Advantages of cantilever-based Scanning Force Microscopes

For most surface science groups tuning-fork based atomic force microscopes have become the prime choice. This is because, virtually every STM can be converted into an AFM when a tuning fork and the required electronics is installed. However, in-spite of the success of these types of AFMs, because of their large mass and low resonance frequency tuning forks cannot match the sensitivity of cantilevers[1] (see table). The latter is particularly advantageous when measuring weak tip-sample interaction forces such as magnetic stray fields. Examples are shown in the sections on magnetic force microscopy.

However, at the cost of the increased instrument complexity, cantilever-based scanning force microscopes also offer considerable advantages for atomic resolution work, that still need to be fully explored.

Microfabricated cantilevers used in atomic resolution AFM work typically have force constants around a few tens of Newtons per Meter. For atomic resolution imaging such cantilevers can be operated with sub-Angstrom oscillation amplitudes if higher flexural oscillation modes are used [2]. The modal stiffness of the cantilever (1178 N/m) is then comparable to that of a tuning fork (1800 N/m, see table). If the first flexural mode is used, larger oscillation amplitudes (typically a few Nanometers) are required for a stable operation of the distance feedback. This is because at small amplitudes the energy stored in the cantilever remains small compared to energy losses that can stochastically occur when the cantilever tip interacts with the sample. The tip-sample distance feedback that typically keeps the resonance frequency shift constant would then fail. In our work we however discovered that stable imaging conditions can be obtained when either the tunneling current or a higher oscillation mode frequency shift is used for the distance feedback. Under these conditions the PLL can track frequency shifts and dissipation signals using the first flexural modes with sub-Angstrom amplitudes. Such small amplitudes match the typical decay length of inter-atomic forces and thus increase the shift of the resonance frequency. The high resonance frequency of these cantilevers (in higher modes up to 10 MHz) further facilitates the detection of dissipation signals (green column of table). Experiments on non-contact dissipation will soon be reported.

Cantilever								
Mode n	k_n [N/m]	f_n [kHz]	Q	T [K]	$dF/dz\|_{min}$ [μN/m /(Hz)$^{1/2}$]	$\Gamma\|_{min}$ [μg/s /(Hz)$^{1/2}$]	Intrinsic loss [meV/cycle]	A_{th} [pm]
1	**30**	**300**	50000	4.3	**5.50**	**2.92**	0.03	1.99
2	**1178**	**1880**	50000	4.3	**13.76**	**1.17**	1.16	0.32
3	**9240**	**5265**	50000	4.3	**23.03**	**0.70**	9.07	0.11
4	**35479**	**10317**	50000	4.3	**32.24**	**0.50**	34.83	0.06
Tuning fork								
	1800	20	12000	4.3	337	2680	7.26	0.26
Kolibri Sensor								
	540000	1000	27000	4.3	550	87.5	982	0.01

Table 1: Properties of a microfabricated silicon cantilever, a tuning fork (properties according [3]), and a Kolibri sensor (properties according [3]). The yellow and green columns display the force gradient sensitivity and energy loss sensitivities, respectively (smaller numbers are better). Allat co values are calculated for an oscillation amplitude of 50 pm according to [1]. The last two columns display the energy lost per oscillation cycle and the thermal noise amplitude at 4.3 K.

Apart from using different flexural modes, cantilevers can also be simultaneously driven on their torsional modes [4]. This allows the simultaneous measurement of vertical and lateral forces. Results obtained with a CO functionalized tip interacting with a CO on Cu(111) will soon be reported.

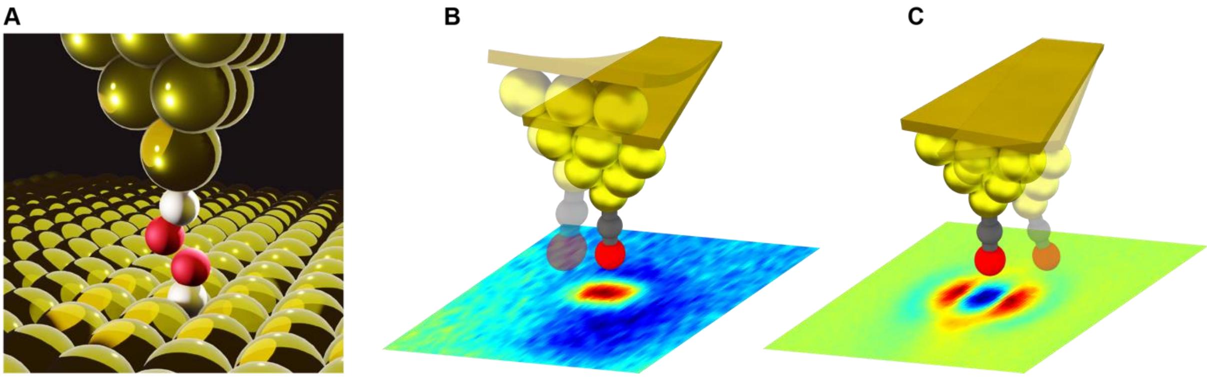

Figure 1: **A** Artistic view of a CO-functionalized metal coated cantilever tip over a CO molecule adsorbed on a Cu(111) surface. **B** 1^{st} flexural oscillation mode of a cantilever shown above 2^{nd} mode frequency shift data obtained at small tip-sample distances. The red part of the image indicates a positive frequency shift arising from a repulsive atomic-scale tip-sample interaction. **C** 1^{st} torsional cantilever oscillation mode displayed above torsional mode frequency shift data obtained simultaneously with the data shown in **B**.

Note that, in principle, the lateral force can also be obtained from calculating the lateral derivatives of the energy field that can be obtained from layered imaging of the flexural mode frequency shift. This procedure however fails when the energy field is not conservative, which is for example the case when an atomic or molecular adsorbate is manipulated.

References:

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[2] Kawai, S., & Kawakatsu, H. *Mechanical atom manipulation with small amplitude dynamic force microscopy*. Appl. Phys. Lett. 89 (2006) 023113

[3] http://www.specs.de/cms/upload/PDFs/SPECS_Prospekte/1404_SPECS-Brochure_red-KolibriSensor_RZ_Web.pdf

[4] This project is financially supported by SNF project 200021_17576