Supplementary material: Highly-sensitive wafer-scale transfer-free graphene MEMS condenser microphones

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S1. Design concept

The main geometry parameters of the proposed devices are shown in Figure S1. These refer to the ideal case where no residual etching of the etching mask SiN_x, under etching, and deformations by stress are considered for simplicity. The design variables are related to the clamping geometry and the free-standing diameter and the air cavity. In geom. A, the black hole is a result of long over-etching under isotropic SF_6 that has merged several venting holes resulting in a fully etched region.

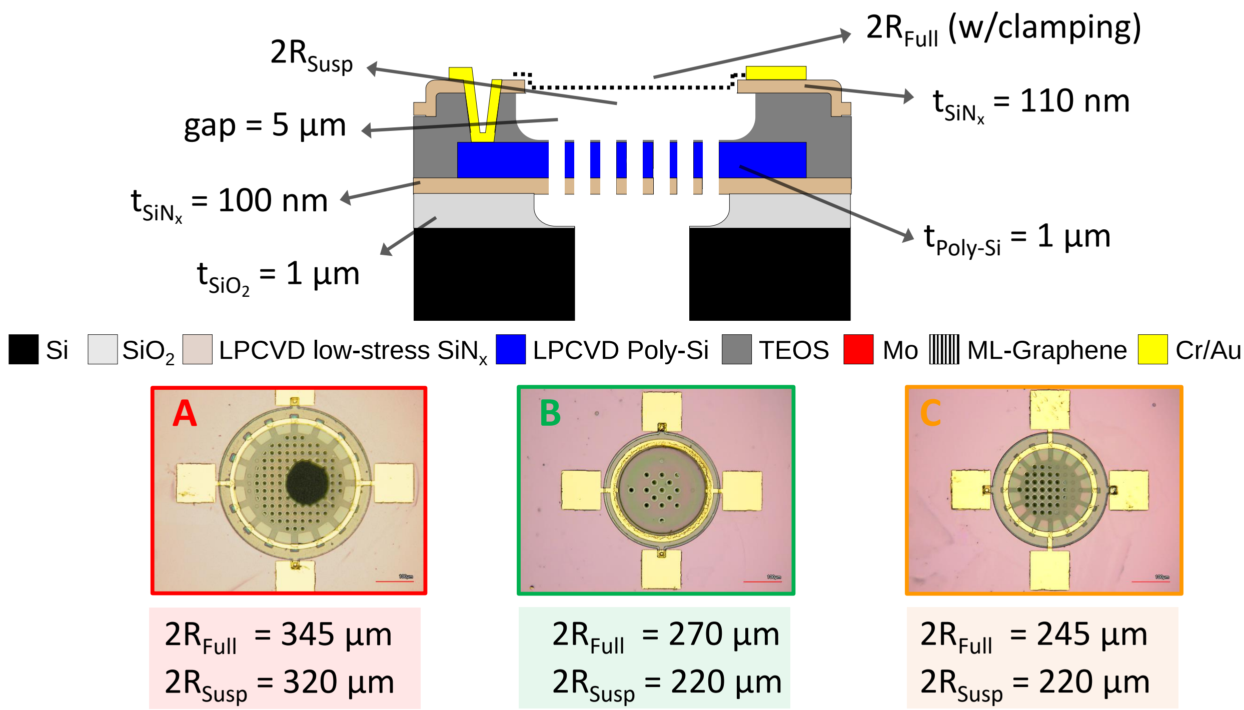

Figure S1: **Geometry schematic of the proposed devices.** Optical microscope images of devices (after VHF) of the three geometries are shown.

S2. VHF and clamping geoemtry

During the isotropic VHF, the top layer etching mask SiN_x is partially etched, and in correspondence of graphene edges, where no Cr/Au is present, graphene starts to delaminate with higher chance (Figure S2). A SEM image of a broken device is shown to highlight the over-etched Polysilicon back-plate as discussed in Figure S1. Membrane cuts can be originated due to large folding after delaminations or residual scratched regions due to wafer handling of the final DRIE step where the front-side faces the mechanical arm and chuck. A possible solution would be an extra capping material such as ALD thin films or polymers.

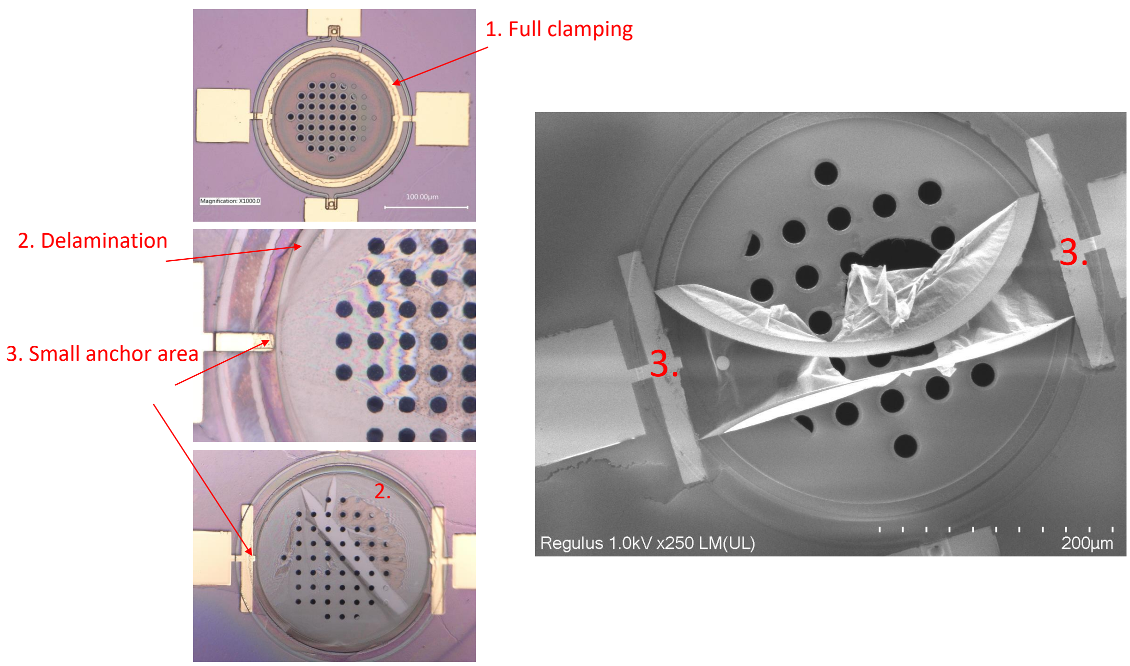

Figure S2: **Comparison of over-etched and broken devices.** An image comparison of a suspended device (geom. B), partially suspended, and broken devices. It is evident the effect of a full electrode clamping that helps to avoid larger delaminations.

S3. Thickness measurement

The AFM thickness measurements are obtained on graphene which is processed with all the reported steps except the VHF. With mechanical shaking and high surface tension of the DI-water, the graphene delaminates and it is scooped on a flat thermal SiO_2 (Figure S3c).

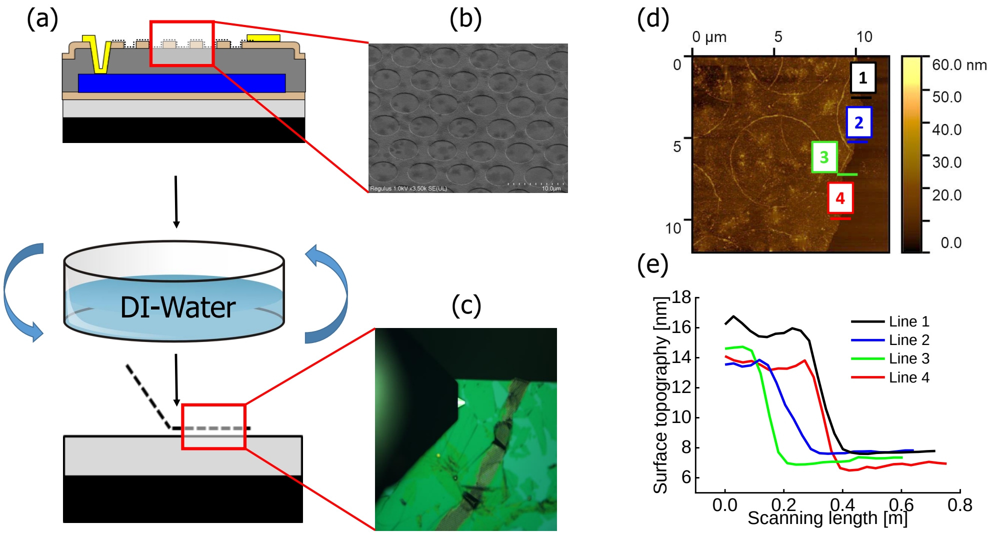

Figure S3: **Graphene thickness.** (a) Wet-transfer method is used to transfer a part of 5 mm x 5 mm patterned area of the graphene, designed and fabricated in the same mask-set for other application. (b) SEM image of the patterned region in a tilted view where graphene is conformally covering the entire topography. (c) Optical image through the AFM camera of the inspected area. Large foldings are present due to the rough transfer step. The flattest areas are used as references. (d-e) AFM thickness measurements in the drawn four regions. The circular foldings are related to the imprinted deformation that arises due to the pre-patterned cavities where the graphene was conformally grown.

S.4 Electrostatic Force vs Displacement (FEA)

The FEA pull-in voltages, solutions can not converge for $V_{bias} > 3.3$ V (geom. A), 3.8 V (geom. C), with respective max downward deformation of 1.45 µm and 1.10 µm. A static displacement of 1.65 µm, that is $\approx 1/3$ of the gap (also considered as pull-in instable position) is found at 8 V for geom. B.

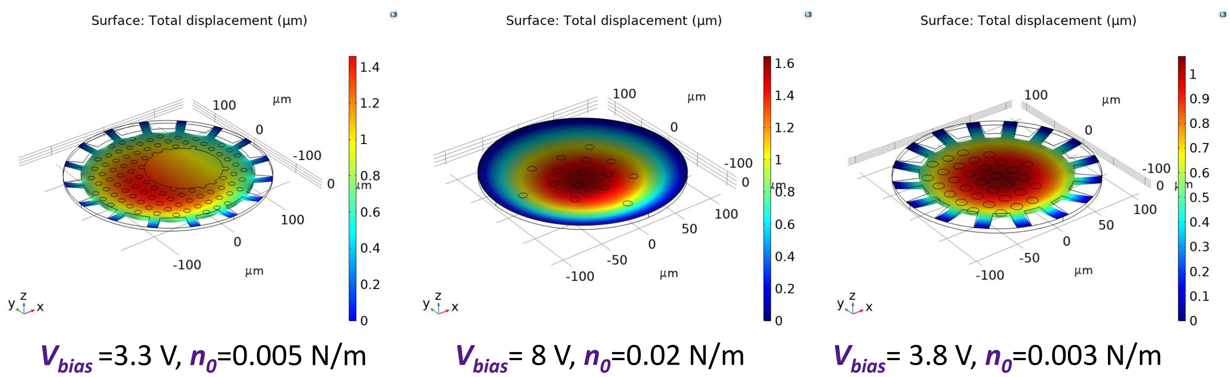

Figure S4: **FEA simulations (COMSOL Multiphysics).** The three geometries are modeled with different V_{bias} to extract the membrane displacement. Solutions geom. A, C couldn't converge at higher voltages of 3.3 V, 3.8 V without reaching the unstable point of 1/3 of the gap (pull-in region). Solution of geom. B reached a point of $\approx 1.6\,\mu\text{m}$ $(1/3gap)$ at 8 V.

S5. C-V characteristics and pull-in

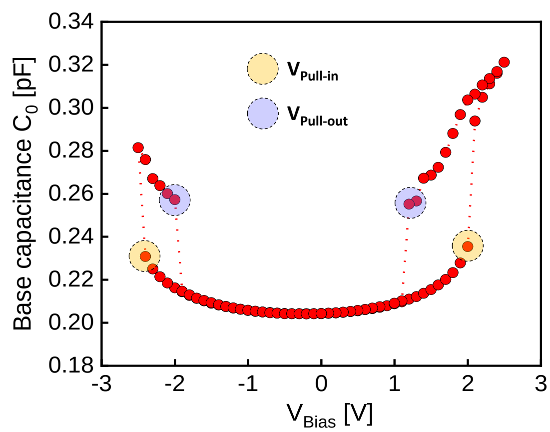

Figure S5: **Hysteresis behavior of C-V relation.** A DUT of geom. A is driven by the impedance analyzer with $V_{AC} = 100\,\text{mV}$ at f_1=100 kHz and a V_{bias} sweep between -2.5 V - 2.5 V. The high potential and high current contacts are connected to the graphene membrane and the respective low terminals to the counter electrode. The hysteresis behavior is related to the non-linearity of the electrostatic force and is further enhanced by electrical charging of the residual TEOS layer in the backplate and adhesive forces in the mechanical contact.