Supporting Information

Suspended graphene membranes with attached silicon proof masses as piezoresistive NEMS accelerometers

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Equation (S1-S9). The equivalent resistance model of our devices.

The change of the overall resistance $R$ of a graphene device as a result of a change in the strain in the suspended graphene sections, caused by a deflection of the proof-mass due to forces acting on the mass, can be approximated by

$$\Delta R = \frac{U}{AI}$$

where $U$ is the measured output voltage, $I$ is the applied input current, and $A$ is the amplification factor of the amplifier in the measurement circuit. According to equation (3), a change in strain in the suspended graphene sections with a corresponding resistance change $\Delta R$ ($\Delta R_7$ and $\Delta R_5$) of the suspended graphene sections, the following equations can be obtained:

$$R'_6 = \frac{1}{\frac{1}{R_7 + \Delta R_7} + \frac{1}{R_8}}$$

(S2)

Because $\Delta R_7 \ll R_7$, equation (S2) can be simplified to

$$R'_6 = \frac{1}{\frac{1}{R_7 + \Delta R_7} + \frac{1}{R_8}} \approx R_6$$

(S3)

Accordingly, equations (2) and (1) respectively result in

$$R'_4 = 2 \left( R_5 + \Delta R_5 \right) + R'_6 \approx 2 \left( R_5 + \Delta R_5 \right) + R_6$$

(S4)

$$R'_2 = \frac{R_3 \times R_4}{R_3 + 2R_4}$$

(S5)

$$R' = 2R_1 + R'_2$$

(S6)

According to equations (2) and (S4),

$$\Delta R_4 = R'_4 - R_4 \approx 2\Delta R_5$$

(S7)

According to equations (1), (S5) and (S6),

$$\Delta R = R'_2 - R_2 \approx \frac{R_3^2 \times \Delta R_4}{(R_3 + 2R_4)^2}$$

(S8)

According to equations (S7) and (S8),
\[ \Delta R_5 \approx \Delta R \times \left( \frac{1}{2} + \frac{2R_4}{R_3} + \frac{2R_3^2}{R_3^3} \right) \] (S9)

Figure S1. High magnification SEM images of a graphene device. (a) SEM image of a graphene device with a 1 µm wide trench and a proof mass size of 40 µm × 40 µm × 16.4 µm. (b) A close-up view of (a) of the suspended graphene membrane with a hole and some PMMA residues on the double-layer graphene surface.
Figure S2. SEM images of the backside of fabricated graphene devices. (a) SEM image of a graphene device with a 3 µm wide trench and a proof mass size of 15 µm × 15 µm × 16.4 µm. (b) SEM image of a graphene device with a 3 µm wide trench and a proof mass size of 100 µm × 100 µm × 16.4 µm. The SEM images of these devices were taken after the proof masses were released and suspended on the double-layer graphene membranes by removing the BOX (SiO₂) layer in the areas of the trench and the proof mass using etching from the wafer backside.
Figure S3. Demonstration of release of the proof masses using white light interferometry.

The release of the silicon proof masses by using a precisely adjusted vapor HF etching step was further confirmed using white light interferometry imaging to a depth of ~17 µm below the substrate surface. In this way residues of the BOX (SiO$_2$) layer in the trenches became visible. The red patches over the trench areas indicate the suspended graphene membranes while the black areas over trench areas indicate holes in the graphene membranes over the trench. The blue area in the images depict residues of the BOX (SO$_2$) layer in the trenches. (a) – (c), A few SiO$_2$ residues (dark blue colour) that partly connect the silicon proof mass with the handle substrate are visible in the trenches, showing that these proof masses are not fully released. (d) - (f), No SiO$_2$ residues remain (no dark blue colour), confirming that the silicon proof mass is fully released. It should be noted that slightly different vapour HF etching times were used for the devices in (a-f).
Figure S4. Measurement of static displacement of the released proof masses in relation to the substrate surface using white light interferometry. (a) Measurement of the top SiO$_2$ surface and the corresponding 3D plot of a device with a 4 µm wide trench and a silicon proof mass size of 30 µm × 30 µm × 16.4 µm. (b) Measurement of the top SiO$_2$ surface and the corresponding 3D plot of a device with a 3 µm wide trench and a silicon proof mass size of 40 µm × 40 µm × 16.4 µm. (c) Measurement of the top SiO$_2$ surface and the corresponding 3D plot of a device with a 3 µm wide trench and a silicon proof mass size of 25 µm × 25 µm × 16.4 µm. As indicated by the arrows, it can be seen that the suspended proof masses are deflected downwards to some extent. The static displacements of the top surface of the proof masses below the device surface are approximately 40 nm (a), 30 nm (b) and 16 nm (c) for the three devices, respectively. The static displacements might be caused by the adhesion of the suspended graphene to the vertical walls at the microscopically rounded edges of the trenches (i.e. the SiO$_2$ surfaces of the substrate and the proof mass) due to van der Waals forces. Pre-existing folds in the graphene prior to the release of the proof mass that stretch out after the proof mass release may contribute to the measured static proof mass deflections.
Figure S5. Raman spectroscopy of the double-layer graphene. (a) Optical microscopy image of a fabricated graphene device a 2 µm wide trench and a silicon proof mass size of 100 µm × 100 µm × 16.4 µm. (b) Raman spectra of the area in (a) that is marked with the blue cross. The Raman spectrum shows typical characteristic peaks of graphene: The characteristic “G-peak” occurring at around 1595 cm⁻¹ and the “2D-peak” occurring at around 2698 cm⁻¹, which demonstrates the presence of graphene. The relatively weak “D-peak” occurring at around 1349 cm⁻¹ illustrates that the quality of the obtained double-layer graphene decreased to some extent during the device fabrication process. (c) Map of the intensity of the 2D band of the area in (a) that is marked with the red rectangular box, illustrating that there are some PMMA residues on the suspended graphene membranes.
Figure S6. Measurement setup and circuit. (a) Schematic of the measurement circuit and the data acquisition setup. (b) Photograph of the measurement setup. (c) Electromagnetic shielding box including the packaged graphene devices and measurement circuits (signal amplification by a factor of 500), placed on the air-bearing shaker during acceleration measurements. Coaxial cables were connecting the measurement circuits inside the shielding box to a spectrum analyser. (d) View inside the shielding box for both electrostatic and magnetic shielding. A ferromagnetic alloy was used as the internal layer of the shielding box for magnetic shielding, separating the graphene devices from the measurement circuits and effectively reducing crosstalk between them.
Figure S7. Force-displacement measurements of suspended graphene membranes with attached proof mass using AFM tip indentation. (a) Schematic of force-displacement measurement by AFM indentation at the centre of the suspended proof mass. (b) Force-displacement measurements using AFM indentation of a device with a 3 µm trench width and a proof mass size of 10 µm × 10 µm × 16.4 µm. When the AFM indentation force gradually increased from 178 nN to 4070 nN, the displacement of the suspended proof mass increased from 40.7 nm to 806.7 nm (see Table S2). When the AFM indentation force was further increased from 4070 nN to 5051 nN, the graphene membrane with suspended proof mass ruptured and the suspended proof mass fell down (see Table S2). This indicates that suspended graphene membranes with attached proof mass are able to withstand an AFM indentation force of at least 4070 nN without device failure. As a reference, the weight of a 10 µm × 10 µm × 16.4 µm large proof mass results in a force of the order of 0.039 nN. (c) High-contrast microscope image of suspended graphene membranes with attached proof mass of the device in (b).
Table S1 Graphene device dimensions and extracted resistances of the different graphene sections of the device.

| Device number | a1     | a2     | a3     | a4     | a5     | a6     | a7     | b1     | B2     |
|---------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Trench width (µm) | 3      | 3      | 3      | 3      | 4      | 3      | 2      | 4      | 4      |
| Mass dimensions (µm×µm×µm) | 10 × 10 × 16.4 | 20 × 20 × 16.4 | 40 × 40 × 16.4 | 40 × 40 × 16.4 | 50 × 50 × 16.4 | 50 × 50 × 16.4 | 50 × 50 × 16.4 | 10 × 10 × 16.4 | 40 × 40 × 16.4 |
| Output voltage U (mV) | 1.1    | 1.124  | 0.406  | 0.322  | 1.706  | 0.481  | 0.344  | 0.176  | 0.364  |
| Overall resistance R (Ω) | 1110   | 600    | 600    | 400    | 440    | 990    | 580    | 476    | 725    |
| Sheet resistance R_s (Ω) | ~731.2 | ~423.7 | ~461.5 | ~307.6 | ~341.1 | ~783.3 | ~468.5 | ~382   | ~634   |
| Resistance of single suspended ribbon R_5 (Ω) | ~137.1 | ~48.9  | ~30.1  | ~20.1  | ~23.53 | ~42    | ~17.35 | ~84.9  | ~52.83 |
| Overall resistance change ΔR (mΩ) | 22     | 22.48  | 8.12   | 6.44   | 34.12  | 9.62   | 6.88   | 3.52   | 7.28   |
| Resistance change of single suspended ribbon ΔR_s (mΩ) | ~24.75 | ~19.22 | ~5.6   | ~4.44  | ~20.77 | ~6.28  | ~4.83  | ~12.52 | ~9.62  |
| Overall resistance change rate ΔR/R (%) | 0.002  | 0.00375| 0.00135| 0.00161| 0.00775| 0.001  | 0.0012 | 0.00074| 0.001  |
| Resistance change rate of Single suspended ribbon ΔR_s / R_s (%) | ~0.0181| ~0.0393| ~0.0186| ~0.0221| ~0.0883| ~0.015 | ~0.028 | ~0.0147| ~0.0182|
Table S2 Displacement of the suspended silicon proof mass at different applied AFM indentation forces.

| AFM tip indentation force (nN) | Displacement of suspended proof mass (nm) | Status of graphene membrane with suspended proof mass |
|-------------------------------|------------------------------------------|-----------------------------------------------------|
| 178                           | 40.7                                     | Intact                                              |
| 260                           | 56                                       | Intact                                              |
| 328                           | 68.7                                     | Intact                                              |
| 511                           | 101.4                                    | Intact                                              |
| 679                           | 129                                      | Intact                                              |
| 849                           | 171                                      | Intact                                              |
| 1021                          | 181.5                                    | Intact                                              |
| 1190                          | 207.5                                    | Intact                                              |
| 1353                          | 236                                      | Intact                                              |
| 1523                          | 264.8                                    | Intact                                              |
| 1684                          | 295.3                                    | Intact                                              |
| 1860                          | 323.4                                    | Intact                                              |
| 2023                          | 351.8                                    | Intact                                              |
| 2377                          | 411.7                                    | Intact                                              |
| 3058                          | 557.5                                    | Intact                                              |
| 3391                          | 624                                      | Intact                                              |
| 3723                          | 696.7                                    | Intact                                              |
| 4070                          | 806.7                                    | Intact                                              |
| 5051                          | -                                        | Ruptured                                            |

Proof mass size: 10 µm × 10 µm × 16.4 µm
Trench width: 3 µm.