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Electronic Supplementary Information

All Two-Dimensional Materials Three-Terminal Graphene Nanoelectromechanical Switch

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1. 2D-transfer process of 2D materials

A schematic illustration of the transfer process by PMMA/PVA assisted transfer of mechanically-exfoliated 2D materials is shown in Figure S1.

1. 300 nm SiO_2/Si substrate with Au/Cr pre-pattern mark.

2. Spin coat water soluble layer

- Use Polyvinyl alcohol (PVA): 150 mg in 20 ml DI water, stir on hotplate 120 ^{0}C in 2 h.

- Filtered with 0.2 µm pore size.

- Speed: step1- 500 RPM- 2 seconds, step2- 5000 RPM- 60 seconds.

3. Spin coat PMMA layer

- Use PMMA C4
- Speed: step1- 500 RPM- 2 seconds, step 2- 5000 RPM- 60 seconds.

4. Dry the substrate (PMMA/PVA/ SiO_2/Si substrate)

Hot plate 110 ^{0}C in 3 min.

5. Exfoliate graphene, h-BN by scotch tape

6. Find the suitable flake

Use an optical microscope to find the desired flake and define the location. Characterization by Raman and AFM.

7. Detach flake/PMMA from SiO_2/Si substrate

Slowly put into hot water (hotplate 130^{o}C) for 5-10 minutes

8. Transfer flake to the holder

Use the holder to take flake/PMMA and dry it on a hot plate at 60 ^{0}C to remove water.

9. Align

- Pre-heat substrate at 150 ^{0}C for 5 min.
- Align the target flake and the flake in the holder, keep the target flake under 80 ^{o}C. After making two flakes contact, increase the temperature up to 150 ^{0}C in 5 minutes.

10. Clean and anneal the sample

- After transfer, take out sample from align machine
- Dip in Acetone on hotplate 60 ^{0}C for 30 min and the IPA to remove PMMA.
- Anneal sample in flowing H_2/Ar gas at 370 °C for 3 h to remove polymer residues and other contaminants and then examined by AFM.

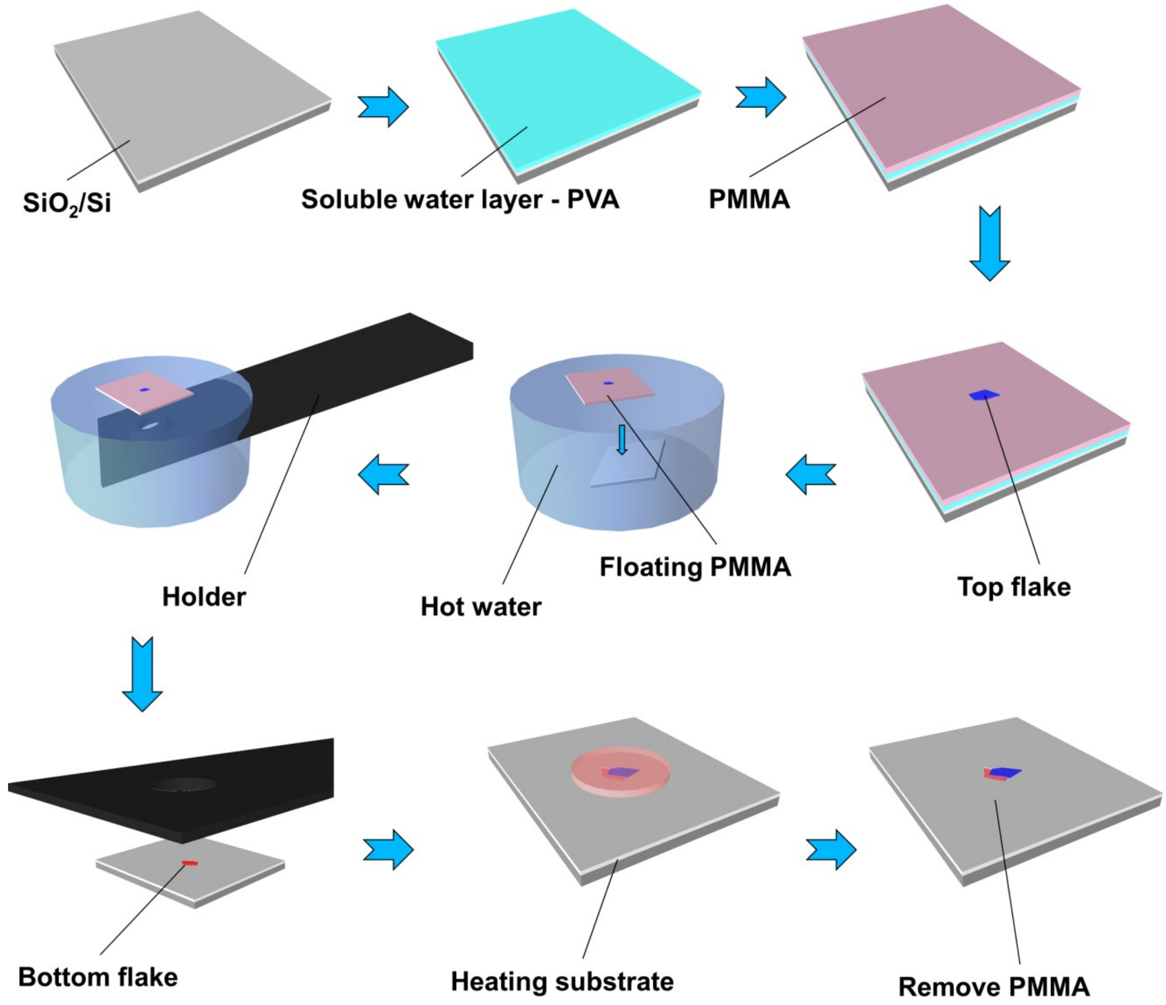


Figure S1. The mechanically-exfoliated 2D materials heterostructure transfer process.

2. Fabrication process of three-terminal graphene nanoelectromechanical switch

The fabrication process of 3T-GNEM switch follows these steps:

- Mechanically-exfoliated 2D materials such as graphene, h-BN flakes on the PMMA/PVA/SiO_2/Si substrate. The intrinsic GaAs substrate is used.

- Pre-pattern Au/Cr mark on GaAs substrate for e-beam lithography (EBL) alignment

- Transfer gate graphene on to GaAs substrate using 2D-transfer system

- Transfer dielectric h-BN on top of the gate graphene

- Transfer source graphene on top of the h-BN dielectric layer

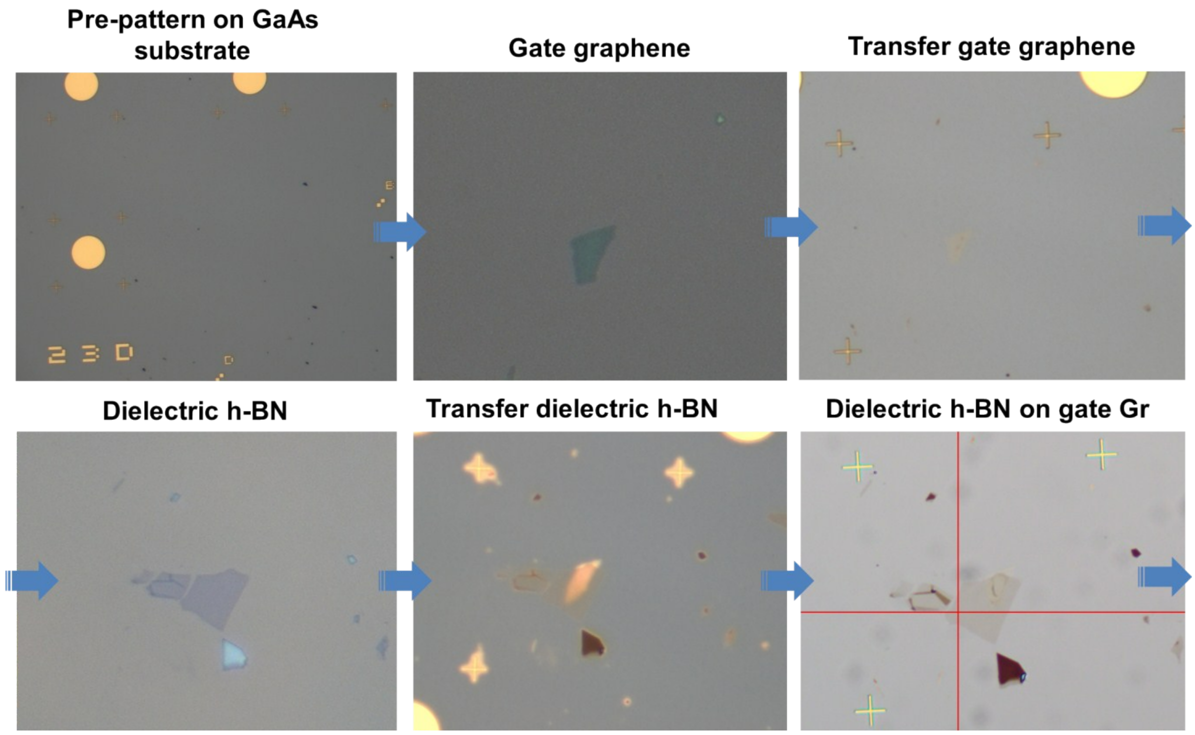
- Definition of 80 nm SiO_2 sacrificial layer

- Transfer drain graphene on top of the SiO_2 sacrificial layer

- Pattern drain graphene by EBL then etching by oxygen plasma

- Pattern and deposition Au/Cr electrodes

- Releasing drain graphene in BHF.



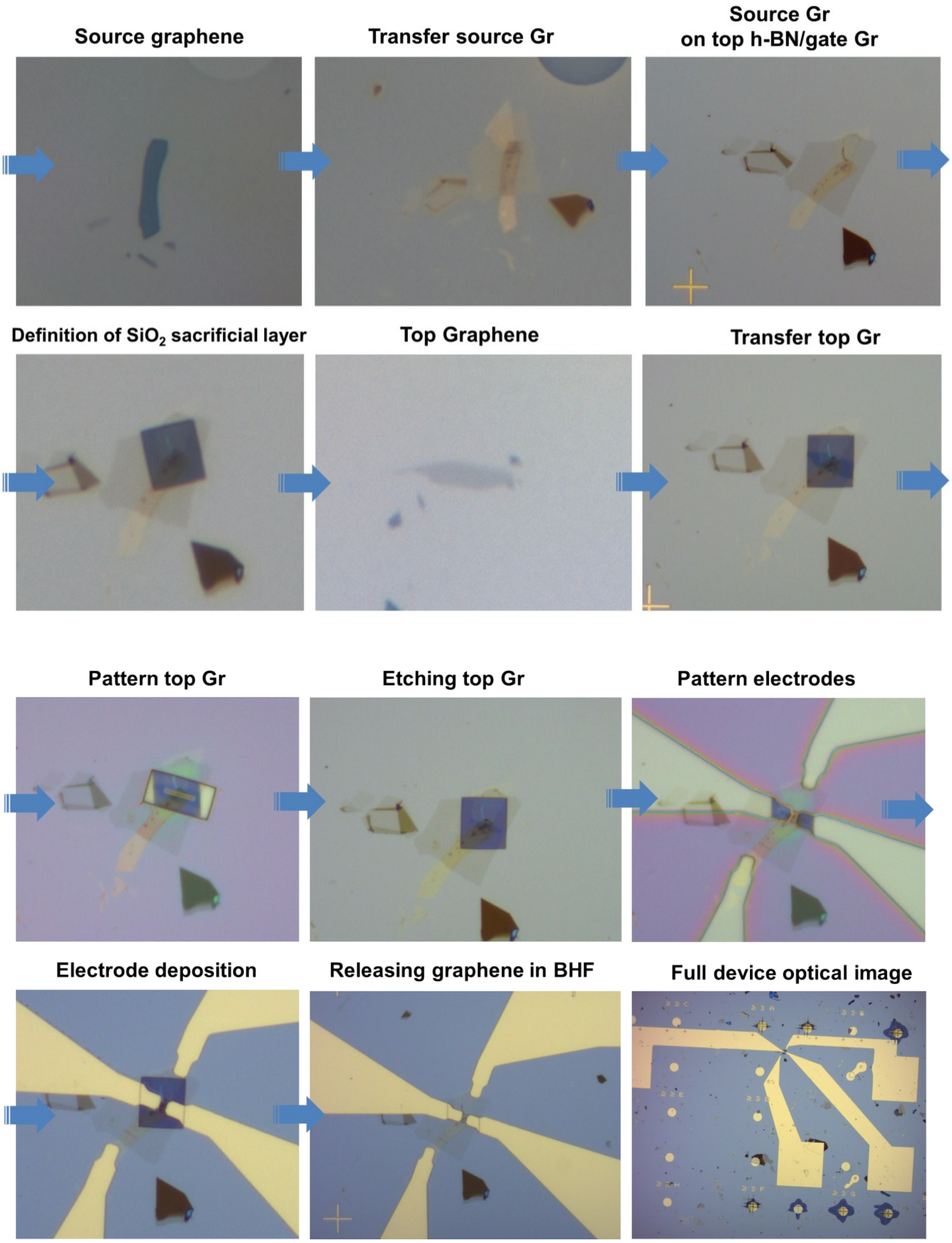


Figure S2. Fabrication process of 3T-GNEM switch on GaAs substrate.

3. AFM images of 3T-GNEM switch

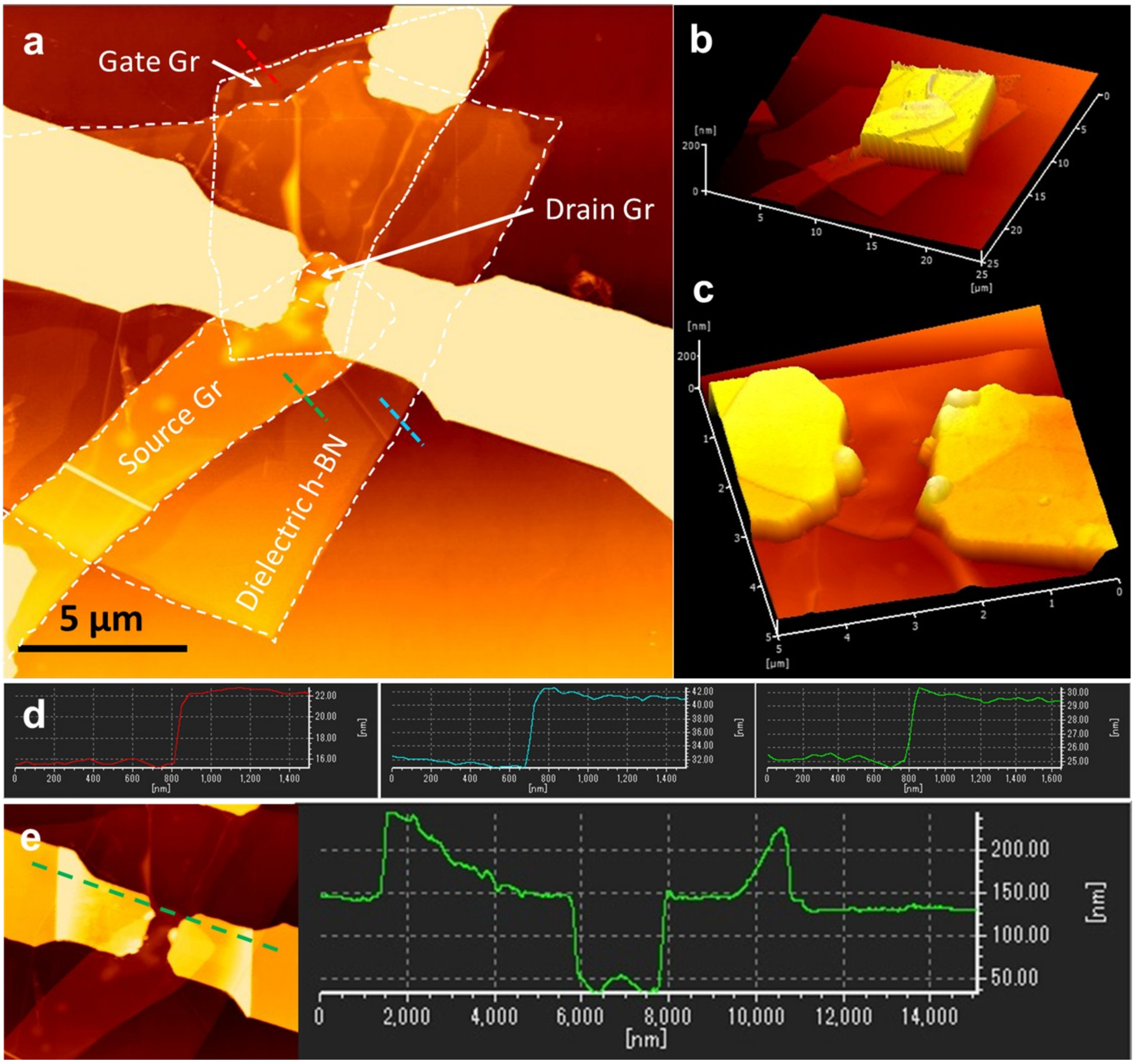


Figure S3. AFM images of 3T-GNEM switch. (a) Full device. (b) After deposit SiO_2 sacrificial layer. (c) Double clamped beam drain-graphene after I-V measurement and stuck on the top of the source-graphene electrode. (d) Height profiles measured along red, blue and green lines is gate-graphene, dielectric h-BN and source-graphene layers, respectively. And, (e) Height profile measured across drain-drain electrodes after I-V measurement.

4. Finite Element Simulation of suspended double clamped gold beam

In order to understand the impact of gate electric field on hanging Au/Cr anchoring electrodes, we performed 3D finite element simulation of this gold 3T-NEM switch by replicating the experimental structure. The electrical and mechanical characteristics of the 3T-NEM switch were simulated using the FEM-based CAD tool IntelliSuite (8.9.4.3, IntelliSense, Lynnfield, MA, USA).[27] The gold beam is used for a double-clamped beam with 1 nm thickness even though it is not possible to fabricate experimentally, and modeled as a linear isotropic material. The initial air gap between the suspended gold beam and the substrate is 80 nm and length and width of the beam are 1.5 μm and 0.8 μm. The model was meshed with global mechanical mesh (20-node brick parabolic elements) to refine the deflection of the suspended beam precisely and to get the accurate results of the beam deflection in the area of the high stress gradients. In this simulation, the entire electrodes and suspended gold regions were allowed to move and only two legs surfaces were fixed. Figure S4c shows the pull-in and pull-out switching characteristics of the gold 3T-NEM switch. As the young modulus of gold is one order lower than graphene, pull-in voltage is lower than 3T-GNEM switch. This result clearly indicates that the partial electric field penetration through the source-graphene electrode and fringe fields leads the electromechanical operation of suspended double clamped graphene beam. Pulled-in state of the gold beam is shown in Figure S4a. From the normalized principle stress distribution analysis, it was found that the electric field induced stress is concentrated in the suspended gold beam region at the pulled-in state in Figure S4b.

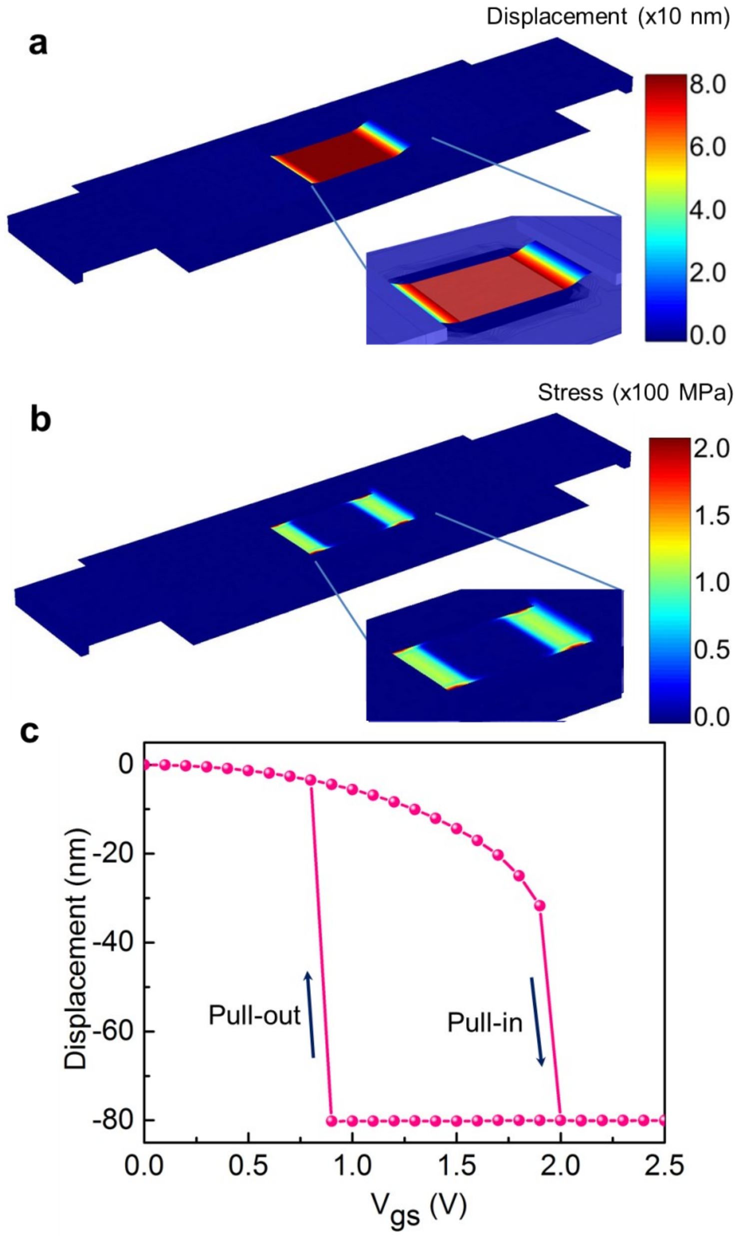


Figure S4. 3D Finite element simulation results of actuation pull-in voltage characteristics for double-clamped gold-based 3T-NEM switch. (a) Pull-in 'on-state'. (b) The gate electric field induced stress in the suspended gold beam region at the pulled-in state. And, (c) Typical actuation voltages characteristics for pull-in, pull-out gate voltages, and hysteresis.

5. Finite Element Simulation of suspended double clamped graphene 3T-NEM Switch with sub-1 V threshold voltage

In order to study the potential to achieve sub-1 V switching threshold voltage of our 3T-GNEM switch, we performed 3D finite element simulation by changing the length of suspended double clamped graphene beam and the air gap between the suspended beam to the source graphene, other structural parameters were kept same as fabricated device. Figure S5c shows the pull-in and pull-out switching characteristics of the sub-1V 3T-GNEM switch. The result clearly shows the pull-in voltage at ~0.9 V and pull-out voltage of ~0.5 V. The graphene beam is used for double clamped beam with 1 nm thickness, 0.8 μm in width and 3 μm in length. The air gap is kept at 60 nm.

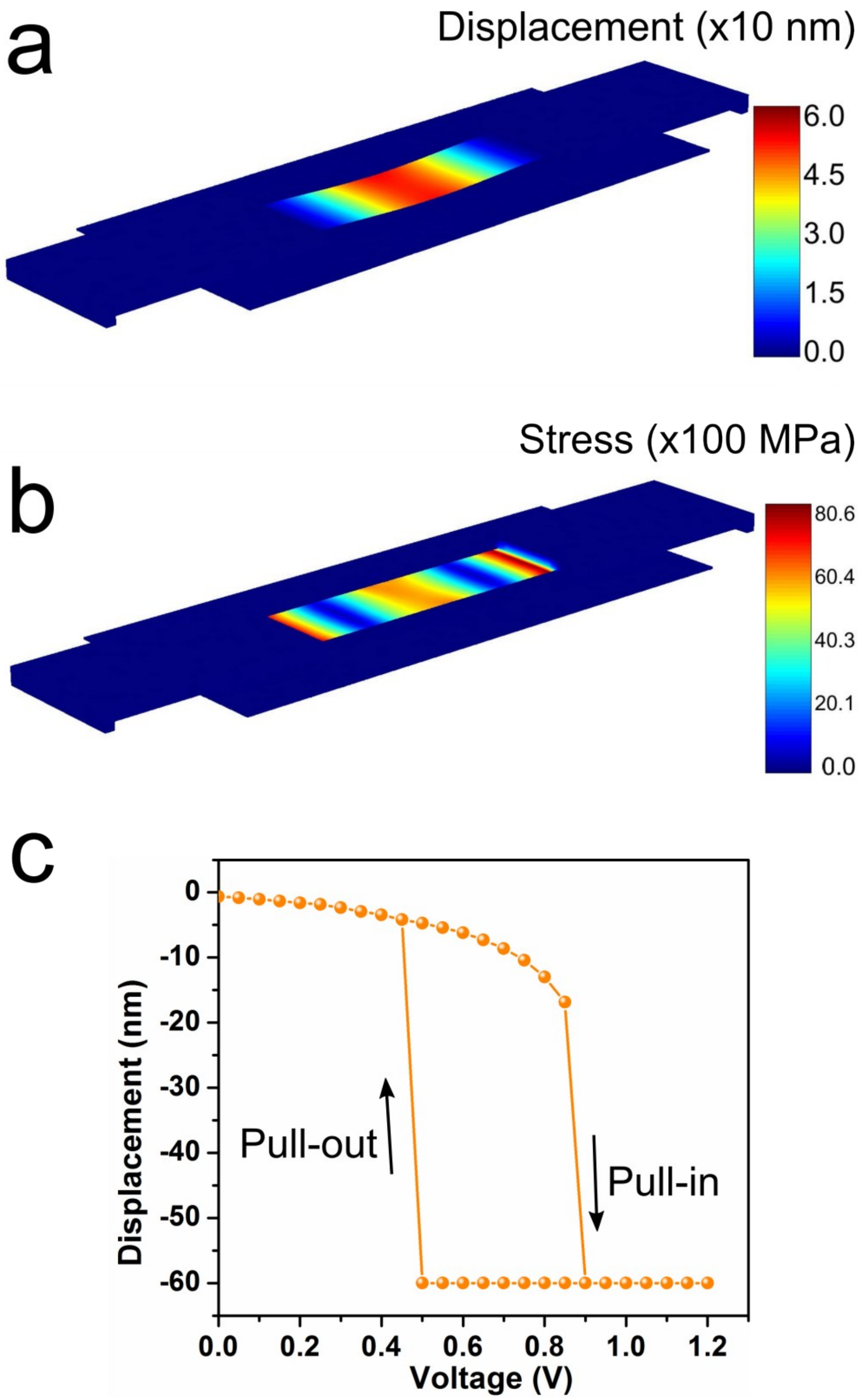


Figure S5. 3D Finite element simulation switching results of sub-1 V 3T-GNEM switch. (a) Pull-in 'on-state'. (b) The gate electric field induced stress in the suspended gold beam region at the pulled-in state. (c) Switching characteristics indicating pull-in, pull-out gate voltages, and hysteresis.