Supporting Information

Highly sensitive electromechanical piezoresistive pressure sensors based on large-area layered PtSe$_2$ films

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S1: PtSe₂ synthesis via a TAC process

Figure S1: (a) Pt is deposited on a Si/SiO₂ substrate and placed into a quartz tube furnace. The Se source is evaporated in zone 1 at 220 °C and transported by the Ar-H₂ flow to zone 2, selenizing the Pt sample at 400 °C. (b) Raman spectra of 4.5 nm and 9 nm PtSe₂ films.
**S2: Fabrication process of the pressure sensor**

Figure S2: (a)-(d) A summary of the device fabrication process; (a) starting with a Si/SiO$_2$ substrate, (b) reactive ion etched (RIE) cavity, (c) the embedded metal contact deposition and (d) the transfer of PtSe$_2$ covered by a PMMA layer. See Methods for the detailed fabrication process description.
S3: Pressure chamber schematic

The chamber is built using standard vacuum components. Sensors included in the chamber are the humidity sensor HIH-4000 (Honeywell International Inc.), the temperature LM35 (Texas Instruments) sensor and the pressure sensor MXP2200AP (NXP Semiconductors).

Figure S3: Home-built vacuum chamber design for the electrical measurement of NEMS pressure sensors.
Figure S4: I-V curve of the PtSe$_2$ channel (1 nm initial Pt thickness) used as membrane for the pressure sensor at environmental pressure.
S5: Further measurements of the PtSe$_2$ pressure sensor

Figure S5: (a) Plot of resistance in Ohm against time showing a resistance decrease under strain with decreasing pressure of the PtSe$_2$ pressure sensor (triangles filled in turquoise); (b) Relative humidity of three devices (two devices with and one device without cavity as a reference) against the time with indicated pressure condition during measurement; (c) More measured devices with the resistance change in % (left y-axis) against the measurement time and the pressure during the experiment (right y-axis): device 1 for comparison, device 4 with the highest response detected and device 5 and 6 measured on a new chip with PtSe$_2$ from 1 nm starting Pt.
**S6: Comparison of various pressure sensor devices**

*Table S1: Comparison of various pressure sensor devices ordered by the normalized sensitivity by membrane area.*

| Device structure | Membrane area (µm²) | Sensitivity (mbar⁻¹) | Sensitivity per membrane area (mbar⁻¹ µm⁻²) | Publication year | References |
|------------------|----------------------|-----------------------|---------------------------------------------|------------------|------------|
| Suspended PtSe₂ covered with PMMA (exceptional device) | 5.00E+01 | 1.64E-03 | 3.28E-05 | 2017 | This work (highest value) |
| Suspended PtSe₂ covered with PMMA | 1.57E+02 | 1.39E-04 | 8.85E-07 | 2017 | This work |
| SWNT | 9.16E+03 | 9.26E-05 | 1.01E-08 | 2006 | Stampfer et al.¹ |
| Suspended Graphene | 3.84E+02 | 1.94E-06 | 5.05E-09 | 2013 | Smith et al.² |
| Si nanowires | 4.00E+04 | 3.47E-05 | 8.67E-10 | 2009 | Kim et al.³ |
| Si nanowires | 4.00E+04 | 3.33E-05 | 8.33E-10 | 2016 | Zhang et al.⁴ |
| Suspended graphene on a perforated SiNₓ membrane | 2.40E+05 | 2.80E-05 | 1.17E-10 | 2016 | Wang et al.⁵ |
| Graphene on a suspended imperforated SiNₓ membrane | 7.84E+04 | 6.67E-06 | 8.50E-11 | 2013 | Zhu et al.⁶ |
| GaAs/AlGaAs | 1.77E+06 | 4.37E-05 | 2.47E-11 | 1995 | Dehe et al.⁷ |
| MWNT embedded into a PMMA diaphragm | 3.14E+06 | 3.27E-05 | 1.04E-11 | 2005 | Fung et al.⁸ |
**S7: PtSe$_2$ strain gauge**

The PtSe$_2$ films were transferred onto a polyimide foil with prefabricated metal contacts to form a PtSe$_2$ strain gauge. The PMMA layer was left on the device to encapsulate the device and protect it against environmental influences, like humidity to avoid cross-sensitivity of the sensor and decrease the noise during the measurement. The strain gauge was then placed on a steel beam with known mechanical properties and glued at a position where high mechanical stress was expected (200 mm away from the point of load, main manuscript, Fig. 4a). Simulations of the stress distribution in the beam under load yield strain of about 0.04% at the sensing position, i.e. where PtSe$_2$ is fixed.\textsuperscript{9} With dimensions of the free beam (300 mm x 30 mm x 3 mm) and the distance between the sensing position and suspension point of the weight (200 mm), the stress ($\sigma$) which a sensor experiences, can be calculated from equation (S7.1, S7.2), where $W$ is the weight attached to the beam, $x_m$ is the distance from the sensor to the suspension point, $w$ is the beam width, $t$ is the beam thickness, and $E$ is the Young’s modulus of the steel beam (0.2 TPa).

$$\sigma = \frac{WT \cdot x_m}{w \cdot t^2}$$ \hspace{1cm} (S7.1)

$$\varepsilon = \frac{\sigma}{E}$$ \hspace{1cm} (S7.2)

The calculated stress at the sensor is estimated to 8.71 x $10^7$ N/m$^2$, therefore, a strain ($\varepsilon$) of $4.36 \times 10^{-4}$ is extracted, which agrees well with the simulations.

A commercially available metal strain gauge was placed next to the PtSe$_2$ device as a reference. While a static bending beam experiment was conducted, the total resistance of the gauges was recorded at +1 V of dc bias. The current-voltage (I-V) characteristics of the PtSe$_2$ device for the unloaded case shows good linearity, i.e. the transferred PtSe$_2$ forms good Ohmic contacts with metal (copper) electrodes (supporting information, Fig. S8). The electrical response of the devices were measured during loading and unloading of a mass of 2 kg and 0.5 kg attached at the end of the cantilever beam. Fig. 4b of the main manuscript compares the absolute resistance change in percentage (%) for the PtSe$_2$ devices to a commercially available metal strain gauge over the measurement time. The applied strain causes a resistance change in the PtSe$_2$ films, implying the presence of a piezoresistive effect. The gauge factor has been calculated using equation (S7.3), where $\Delta R$ is the difference in resistance, $R$ is the initial resistance in the unloaded case and $\varepsilon$ is the strain.

$$GF = \frac{\Delta R}{R \cdot \varepsilon}$$ \hspace{1cm} (S7.3)

The resistance of the PtSe$_2$ gauge decreases with applied strain, in contrast to a resistance increase of the metal strain gauge (supporting information, Fig. S9a). The electrical data result in an average negative GF of -84.8 for the PtSe$_2$ sensor. The GF of the commercial metal strain gauge is 2, in agreement with the specifications.\textsuperscript{9} The measurements were conducted for two different PtSe$_2$ thicknesses of 4.5 nm and 9 nm and repeated several times (supporting information, Fig. S9b). The measured devices highlight the consistent performance of the PtSe$_2$ film. The GF of these PtSe$_2$ layers is approximately 40 times higher than in metal \textsuperscript{9} and graphene,\textsuperscript{2,10} and comparable to MoS$_2$-based strain gauges.\textsuperscript{11,12} Due to its 2D nature, the PtSe$_2$-based strain gauge is believed to be more...
advantageous in flexible electronics than metal strain gauges suggesting high potential for applications in the area of wearable electronics.
Figure S8: I-V curve of the PtSe$_2$ (4.5 nm thick PtSe$_2$) strain gauge for the unloaded case.
S9: Further measurements of the PtSe$_2$ strain sensor

Figure S9: a) Measured values plotted as resistance in Ohm against the time with the metal strain gauge (empty circles with red outline), with a resistance increase under load and the PtSe$_2$ strain gauge (diamond filled in blue) with a resistance decrease under load; b) Plot of multiple measurements of the PtSe$_2$ strain gauges with PtSe$_2$ of 4.5 nm (shades of blue color) and 9 nm (shades of green color) thickness as well as the reference metal strain gauge (empty circles with red outline); c) Bending beam measurement for a 4.5 nm thick PtSe$_2$ film and a mass of 0.5 kg; d) Multiple cycles with a mass of 2 kg for a 4.5 nm thick PtSe$_2$ film.
Figure S10: (a) Density of states close to the Fermi level (shifted to zero) under applied tensile strain and compression. The inset shows a top view of the PtSe$_2$ bulk with the in-plane lattice vector $a$ and the direction of the biaxial strain ($\varepsilon_a$). (b) Density of states close to the Fermi level (shifted to zero) under applied tensile strain and compression. The inset shows the side view of the PtSe$_2$ bulk shown with the out-of-plane lattice vector $c$ and the direction of the interlayer strain ($\varepsilon_c$); (c) Calculated band structure close to the Fermi level (shifted to zero) under tensile strain (compression) in-plane and tensile compression (strain) out-of-plane of PtSe$_2$ bulk.
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