Self-oscillating tapping mode atomic force microscopy

L. Manning, B. Rogers, M. Jones, and J. D. Adams
Department of Mechanical Engineering and the Nevada Ventures Nanoscience Program, University of Nevada, Reno, Reno, Nevada 89557

J. L. Fuste and S. C. Minne
Nanodevices Incorporated, 5571 Ekwill Street, Santa Barbara, California 93111

(Received 8 April 2003; accepted 29 June 2003)

A piezoelectric microcantilever probe is demonstrated as a self-oscillator used for tapping mode atomic force microscopy. The integrated piezoelectric film on the cantilever serves as the frequency-determining component of an oscillator circuit; oscillation near the cantilever’s resonant frequency is maintained by applying positive feedback to the film via this circuit. This new mode, which is a step towards more compact and parallel tapping mode AFM imaging, is demonstrated by imaging an evaporated gold film on a silicon substrate. A self-oscillating frequency spectrum and a force–distance curve are also presented. © 2003 American Institute of Physics.

Tapping mode atomic force microscopy (AFM) lessens lateral, frictional forces imparted from the scanning probe to the sample surface. The microcantilever probe is oscillated so as to make intermittent contact with the surface, thereby minimizing sample damage especially for delicate samples. For the cantilever probe to oscillate with sufficient amplitude (typically 10–100 nm), its resonant frequency is first determined. The cantilever is forced into vibration at or near this frequency by an actuator. Cantilever oscillation is conventionally monitored optically by focusing a laser beam onto the cantilever, which reflects the beam into a photosensitive detector. Vibrating the cantilever can be done by external actuators, such as the AFM piezotube or small piezoelectric stacks inside the cantilever chip holder; cantilevers having integrated piezoelectric actuators, however, can provide more accurate tuning and stable operation without spurious vibrational modes. Such cantilevers have been well documented, but all of these examples have required an external oscillator to drive the actuator at the desired tapping frequency.

Noncontact AFM, in which force gradients that act on the oscillating tip are detected as shifts in the resonant frequency, also necessitates an oscillating cantilever probe. Self-oscillation of a cantilever at its resonant frequency has been accomplished for frequency modulation (FM) mode. In this mode of operation, the cantilever is used as the frequency-determining component of an oscillator circuit. Sample interaction with the tip causes variations in the frequency of the oscillator. Measurement of the oscillator frequency can be done using a variety of methods including frequency counters or FM demodulators. This technique has also been demonstrated using quartz tuning fork probes, as well as with cantilevers that have integrated piezoelectric actuators and/or sensors.

Finally, the advantages inherent in miniaturizing scanning probe microscopes have led to advances in this area, including the development of a microminiaturized scanning tunneling microscope array incorporating integrated circuitry, and an AFM array probe with an integrated deflection sensor and amplifiers for signal readout all combined on the same chip. In this Note, we present a self-oscillating cantilever that combines the advantages of tapping mode imaging with the simplicity of the self-oscillator for imaging in tapping mode utilizing an active probe cantilever from Nanodevices. The self-oscillation of the cantilever eliminates the need for an external oscillator and is a step toward more compact and multiple probe tapping mode AFM systems.

The self-oscillating circuit uses one operational amplifier with positive feedback and a gain greater than 1 to sustain oscillation. The gain was achieved by a potentiometer in negative feedback. The cantilever was connected in the positive feedback position through wires from the circuit. In this work, the circuit was housed in a shielded case external to the cantilever; however, the circuit could in later versions be integrated onto a single chip with the cantilever. The cantilever, which has a thin film of zinc oxide, was used as the frequency-determining component of the oscillator circuit. For example, the resonant frequency of one cantilever used was 52 kHz and the quality factor was on the order of 100. A band-pass filter ensured that the cantilever was driven near its first resonance frequency. Imaging with the self-oscillating cantilever involved monitoring its amplitude optically. No circuitry was employed to actively control the tapping amplitude of the cantilever. At the resonant frequency of the cantilever the photodetector of the Dimension 3000 scanning probe microscope (Digital Instruments) was not able to measure the amplitude due to its large size. Based on the values selected for the passive filter elements and adjustments made to the gain of the positive feedback circuit, the oscillation frequency could be effectively filtered, causing the cantilever to either be driven with a frequency above...
or below the resonance frequency, depending upon the setting. By driving slightly off resonance, but still on the resonance curve, standard tapping mode root mean square \( \text{rms} \) amplitudes were achieved. This filtering process need only happen once, and, in comparison to current tapping mode tuning, does not require an external oscillator. To begin self-oscillation, power is simply applied to the operational amplifier. Figure 1 illustrates the experimental setup.

To demonstrate the self-oscillating cantilever, a 10 \( \mu \text{m} \) image of an evaporated gold film on a silicon substrate was taken (Fig. 2). Gold grains are clearly visible in the image, especially in the inset, which was taken from the original data (dotted section) and was not a rescan. The error signal indicates a standard constant force/amplitude tapping mode image. The oscillation circuit was filtered to drive the cantilever at 55.2 kHz, which was slightly above the resonant frequency of the cantilever, and excited a free-air amplitude of 84 nm. A tapping mode force curve was taken after the image with this cantilever, and is shown in Fig. 3. The sensitivity was 70 nm/V.

Figure 4 is a spectral plot of cantilever motion excited by the self-oscillator circuit as observed by the laser; shown is a cantilever with a resonant frequency of 54.794 kHz, driven at 53.944 kHz by the self-oscillator circuit to achieve a free-air amplitude of 167 nm. The oscillation frequency of 53.944 kHz was selected by adjusting the gain of the oscillator circuit. The inset shows all of the spectral data from 10 to 200 kHz. It is clear to see from the spectral plots that the motion of the cantilever was sinusoidal at the drive frequency. The small peak, five orders of magnitude smaller than the drive peak, to the right of the

---

**FIG. 1.** Self-oscillating setup. The piezoelectric cantilever is the frequency-determining component of the oscillator circuit that consists of an operational amplifier provided with positive feedback and a gain greater than 1 to sustain oscillation. Passive band-pass filter elements along with a feedback potentiometer allow the oscillation circuit to be driven slightly before or after the resonance frequency of the piezoelectric cantilever. The amplitude of the oscillation is monitored using a laser and a photodetector. The piezotube of the atomic force microscope is employed to keep the tapping amplitude at a desired amplitude setpoint.

**FIG. 2.** 10 \( \mu \text{m} \) sq image of evaporated gold on a silicon substrate. An image of the height is on the left and the error signal is on the right. The \( z \) scale of the height image is 100 nm. The inset is an expanded view of the area indicated by the dotted box and shows the individual gold grains. The cantilever was driven slightly above the cantilever resonance with an oscillation frequency of 55.2 kHz.

**FIG. 3.** Tapping mode force curve taken using a self-oscillating cantilever. The cantilever had a resonant frequency of 52.0 kHz. The frequency of the oscillator circuit was 55.2 kHz and the free-air amplitude was 84 nm. The sensitivity of the cantilever determined from the slope of the force curve was 70 nm/V.

**FIG. 4.** Spectral plot of cantilever motion excited by the self-oscillator circuit. Motion was observed by the laser detection system. A cantilever with resonant frequency of 54.794 kHz was driven at 53.944 kHz by the self-oscillator circuit to achieve a free-air amplitude of 167 nm. The oscillation frequency of 53.944 kHz was selected by adjusting the gain of the oscillator circuit. The inset shows all of the spectral data from 10 to 200 kHz. It is clear to see from the spectral plots that the motion of the cantilever was sinusoidal at the drive frequency.
drive peak is at the cantilever resonance. Cleveland et al. have previously shown that the tapping amplitude in standard, externally oscillated tapping mode remains sinusoidal at different tapping amplitude setpoints.\(^\text{14}\) The self-oscillating circuit presented here also remained sinusoidal at different setpoints and appeared to be stable within 10 Hz (\(\sim 0.02\%\)) at a given setpoint.

The authors would like to thank Douglas Manning for his advice. One of the authors (L.M.) acknowledges the support of a Nevada Space Grant Consortium fellowship. A second author (M.J.) acknowledges a Nevada Space Grant Consortium undergraduate scholarship and a University of Nevada undergraduate research award.

\(^8\) F. Giessibl, Appl. Phys. Lett. 73, 3956 (1998).
\(^13\) http://www.nanodevices.com/activeprobe.html.