Supporting PDF

Sensing capabilities of single nanowires studied with correlative \textit{in situ} light and electron microscopy

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SI2: Illustration of the gas flow regimes defined by the Knudsen number $K_n$ and measurement regions. The cantilever is most sensitive in the transition region bordering the molecular flow regime, where gas/cantilever interactions can still be seen as independent while there are enough collision to achieve a measurable effect on the quality factor.
ISI3: Evaluation of the resonance frequency via automated image analysis/line profiling. a) Exemplary light microscopy images of a vibrating nanowire at the resonance frequency of 80.1 kHz and at 70 kHz and 90 kHz. The line scan is performed close to the nanowire tip at a consistent distance of 500 nm (line width 20 px). The broadness of the lineprofile (nom. grey value/distance) describes the amplitude (difference between 81 kHz and 90kHz/70kHz) of the vibration. b) Automated image analysis (written in Python 3.6 based on the line scanning routine of the OpenCV software library) provides subpixel accurate measurement with a resolution of 20 nm (used objective LWD 50x, NA:0.6). c) Exemplary extracted resonance curve used for quality factor analysis.
SI4: Error propagation

Calculation of the error propagation arising from the measurement of the differential pressure \( p \) and the beam width \( w \) to calculate the molar mass \( M_n \). The beam \( w = 295 \text{ nm} \) was obtained by tilting the nanowire in the SEM. We assume a relatively large uncertainty of this measurement of \( \pm 35 \text{ nm} \). The accuracy of the differential pressure gauge is 1.6% of the maximum range. In comparison to the beam dimensions, the error of the overall pressure measurement is small. We therefore expect around 25% total error due to these measurement errors. The molar mass has been calculated for each quality factor and pressure pair in the gas environment (shown exemplarily for helium). The error bar (red) indicates the standard deviation from the mean value. The black error bars indicate the 25% error induced by the measurement.

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\begin{align*}
\Delta z &= \sqrt{(n \cdot \frac{\Delta x}{x})^2 + (m \cdot \frac{\Delta y}{y})^2} \\
M_n &= w^2 \cdot p^{-2} \cdot C \\
\Delta M_n &= \sqrt{\left(2 \cdot \frac{\Delta w}{w}\right)^2 - \left(2 \cdot \frac{\Delta p}{p}\right)^2}
\end{align*}
\]

C: constant
\[
C = \frac{R_0 \cdot T \cdot \left(\frac{\pi}{2}\right)^3 \cdot \rho^2 \cdot f}{Q^2}
\]

Beam width \( w : 295 \text{ nm} \pm 35 \text{ nm} \)
Differential pressure \( p \)
accuracy class 1.6
e.g. 5000 Pa \( \pm 160 \text{ Pa} \)
SI5: Effect of the nanowire/cantilever width \( w \) on the measurable pressure range. a) Knudsen number vs. pressure (in ambient air) calculated for a conventional cantilever (\( w = 1500 \text{ nm} \)) and nanowires with different widths (\( w = 371 \text{ nm}, 180 \text{ nm} \)). The measurement region is enlarged for nanowires and shifted to higher pressure values. b) Measurement data for the nanowire with \( w = 180 \text{ nm} \). The regimes are calculated for ambient air (30 -290 mbar), helium (90-700 mbar) and nitrogen (40-380 mbar). Within the measurement region we see the inverse relationship of the quality factor and the pressure level.
SI6: Workflow to characterise the intrinsic quality factor of nanowires: plan-view and cross-section analysis in TEM. 1. Nanowires are transferred to a micromanipulator tip via mechanical picking. 2. Resonance measurements via electrical excitation in SEM. 3. Transfer of the nanowire to a TEM grid: silicon nitride membrane. 4. Plan-view analysis in TEM (exemplary CTEM image). 5. Preparation of the nanowire cross-section (lamella) using the Focused Ion Beam (FIB). 6. Cross-section analysis in TEM (exemplary STEM image).

SI7: Exemplary study with copper nanowires. Effect of surface quality on the quality factor. Workflow according to SI6. a) Resonance curves of a copper nanowire and b) Overview image of the nanowire and SEM images at resonance frequency at 480.4 kHz and 596 kHz. c) Same nanowire transferred to TEM. Plan-view imaging reveals surface voids. d) Resonance curve of a copper nanowire. An overview SEM image and corresponding images at the resonance frequency 120.5 kHz and 298.5 kHz are shown in e. d) plan-view TEM image of the same nanowire showing no surface voids.