{-2}(\frac{ea|V - V_{peak}|}{2.5k_B T})$$

Equation B- 2

where $a = C_g/C_\Sigma$ is determined from the slopes of Coulomb diamonds, and V_{peak} is the back-gate voltage at resonance peak. Thus, the electron temperature in our measurements can be extracted from Coulomb blockade fits by using Equation B-2 for the classical region.

REFERENCES

1. C. W. J. Beenakker, *Physical Review B*, 1991, **44**, 1646-1656.