5 High-Frequency Dynamic Force Microscopy

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5.1 Introduction

One objective in the instrumentation of atomic force microscopy (AFM) [1] is to measure and control the force acting between the tip apex and the sample surface with as high a resolution as possible in terms of force as well as the volume concerned. Lateral resolution has been pursued by using a sharp tip, and vertical resolution has been pursued by using a small amplitude of drive of the cantilever, choosing parameters that allow probing for a wide range of tip–sample distances, hence enabling different contribution of the short and long range forces to be sensed. Low-noise detection schemes have been studied to give sufficient signal-to-noise margin for a given set of imaging parameters which mainly comes from the mechanical characteristics of the cantilever. This chapter explains some of the recent trends in dynamic force microscopy where stiffer cantilevers are used at higher frequencies and with lower amplitude of drive to improve the local probing capability of the microscope.

5.2 Instrumental

5.2.1 Cantilever

In dynamic force microscopy (DFM) [2], an oscillator, such as a cantilever, is oscillated to measure the force gradient around the tip apex. Since the local force gradient acts as an additional spring, a change in the force gradient results in a change in the oscillating frequency of a self-excited cantilever. The detection technique employed in DFM is a differential measurement technique, where the component of the force gradient in the direction of the position modulation is detected. In order to acquire a local force gradient with as little averaging by distance as possible, it is preferable to use a smaller amplitude of drive of the cantilever. The common DFM cantilever, whose spring constant is typically in the 40-N/m range, is not stiff enough to overcome the surface force gradient, which may result in snap-in of the tip to the surface, or the necessity to employ a certain level of amplitude of drive to maintain stable self-excitation of an oscillator placed in a nonlinear force gradient.
Detailed explanation and simulation can be found in the literature [3]. Since the force gradient can be up to around 100 N/m, a stiffer cantilever in the 100–1000 N/m range is a more favourable choice for probing of force with a small amplitude, at once allowing a wider range of working points or centres of oscillation to be chosen. However, a cantilever with a high spring constant gives higher demands on the required signal-to-noise margin of the detection scheme.

The minimum detectable force gradient of a free-oscillation cantilever is given by

\[ \delta F'_{\text{min}} = \left( \frac{2kk_B TB}{\omega_0 QA} \right)^{1/2}, \]  

where \( k \) is the spring constant, \( k_B \) is the Boltzmann constant, \( T \) is temperature, \( B \) is the measurement bandwidth, \( Q \) is the quality factor and \( \omega_0 \) the natural frequency of the oscillator, and \( A \) is the mean-square amplitude of the cantilever oscillation [4].

Increases of \( Q \), \( 1/k \) and \( \omega_0 \) contribute to improvement of sensitivity. Since the choice of a stiffer cantilever acts against improving force sensitivity, we are left with the choice of increasing \( \omega_0 \) and/or \( Q \) of the cantilever. A smaller cantilever acts in favour of increasing \( \omega_0 \) for a given value of the spring constant \( k \). Decreasing the amplitude of drive or \( A \) goes against improving sensitivity and frequency noise, but the merit of having the tip apex within the distance of short-range forces throughout the cycle of the oscillation is more important [3]. Various attempts have been made so far in fabricating small cantilevers with high natural frequency [5–18]. In the fabrication of small cantilevers, various issues, such as alignment accuracy and base overhang, which were not important or were overlooked in the case of 100-µm-sized cantilevers become important and non-negligible. Some of the important issues are:

1. The support should be well defined in comparison to the dimensions to improve the \( Q \) factor.
2. Overhang of the cantilever base should be zero or made small enough compared with the length of the cantilever to avoid shading the top surface of the cantilever for optical detection.
3. The shoulders of the cantilever base need to be made narrower to avoid shoulder-to-sample contact.
4. Alignment error of the tip to the cantilever.
5. The length of the cantilever should be accurate.

Video rate biomolecular imaging has been accomplished by Ando [19] using a silicon nitride cantilever supported on a ridge to avoid the shoulders touching the sample. Yang et al. [18] implemented a fabrication method that ensures high stability of cantilever length. Figure 5.1 shows a cantilever fabricated by silicon-to-silicon bonding. The method eliminates unwanted overhang and wide shoulders of the silicon base which become nonnegligible as the structure becomes smaller. Saya et al. [15] fabricated a series of small cantilevers based on anisotropic etching of silicon by KOH. Figure 5.2 shows a self-assembling cantilever structure where a bellows structure is shut by the meniscus force upon drying of water, causing the cantilever to protrude a designated length over the edge. Figure 5.3 shows a cantilever with a natural frequency of 10.5 MHz fabricated by conventional techniques [20].