Achieving high effective $Q$-factors in ultra-high vacuum dynamic force microscopy

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Abstract
The effective $Q$-factor of the cantilever is one of the most important figures-of-merit for a non-contact atomic force microscope (NC-AFM) operated in ultra-high vacuum (UHV). We provide a comprehensive discussion of all effects influencing the $Q$-factor and compare measured $Q$-factors to results from simulations based on the dimensions of the cantilevers. We introduce a methodology to investigate in detail how the effective $Q$-factor depends on the fixation technique of the cantilever. Fixation loss is identified as a most important contribution in addition to the hitherto discussed effects and we describe a strategy for avoiding fixation loss and obtaining high effective $Q$-factors in the force microscope. We demonstrate for room temperature operation, that an optimum fixation yields an effective $Q$-factor for the NC-AFM measurement in UHV that is equal to the intrinsic value of the cantilever.

Keywords: cantilever, $Q$-factor, mounting loss, force microscopy, NC-AFM

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Scanning force microscopy operated in the non-contact mode (NC-AFM) has become a standard tool for atomic scale surface characterization [1, 2] and is specifically well suited for imaging and manipulation on electrically insulating substrates [3–10]. Highest resolution measurements are obtained in ultra-high vacuum (UHV) using the frequency modulation method (FM-AFM) [11]. In this mode, the tip is periodically approached to the surface by oscillating the cantilever at its resonance frequency $f_0$. Upon close approach of the tip to the surface, the resonance frequency is shifted due to the interaction of the tip with the surface. The resonance frequency shift $\Delta f$ of the cantilever oscillation is a measure of the forces acting between the tip and the surface. Considering thermal excitation as the source of fluctuations limiting the detection, the minimum detectable force gradient $\delta F'_\text{min}$ is defined via the minimum detectable frequency shift $\delta f$ as

$$ \delta F'_\text{min} = \frac{2k\delta f}{f_0} = \sqrt{\frac{4kk_BTB}{\pi Qf_0^2A^2}}, \quad (1) $$

where $k_B$, $T$, $A$ and $B$ denote the Boltzmann constant, temperature, oscillation amplitude and detection bandwidth, respectively, $k$ is the spring constant of the cantilever and $Q$ its quality factor commonly referred to as the $Q$-factor [11]. From equation (1) it is evident that using high-$Q$ cantilevers improves the force sensitivity in a non-contact atomic force microscope. For atomic resolution measurements in UHV,
cantilevers with $Q$-factors exceeding 10,000 are typically used [2]. Therefore, it is desirable to measure the $Q$-factor of the cantilever as produced and to explore how the effective $Q$-factor relevant for NC-AFM measurements may change through steps of handling and mounting in the UHV force microscope. Here, we entirely focus on the $Q$-factor of the oscillation of the first eigenmode of the cantilever, although investigating the $Q$-factor of higher eigenmodes is of interest for advanced force microscopy techniques [12–17].

To facilitate testing of cantilevers prior to their use in the force microscope, we designed a test setup allowing the measurement of $Q$-factors in a separate vacuum chamber without irreversibly gluing cantilevers to a specific cantilever holder as used in the NC-AFM. We compare $Q$-factors measured in the test setup to $Q$-factors of the same cantilevers measured in a force microscope, and investigate in detail differences in the measured values depending on the fixation technique of the cantilever support chip on the cantilever holder. Furthermore, we investigate the influence of the fixation of the cantilever holder in the AFM systems on the effective $Q$-factor. Comparative measurements are performed in two systems, namely a modified Omicron UHV AFM/STM further on referred to as system A [18, 19], and an Omicron VT-AFM 25, further on referred to as system B. We use uncoated silicon cantilevers with resonance frequencies of about 75 kHz (type FM) and about 300 kHz (type NCH). Experiments are complemented by a comparison of measured $Q$-factors to predictions by analytical formulae relating the $Q$-factor to geometrical parameters of the cantilever. As illustrated in figure 1(a), cantilevers are rods of length $l$ and thickness $t$ and generally have a trapezoidal cross-section. For calculations they are, however, assumed as a rectangular bar with a width $w$ that is equal to the mean width of the trapezoidal rod.

The $Q$-factor of a damped system is defined as the ratio of the energy $W$ stored in the oscillating system to the energy $\Delta W$ dissipated per cycle [20]:

$$Q = \frac{2\pi W}{\Delta W}. \quad (2)$$

A high quality factor results in a narrow resonance peak that is generally described by the following expression for the frequency-dependent amplitude $A$:

$$|A| = \frac{|A_{\text{exc}}|}{\sqrt{(1 - f_{\text{exc}}^2/f_0^2)^2 + f_{\text{exc}}^2/(f_0^2Q^2)}}, \quad (3)$$

where the cantilever is assumed to be a damped harmonic oscillator excited at the frequency $f_{\text{exc}}$ with the amplitude $A_{\text{exc}}$. From a fit of this formula to a measured resonance curve, the fit parameters $f_0$ and $Q$ can be obtained.

There are several mechanisms contributing to the damping of an oscillating cantilever. The reciprocal of the effective $Q$-factor $1/Q_{\text{eff}}$ describes the total damping, which is determined by the intrinsic damping $1/Q_0$ of the cantilever, the damping $1/Q_{\text{mount}}$ of the cantilever fixation in the force microscope and the air damping $1/Q_{\text{air}}$, which needs to be considered when experiments are not performed under UHV conditions:

$$\frac{1}{Q_{\text{eff}}} = \frac{1}{Q_0} + \frac{1}{Q_{\text{mount}}} + \frac{1}{Q_{\text{air}}}. \quad (4)$$

The intrinsic $Q$-factor can be represented as the sum of the following major contributions [21]:

$$\frac{1}{Q_0} = \frac{1}{Q_{\text{vol}}} + \frac{1}{Q_{\text{support}}} + \frac{1}{Q_{\text{TED}}} + \frac{1}{Q_{\text{surf}}}. \quad (5)$$

which are the volume loss $1/Q_{\text{vol}}$, support loss $1/Q_{\text{support}}$, thermoelastic damping $1/Q_{\text{TED}}$ and surface loss $1/Q_{\text{surf}}$. The effective $Q$-factor cannot exceed the value of the smallest $Q$ contribution. A quantitative determination of all contributions to the damping is most difficult; however, for practical purposes it is sufficient to focus on the dominant damping mechanisms, namely support loss, surface damping and thermoelastic damping. The term $1/Q_{\text{vol}}$ can be neglected as commercial standard cantilevers are made from monocrystalline material of highest purity.

Therefore, we consider the following contributions to the effective $Q$-factor:

$$\frac{1}{Q_{\text{eff}}} \approx \frac{1}{Q_{\text{support}}} + \frac{1}{Q_{\text{TED}}} + \frac{1}{Q_{\text{surf}}} + \frac{1}{Q_{\text{mount}}} + \frac{1}{Q_{\text{air}}}. \quad (6)$$

Support loss determining $Q_{\text{support}}$ is the vibration energy of the cantilever dissipated by transmission through the support chip to which it is firmly attached (see figure 1(a)) [22]. The excited cantilever beam exerts both oscillating shear force and moment on its clamped end that, in turn, excite elastic

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waves propagating into the support chip where their energy is dissipated. An analytical model for support loss in a micromachined beam resonator fixed at one end and free at the other with in-plane flexural vibrations presented by Hao et al [22] yields

$$ Q_{\text{support}} = 2.081 \times \left( \frac{1}{f_0} \right)^3, \quad (7) $$

and we use this model to describe the support loss of cantilevers.

The thermoelastic damping (TED) in cantilevers was studied by Zener already in 1937 [23] and TED in silicon cantilevers was afterwards investigated by several groups [24–26]. Any bending of the cantilever is related to temperature changes, and an irreversible flow of heat driven by the generated temperature gradients gives rise to $Q_{\text{TED}}$ [27]. For a cantilever made of perfect material with a non-zero thermal expansion coefficient $\alpha$, the energy dissipation caused by TED determines the upper limit for the intrinsic $Q$-factor. The contribution of TED can be derived approximately as [24]

$$ Q_{\text{TED}} = \frac{\rho C_p}{E \alpha^2 T} \left[ 1 + \left( \frac{2\pi f_0 \tau}{1 - \xi} \right)^2 \right], \quad (8) $$

with

$$ \tau = \frac{\rho C_p t^2}{\pi^2 \kappa_\text{th}}, \quad (9) $$

with the Young modulus $E$, density $\rho$, thermal conductivity $\kappa_\text{th}$, and specific heat capacity $C_p$ referring to a cantilever in equilibrium with a bath of temperature $T$. Lifshitz and Roukes derived a refined solution for TED which we will use in the following [27]:

$$ Q_{\text{TED}} = \frac{\rho C_p}{E \alpha^2 T} \left[ \frac{6}{\xi^2} - \frac{6}{\xi} \times \frac{\sinh(\xi) + \sin(\xi)}{\cosh(\xi) + \cos(\xi)} \right]^{-1}, \quad (10) $$

with

$$ \xi = \sqrt{\frac{2\pi f_0 \rho C_p}{2\kappa_\text{th}}}. \quad (11) $$

The damping $1/Q_{\text{surf}}$ caused by the surface layer of the cantilever can be expressed as [28]

$$ Q_{\text{surf}} = \frac{wt}{2\delta(3w + t)} \frac{E_2}{E_3^2}, \quad (12) $$

introducing the thickness $\delta$ of the surface layer and a parameter $E_2$ being a property of the surface layer and its defects [29]. Yang et al observed an increase in the $Q$-factor by an order of magnitude when removing the oxide layer from ultra-thin cantilevers (thickness $\approx 170$ nm) [29]. For typical cantilevers investigated here (thickness $\approx 4$ $\mu$m), the effect of surface damping is, however, about 20 times smaller than for ultra-thin cantilevers.

As will be demonstrated below, $Q_{\text{mount}}$ can be the most important contribution; however, it cannot be described by a simple formula as it depends on details of the mechanical contact of the cantilever support chip with the holder or of the cantilever holder with the body of the force microscope. The contact is influenced by subtleties that are difficult to describe mathematically and difficult to control practically. When the intrinsic damping characteristics $Q_0$ of the cantilever are known, $Q_{\text{mount}}$ can be obtained from the difference between theoretical $Q_0$ and experimental $Q_{\text{eff}}$ and taken as a measure for the quality of the cantilever fixation in the AFM:

$$ \frac{1}{Q_{\text{mount}}} \approx \frac{1}{Q_{\text{eff}}} - \frac{1}{Q_0}. \quad (13) $$

In the case of an optimum fixation of the cantilever, $1/Q_{\text{mount}}$ is zero.

The dependence of the $Q$-factor of silicon cantilevers on the pressure in the ambient gas has been investigated by Bianco et al [30] as well as by Blom et al [20] for certain ranges of the ambient pressure. It is possible to distinguish between pressure regimes that are dominated by different damping mechanisms, namely the molecular flow regime and the viscous flow regime [20]. For measurements performed under UHV conditions, only the molecular flow regime is relevant. For this regime, the pressure-dependent $Q$-factor is calculated based on models derived by Christian and Bianco [30, 31]:

$$ Q_{\text{molecular}} = \frac{(\rho t_0 \rho_0) \sqrt{\pi}}{4} \left[ \frac{RT}{2} \right] \frac{1}{M^2 p}, \quad (14) $$

with the mass of the gas molecules $M$, the gas constant $R$, the temperature $T$ and the pressure $p$ of the gas. From this formula we find that $Q_{\text{molecular}}$ exceeds $10^{12}$ if the pressure is below $10^{-5}$ mbar. Therefore, this contribution is considered to be negligible in the context of this study.

To illustrate the importance of different contributions to the cantilever damping, we compile respective results in table 1. Using the known material properties of silicon cantilevers and typical dimensions, we calculate $Q_0$ considering the contributions of $Q_{\text{support}}$, $Q_{\text{TED}}$ and $Q_{\text{surf}}$ for the two types of cantilevers used here. $Q_{\text{surf}}$ is estimated by a procedure described in detail in section 3.3.

Table 1. Contributions to the $Q$-factor calculated from the models described in the text for typical cantilever dimensions ($l = 225$ $\mu$m, $w = 28$ $\mu$m, $t = 3$ $\mu$m for 75 kHz cantilevers and $l = 125$ $\mu$m, $w = 30$ $\mu$m, $t = 3.6$ $\mu$m for 300 kHz cantilevers). $Q$-factors refer to a situation where cantilevers are kept at room temperature and $Q_{\text{surf}}$ is calculated assuming $\delta \times E_3^2 = 0.06$ (see section 3.3).

<table>
<thead>
<tr>
<th>$f_0$ (Hz)</th>
<th>$Q_{\text{support}}$</th>
<th>$Q_{\text{TED}}$</th>
<th>$(Q_{\text{TED}}^{-1} + Q_{\text{surf}}^{-1})^{-1}$</th>
<th>$Q_{\text{surf}}$</th>
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<tr>
<td>300 000</td>
<td>87 100</td>
<td>180 000</td>
<td>58 700</td>
<td>1594 000</td>
<td>56 700</td>
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Two major conclusions can be drawn from table 1. First, the $Q$-factor is principally limited to about 350 000 for 75 kHz cantilevers and to about 57 000 for 300 kHz cantilevers mainly due to the cantilever geometry. Second, there is limited room for an improvement of performance for the higher $Q$ cantilevers (75 kHz) by reducing surface losses, while this contribution does not play any role for the lower $Q$ cantilevers (300 kHz).
2. Experimental details

The oscillation behaviour of cantilevers is investigated either in situ in one of the force microscopy systems A or B or in a test setup that is described below. The fixation mechanisms are different for the force microscopy systems. In system A, the holder consists of a V-shaped spring clamped to a counterpart on the AFM stage (see figure 1(b)). The cantilever holder of system B is positioned by three legs fitting into a socket and the holder is additionally fixed magnetically on the socket in the AFM stage (see figure 1(c)). In the test setup, cantilevers are mounted with a clamp fixation (see figures 2(a) and (b)) so that they can easily be removed and later be glued onto a cantilever holder, which is introduced into the AFM stage. All measurements reported here are performed with a system in thermal equilibrium at room temperature.

The test setup is housed in a compact vacuum chamber equipped with a turbomolecular pump and an ion getter pump. A combined Pirani/cold-cathode vacuum gauge allows us to measure the pressure from normal to UHV conditions. The detection of the cantilever oscillation is realized by the beam deflection method similar to the optical systems of our NC-AFM systems. Details of the test setup are shown in figure 2(a). A laser beam with a wavelength of 635 nm provided by a laser diode is coupled into the UHV by a single-mode optical fibre and focused by an in-vacuo lens (10 mm focal length) onto the backside of the cantilever. From there, the beam is reflected onto a four-quadrant photosensitive detector (PSD). The photodiode has a spectral sensitivity of 0.5 A W⁻¹ at the used wavelength yielding a typical photocurrent in the order of 0.1 mA. Current signals from the quadrants are amplified and converted to voltage signals by home-built vacuum compatible pre-amplifiers directly attached to the four-quadrant diode. The deflection signal is generated by a difference amplifier processing the pairwise added voltage signals from the quadrants. The optical system of the test setup is similar to the setup used by system A, where the beam is deflected in a plane perpendicular to the plane defined by the incoming and reflected laser beams.

Cantilevers to be examined are mounted on a stage capable of holding up to 12 cantilevers. The cantilevers are aligned by milled recesses and fixed with copper–beryllium springs (see figure 2(a)), which allow for reuse of the cantilevers in a force microscope after the initial characterization. Details of the spring clamping mechanism are shown in figure 2(b). The cantilever mounting stage is equipped with a linear drive to select 1 out of the 12 cantilevers for the measurement. Precise alignment in the optical path is facilitated by an X–Y positioning table. The base plate of the mounting stage is glued to a piezo ceramic plate with gold electrodes that is excited to vibration by applying an ac voltage of typically 0.1 mV amplitude. For the replacement of cantilevers, the entire mounting stage is removed from the vacuum chamber.

To measure the Q-factor, we use a sine wave generator to excite the cantilever at a certain excitation amplitude and sweep the frequency in a range centred on the resonance frequency of the cantilever. A lock-in amplifier records the deflection signal as a function of the excitation frequency. A frequency sweep collecting 6400 data points is typically performed in 200 s. The resonance frequency and the Q-factor are obtained from the frequency spectrum by a least-squares fit of equation 3 to the data.

A typical resonance curve together with a fit result is displayed in figure 3. Measured values representing data obtained under UHV conditions can be well described by equation 3 for f = 67 412.0 Hz and Q = 193 700. For the class of high-Q 75 kHz cantilevers, the width of the sweep is chosen to be 6 Hz or less to obtain a sufficiently high density of data points in the range of the maximum to facilitate a good fit. Q-factors can be determined with an accuracy of 2% taking into account errors due to changes of parameters such as ambient temperature, excitation amplitude, laser light intensity or adjustment of the optical system. However, we find that the measured Q-factor is most sensitive to the precise fixation of the cantilever support chip on the cantilever holder as will be discussed in the following section.
Figure 3. Measured resonance curve (solid line) with fit (dashed line) according to equation (3) yielding the fit parameters $f_0 = 67412.0 \text{ Hz}$ and $Q = 193700$.

3. Results

3.1. Fluctuations of the effective $Q$-factor for clamped cantilevers

We investigate the reproducibility of $Q$-factor measurements in the test setup. The $Q$-factors of a set of 75 kHz cantilevers and of a set of 300 kHz cantilevers are compared to each other. Each set consists of ten cantilevers taken from the same wafer. For 75 kHz cantilevers as well as for 300 kHz cantilevers, it appears that $Q$-factors cannot be measured with great reproducibility when cantilevers are removed from the cantilever holder and re-inserted, as evident from the diagrams shown in figure 4.

Frequently, we determine effective $Q$-factors that dramatically differ from $Q_0$, which is caused by additional damping due to peculiarities of mounting the cantilever. Measurement experience yields that a very large number of measurements is required to obtain $Q_0$ with a precision limited by the fit of the resonance curve, however, at least half of the measured effective $Q$-factors are fairly close to the real $Q$-factor of the cantilever. If an error margin of 20% of $Q_0$ is acceptable, it is enough to measure the $Q$-factor three times while removing and re-inserting the cantilever support chip into the cantilever holder between the measurements. The largest $Q$-factor measured for a cantilever is always assumed to be the best approximation to $Q_0$. Occasionally, this method fails as seen in figure 4 where cantilever no 20 exhibits a maximum $Q$-factor of 10 900 when measured three times. A fourth measurement on this cantilever yields a $Q$-factor of 35 100, similar to all the other cantilevers from this batch. Having this cantilever inserted into system A, a value of 40 100 is obtained (see cantilever 4 in figure 8).

Most of the cantilevers with a resonance frequency of 75 kHz yield $Q_0$ values around 200 000, while the 300 kHz cantilevers typically yield $Q_0$ values of 35 000. Results demonstrate that there are only minor variations of the $Q$-factor caused by the manufacturing process; however, large variations may result from the clamping fixation of the cantilevers in the mounting stage. This points to the general difficulty in reliably establishing a high-$Q$ oscillation with a cantilever that is clamped rather than glued to the cantilever holder.

To test whether an improved result can be obtained by an optimized cantilever support, we equipped one slot of the stage with a cantilever alignment chip precisely fitting the cantilever support plate (see figure 5). Repetitive $Q$-factor measurements with this chip for two 75 kHz cantilevers are shown in figure 6. While generally the alignment chip provides a high reproducibility, also in this case some measurements yield dramatically reduced $Q$-factors. As one of the major causes of poor reproducibility, we identify small particles of silicon on the cantilever support chip prohibiting firm contact between mounting stage and cantilever support chip (see figure 7). These particles break off the chip when it is handled with tweezers to place the chip onto the mounting stage or when removing it. Possibly related observations have recently been reported as false resonance peaks of cantilevers operated in air where these peaks disappeared after readjusting the cantilever position [32]. In a more recent paper it has, furthermore, clearly been demonstrated that clamping a cantilever by a spring with a point or line contact likely results in a spurious response but a much cleaner frequency response.

12 Alignment chip, version 4.2, Nanoworld, Neuchâtel, Switzerland.
Figure 5. Cantilever alignment chip (left) precisely fitting to the backside of the cantilever support chip (right).

Figure 6. $Q$-factors of two cantilevers mounted onto the cantilever alignment chip measured in the test stage. Between measurements, the cantilever is removed and the alignment chip but not the cantilever support chip is cleaned with isopropyl alcohol before the cantilever is reinserted.

can be obtained when fixing the cantilever support chip with a rigid cover [33]. As will be evident from the following section, however, gluing the support chip on the cantilever holder is the most reliable method to obtain a high $Q$-factor.

3.2. Fluctuations of the effective $Q$-factor for glued cantilevers

We investigate how well $Q_0$ can be reproduced by effective $Q$-factors determined in the NC-AFM under realistic measurement conditions. In both force microscopes, the cantilever support chip is glued onto a removable cantilever holder (see figures 1(b) and (c)). For this type of fixation, a planar face of the cantilever holder is covered by a thin layer of glue and the cantilever support chip is pressed against the glue where it can be laterally positioned as long as the glue is not hardened. The final gluing result for a cantilever used in system A is shown in figure 2(c). We measure effective $Q$-factors $\text{in situ}$ and test their reproducibility upon removal and re-insertion of the cantilever holder. Representative results for both systems are compiled in figure 8.

Figure 7. Left picture: image of the cantilever support chip of an unused AFM probe. Right picture: image of a similar cantilever support chip that has been handled with tweezers before mounting in the test setup. The dark dots represent small pieces of silicon broken off from the edges of the support chip.

Figure 8. Measured $Q$-factors of cantilevers tested in NC-AFM systems A and B. Between individual measurements, the cantilever holder is removed and re-inserted into the AFM stage.
Table 2. Estimated values for $Q_{surf}$ and $Q_{mount}$ based on the discrepancy between the calculated $(Q_{\text{ TED}}^{-1} + Q_{\text{ support}}^{-1})^{-1}$ and the measured $Q_{\text{ exp}}^{-1}$. $Q_{\text{ theo}}^{-1}$ values are calculated according to equation (6) assuming $\delta \times E_s^2 = 0.06$ for all cantilevers and assuming that the additional damping is due to $Q_{\text{ mount}}$.

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<th>$w$ (\text{\textmu m})</th>
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In system A, a large variation of the $Q$-factor is found for the 75 kHz cantilevers, while effective $Q$-factors for the 300 kHz cantilevers remain nearly constant indicating that the $Q$-factors of the 75 kHz cantilevers are more sensitive to the mounting mechanical contact. This can be understood as the intrinsic $Q$-factor of 300 kHz cantilevers is significantly smaller than the intrinsic $Q$-factor of 75 kHz cantilevers and, therefore, the relative effect of additional losses by mounting is smaller for 300 kHz cantilevers. The high reproducibility of the effective $Q$-factor for 300 kHz cantilevers is confirmed by measurements in system B, also yielding only very small variations of the $Q$-factor. From a comparison of these results to those described in the previous section, we find that $Q$-factor fluctuations of cantilevers glued in the NC-AFM systems are much less than fluctuations observed for the test setup where cantilevers are clamped.

### 3.3. Estimating surface damping

Surface damping is the contribution to $Q_0$ that is most difficult to handle as the respective material parameters are neither tabulated nor can they be measured directly. As the parameters $\delta$ and $E_s^2$ controlling surface damping are not known, we fit equation (12) to the measured data using the product $\delta \times E_s^2$ as a fit parameter. We adopt the procedure of Hao et al who fit $\delta \times E_s^2$ to explain the discrepancy between $Q_{\text{ TED}}^{-1} + Q_{\text{ support}}^{-1}$ and $Q_{\text{ eff}}^{-1}$ by surface damping [22], however, extend this by including $Q_{\text{ mount}}$ that we identified as a possibly most important contribution. We assume all uncoated silicon cantilevers investigated to be covered with a native oxide layer of the same thickness $\delta$ and the same property $E_s^2$. According to equation (6) we then obtain the equation

$$\frac{1}{Q_{\text{ mount}}} + \frac{1}{Q_{\text{ surf}}} = \frac{1}{Q_{\text{ eff}}} - \left(\frac{1}{Q_{\text{ TED}}} - \frac{1}{Q_{\text{ support}}}\right),$$

where $Q_{\text{ mount}}$ is an unknown contribution depending on the experimental details, while $Q_{\text{ surf}}$ is a predictable contribution depending on the known cantilever geometry and the yet unknown parameter $\delta \times E_s^2$. To determine this parameter, we investigate 15 cantilevers from one batch that nominally have the same properties. For each of these cantilevers, we determine the resonance frequency $f_0$ and $Q_{\text{ exp}}^{-1}$ from the measurements in system B and determine $Q_{\text{ TED}}^{-1} + Q_{\text{ support}}^{-1}$ from the measured dimensions and known material parameters. The respective results are compiled in columns 4, 5 and 6 of table 2.

According to equation (15) the difference between these two quantities provides the sum of the damping contributions of $Q_{\text{ mount}}$ and $Q_{\text{ surf}}$. From table 2 we find that the difference is negligible or small for some of the measurements and anticipate that this indicates a small or vanishing mounting loss. For the cantilever with the smallest difference, we assume $Q_{\text{ mount}}^{-1}$ to vanish and associate the difference with $Q_{\text{ surf}}^{-1}$. From the results of this measurement we can deduce the parameter $\delta \times E_s^2 = 0.06$ according to equation (12) and take this as a universal parameter not only for this batch of cantilevers but for all cantilevers (300 kHz and 75 kHz) produced under similar conditions. Using the parameter $\delta \times E_s^2$, we can calculate $Q_{\text{ surf}}^{-1} + Q_{\text{ mount}}^{-1}$ and the intrinsic damping $Q_{\text{ theo}}^{-1}$ where the respective results are shown as columns 7, 8 and 9 of table 2. We find that $Q_{\text{ surf}}$ is a small contribution for the investigated 300 kHz cantilevers while $Q_{\text{ mount}}$ is of the order of $Q_{\text{ TED}}$ or $Q_{\text{ support}}$ except for a few cases where it greatly exceeds these contributions due to the perfect mounting of the cantilever. Any variation of measured $Q_{\text{ eff}}^{-1}$ for cantilevers with identical dimensions is explained by individual values of $Q_{\text{ mount}}^{-1}$.

### 3.4. Maintaining a high effective $Q$-factor in the NC-AFM

The figure-of-merit related to the cantilever oscillation properties relevant for high resolution NC-AFM measurements is $Q_{\text{ eff}}$ as determined in the NC-AFM. To investigate to what extent high values for $Q_{\text{ eff}}$ determined in the test setup can be maintained when using a cantilever in a NC-AFM system,
we perform comparative measurements on the same cantilever investigated in both environments.

After having been studied in the test setup, cantilevers are glued onto cantilever holders of the AFM systems (see figure 2(c) as an example). In all cases, the same conductive silver-epoxy glue is used\(^\text{14}\); however, the thickness of the glue film under the cantilever support chip may differ. Results are compiled in figure 9. In both systems, the highest value of multiple measurements was taken to minimize mounting effects.

In system A, results show a slight decrease in the \(Q\)-factors of the 75 kHz cantilevers and a slight increase in the \(Q\)-factors of the 300 kHz cantilevers when moved from the test setup to the NC-AFM. For this cantilever holder, we find that the glue has only a small influence on the \(Q\)-factor while the fixation of the cantilever holder in the scan head can result in some change of the \(Q\)-factor (see cantilever 2 in figure 8).

In system B, we generally find highest reproducibility; however, peculiarities in gluing the cantilever may exceptionally result in a dramatic reduction of the effective \(Q\)-factor as observed for cantilever 5 in figure 9.

These results demonstrate that it is possible to routinely exploit the high intrinsic \(Q\)-factors of commercially available cantilevers provided care is taken in gluing and mounting them. Best values obtained for \(Q_{\text{eff}}\) are 300,000 for 75 kHz cantilevers and 45,000 for 300 kHz cantilevers. From a total of 50 measurements with 300 kHz cantilevers from one batch, we find mean \(Q_{\text{mount}}\) values of 68,000 for the test setup, 198,000 for system A and 263,000 for system B. This implies that \(Q_{\text{eff}}\) has to be measured in the respective system prior to any critical experiment where highest performance is required. Apparently, system B exhibits the smallest mounting loss on average and is, therefore, used as the reference system for \textit{in situ} studies for the present work.

The values given above determine the principal limits of the force detection sensitivity for cantilever-based NC-AFM measurements performed under UHV conditions. In table 3, the minimum detectable force gradients calculated from equation (1) are given for 75 kHz and 300 kHz cantilevers assuming routinely observed \(Q\)-factors and operation at room temperature. We find a minimum detectable force gradient better than \(10^{-5}\) N m\(^{-1}\) where 75 kHz cantilevers yield half an order of magnitude more force sensitivity than 300 kHz cantilevers. Practically, the sensitivity will in most systems be reduced by the noise from the light source, pre-amplifier and demodulation electronics used in the NC-AFM system.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\(f_0\) & \(k\) & \(Q_{\text{typical}}\) & \(Q_{\text{best}}\) & \(\delta F_{\text{min}}\) \\
\hline
75 kHz & 2.8 N m\(^{-1}\) & 200,000 & 300,000 & \(1.4 \times 10^{-6}\) N m\(^{-1}\) \\
300 kHz & 42.0 N m\(^{-1}\) & 35,000 & 45,000 & \(7.0 \times 10^{-6}\) N m\(^{-1}\) \\
\hline
\end{tabular}
\caption{Minimum detectable force gradient \(\delta F_{\text{min}}\) for typical cantilever properties \(f_0\), \(k\) and \(Q\) as resulting from equation (1). The \(Q\)-factors are typical effective and best values measured for the respective types of cantilevers. Other parameters: temperature \(T = 300\) K, detection bandwidth \(B = 300\) Hz, oscillation amplitude \(A = 10\) nm.}
\end{table}

### 4. Conclusions

Commercially available high quality cantilevers generally have high intrinsic \(Q\)-factors; typical values are 200,000 for 75 kHz cantilevers and 35,000 for 300 kHz cantilevers, while the best obtained values are 300,000 and 45,000, respectively. The best measured \(Q\)-factors relevant for NC-AFM measurements in UHV are close to the intrinsic values; however, the \(Q\)-factor may be strongly reduced by mounting the cantilever. Gluing the cantilever to the holder is the most reliable method to yield a high effective \(Q\)-factor, while clamping yields large fluctuations unless utmost care in positioning the cantilever and cleanliness of cantilever and holder is taken. Taking the necessary care in mounting the cantilever, it is possible to routinely obtain an effective \(Q\)-factor in NC-AFM measurements in high or ultra-high vacuum that is within a 20% margin of the intrinsic \(Q\)-factor. However, for critical measurements, this has to be verified by a \(Q\)-factor measurement with the cantilever mounted in the NC-AFM system and cannot be inferred from any \textit{ex situ} measurement. The \(Q\)-factor that realistically can be expected in a NC-AFM system defines a principal limit of the minimum detectable force gradient for room temperature measurements in the order of \(10^{-6}\) N m\(^{-1}\).
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References

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