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Components for high speed atomic force microscopy

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Abstract

Many applications in materials science, life science and process control would benefit from atomic force microscopes (AFM) with higher scan speeds. To achieve this, the performance of many of the AFM components has to be increased. In this work, we focus on the cantilever sensor, the scanning unit and the data acquisition. We manufactured 10 μm wide cantilevers which combine high resonance frequencies with low spring constants (160–360 kHz with spring constants of 1–5 pN/nm). For the scanning unit, we developed a new scanner principle, based on stack piezos, which allows the construction of a scanner with 15 μm scan range while retaining high resonance frequencies (> 10 kHz). To drive the AFM at high scan speeds and record the height and error signal, we implemented a fast Data Acquisition (DAQ) system based on a commercial DAQ card and a LabView user interface capable of recording 30 frames per second at 150 × 150 pixels.

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1. Introduction

The possibilities for high speed atomic force microscopy (AFM) have been impressively demonstrated by several groups since the 1990s [1–8]. Great technological advances have been made in the areas of sensitive low noise cantilever sensors [9,10], faster cantilevers [11], high rigidity scanners [12,13] and control schemes [14–16]. The applications in which high speed AFM has been successfully used, however, are limited, since only a small number of dedicated research labs have high speed AFM capability, and these instruments are highly specialized. The need arises for a versatile, easy to use AFM that allows higher imaging speeds for a broader range of applications. In this work, we discuss three areas necessary for high speed AFM and present modular solutions that allow for the increase of AFM imaging speeds.

2. Small cantilevers

Higher speed AFM puts greater demands on the detection of the interaction between the sample and the cantilever sensor. As with all sensors, the speed performance of the sensor is limited by the sensor bandwidth. For a cantilever sensor, the maximum scan speed is determined by the spring constant, the effective mass of the cantilever, the damping of the cantilever in the surrounding medium, and the sample stiffness. The maximum achievable scan rates are

$$v \ll \frac{\lambda D}{2m} \tag{1}$$

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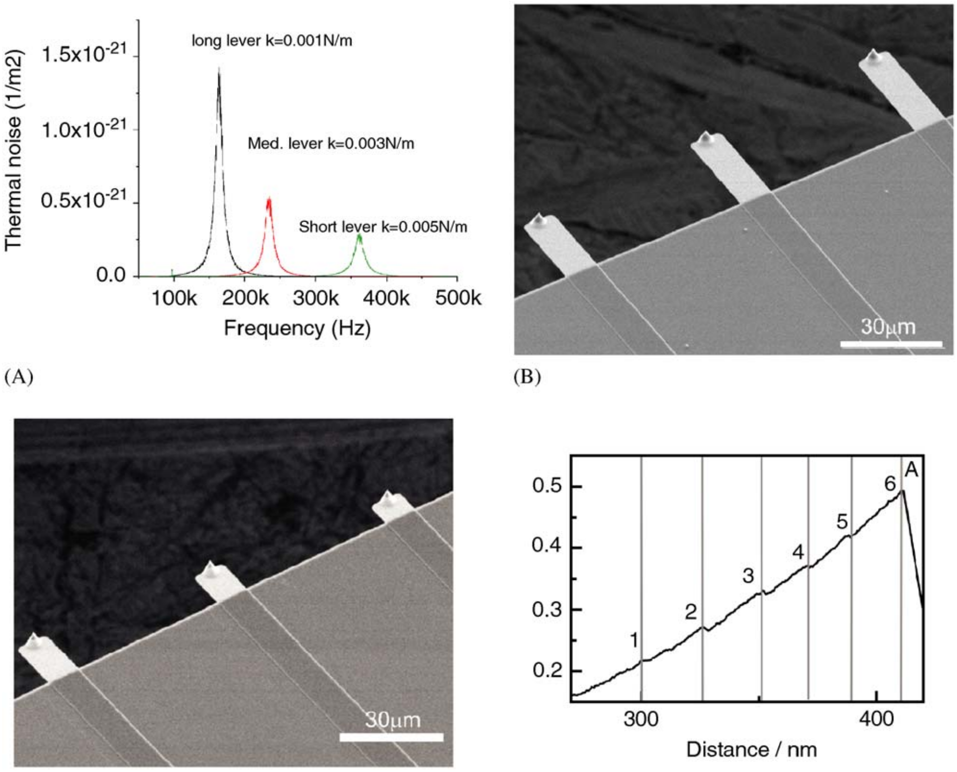

(A) (B) (C) (D)

Fig. 1. Smaller cantilevers give higher speed performance and allow lower noise measurements. (A) Thermal spectra of small cantilevers. (B) Batch fabricated 10 μm wide cantilevers with integrated tips. These cantilevers have a length of 25, 30 and 35 μm, respectively, and are designed for contact mode imaging. (C) Small cantilevers for tapping mode imaging. These cantilevers have a length of 10, 15 and 20 μm, respectively. (D) Molecular force spectroscopy curve taken on a collagen fibril with 5 μm wide levers reveal a fine structure in the pulling curve that was not observable with conventional cantilevers [19].

or

$$v \ll \frac{\lambda}{2}\sqrt{\frac{k+S}{m}-\frac{D^2}{2m^2}}, \tag{2}$$

where v is the maximum achievable velocity, λ the periodicity of surface features, D the damping, k the spring constant, m the effective cantilever mass, S the surface elasticity, for the cases of low damping and high damping, respectively [17]. From Eqs. (1) and (2) it is clear that the maximum achievable scan speed increases if the mass of the cantilever is reduced by making the cantilever smaller. A cantilever with the dimensions 25 μm × 10 μm × 0.1 μm having a mass of 77 pg can (according to Eq. (1)) image a sample 10 times faster, compared to the smallest cantilevers currently commercially available (to our knowledge the Olympus biolevers). It also has been shown that making the cantilever smaller reduces the noise for a given bandwidth in the cantilever measurement [18]. For these reasons we have manufactured cantilevers 10 μm wide, 100 nm thick and with various lengths (see Fig. 1(A) and (B)). These cantilevers have resonance frequencies (f_0) in air between 150 and 350 kHz with spring constants between 0.001 and 0.005 N/m. The Q-factors in air are between 13 and 21. The cantilevers are fabricated from a low stress SiN composite. These small cantilevers have batch produced integrated tips, unlike the cantilevers we previously made in our lab [9] where the tips were individually deposited by electron beam deposition (EBD) [10]. Fig. 1(C) shows cantilevers intended for tapping mode. These cantilevers have resonance frequencies of up to 2 MHz while still keeping spring constants below 2 N/m. Fig. 1(D) from Ref. [19] shows a pulling curve taken with a 5 μm wide cantilever on whole collagen fibrils from a rat tail tendon.The reduced noise of the small cantilever allowed to observe small force ruptures within the pulling spectrum.

Fig. 2 shows tapping mode images of plasmid DNA acquired with a 10 μm wide cantilever ($f_0 = 263$ kHz) using a prototype small cantilever head[2] and scanning at 8 Hz line rate. The width of the DNA molecules gives an upper bound for the tip sharpness of the small cantilevers to be 6 nm. For higher line-scan rates in tapping mode imaging, cantilevers with an even higher ratio of Q/f_0 [20] will be required.

3. High rigidity scanner design

One of the factors that limit the scan speed in commercial AFMs is the low mechanical resonance frequency of most commercial systems. The triangular

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[2] Courtesy of Veeco Metrology Inc., Santa Barbara, CA.