DESIGN OF RESONANT BEAM TRANSDUCERS: AN AXIAL FORCE PROBE FOR ATOMIC FORCE MICROSCOPY

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ABSTRACT

Guidelines for the mechanical design of resonant beam force transducers are developed. By considering the effects of beam dimensions on the force sensitivity, it is shown that thin, narrow beams are optimal for resonant sensing. Sensitivity is also shown to be inversely dependent on the amplitude of oscillation, and linear with the resonance quality (Q) of the oscillator. Based on this analysis, an axial resonant force detector was developed for use in atomic force microscopy. Initial measured results in air with a Q of 15 and 60nm oscillations give 33nN force resolution in a 1kHz bandwidth. The Q improves to 1200 in moderate vacuum, yielding an expected force resolution of 10pN in a 1kHz bandwidth. Due to its high axial spring constant (~200N/m) and vertical orientation, this force probe has the added benefit for surface force measurements that it is not susceptible to snap-down or other force instability.

INTRODUCTION

Measuring shifts in resonant frequency due to force loading of micromachined beams is a useful technique for a variety of sensing applications. High resolution pressure sensors and accelerometers have been constructed based on this principle[1-3]. A generic set of guidelines for the design of such sensors has not been provided, however. It is particularly important to understand the sensitivity implications of a particular geometric design, and to have a quantitative relationship for the effect of resonance quality and oscillation amplitude on performance. Based on a sensitivity analysis, a resonant beam force transducer for an atomic force microscope (AFM) has been constructed. This paper will explain the design issues, and provide experimental data from the resulting AFM sensor.

The main benefits of resonant beam transducers are their potential for high resolution and stability compared to DC measurements. An additional benefit of resonant detection is that resonant sensors do not place such high demands on the secondary detection mechanism (e.g. piezoresistive or capacitive sensing), since the oscillation amplitudes may be relatively large. Related to this benefit of resonance detection is that the secondary detector is often operated in a frequency range where its performance is improved. A piezoresistor has large 1/f noise at low frequencies, for instance, but should approach the Johnson noise limit at the oscillation frequencies of most micromachined resonant sensors.

A schematic showing the principle of the axial resonant sensor is shown in figure 1, along side a conventional AFM cantilever. The resonant beam is mounted vertically relative to the surface, and is constrained from oscillating near the tip. Ideally this constraint would be a guided end condition, which prevents the tip from oscillating laterally but allows vertical forces to be transmitted unimpeded. In a conventional atomic force microscope, the cantilever is mounted parallel to the surface, and deflections are measured with a laser and photodetector.

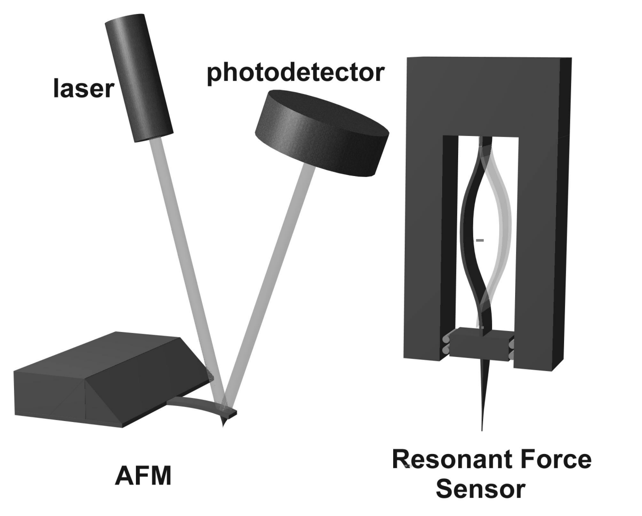

Figure 1. Schematic illustration of AFM force measurement and resonant beam force measurement.

The particular sensor under discussion for this paper exploits the previously mentioned advantages of resonant sensors, but also has another important benefit for atomic force microscopy. Due to its axial stiffness, it is not susceptible to any force instabilities. In most surface force measurements, the static deflection of a cantilever beam is used to measure applied forces. Since a flexible cantilever deflects more than a stiff one for a given force, softer cantilevers are required to increase force resolution. However, if a cantilever experiences a force gradient greater than its spring constant, it becomes unstable.

In the case of common attractive force measurements, such as those of Van der Waals, electrostatic and capillary forces near a surface, the cantilever snaps down onto the surface when this instability occurs. It similarly snaps free when being pulled off the surface. These jumps correspond to the vertical lines in typical AFM force curves[4] illustrated in figure 2. In both these regions of instability there is no force information available. Recently, AFMs have been used to stretch biological macromolecules such as DNA and various proteins[5,6]. A similar problem occurs in these measurements. After a single strong bond gives way, weaker bonds behind it may break uncontrollably until the beam has sufficiently relaxed and is exerting less force on the molecule. These instabilities again arise because soft cantilevers are required for high force resolution AFM. In the resonant beam force transducer described here, the loading is applied axially to the resonator, so the forces put the beam in tension or compression, but do not bend it laterally. This results in an extremely stiff transducer that should not experience a force instability, yet still has good force resolution.

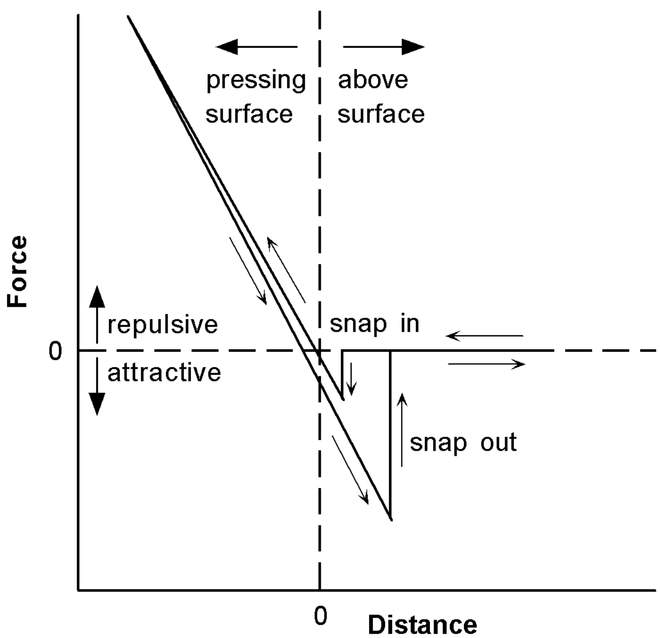

Figure 2. AFM Force curves.

FORCE SENSITIVITY OF RESONANT BEAMS

Detection of loads on a resonant beam sensor is achieved by measuring the shift in the resonant frequency with applied load. An expression for resonant frequency under an applied axial load can be derived analytically by solving the differential equation of the deflection curve under loading. For a pinned-pinned cantilevered beam in its fundamental mode it can be written as[7]:

$$w = \frac{p^2}{l^2}\sqrt{\frac{EI}{rA}\left(1+\frac{Fl^2}{p^2 EI}\right)} \qquad (1)$$

where F is the applied load, l is length of the beam, I is the second moment of inertia of a cross section of area A, E is Young's modulus, and r is the density. For a fixed-fixed beam the constants are somewhat different, but the form is the same, so the design trends do not change and the simpler case is given here.

Taking the derivative of this equation with respect to an applied load gives the force sensitivity of the resonant frequency as

$$\frac{dw}{dF} = \frac{1}{2}\sqrt{\frac{1}{rAEI}}\left(1+\frac{Fl^2}{p^2 EI}\right)^{-\frac{1}{2}} \qquad (2)$$

so when the applied load is small relative to the Euler buckling load (F~0), the sensitivity can be approximated as

$$\frac{dw}{dF} = \frac{1}{2}\sqrt{\frac{1}{rAEI}} \qquad (3)$$

For a beam with a rectangular cross section of width w and thickness t, the sensitivity of the resonant frequency to small applied loads is

$$\frac{dw}{dF} = \frac{1}{wt^2}\sqrt{\frac{3}{rE}} \qquad (4)$$

The resonant shifts could be artificially augmented without any real gain in resolution by multiplying the resonant frequency or tracking higher frequency modes of oscillation. Therefore a normalized version of this equation is necessary for design rules.

$$\frac{dw}{w} = \frac{6l^2}{p^2 wt^3 E}\, dF \qquad (5)$$

This equation illustrates the geometrical parameters which should be emphasized in the design of beam resonators. Typical surface micromachined resonant sensors have a thickness of 2µm, a width of some tens of microns, and length of several hundred microns. We have chosen a similar length, but decreased the thickness and width by a factor of 10 each. For pinned-pinned silicon beams, this should improve dw/w by four orders of magnitude.

EFFECTS OF NOISE ON FREQUENCY RESOLUTION

Perhaps the most common method of measuring resonant frequency shifts in micromachined sensors is to determine the resonant frequency by an accurate measurement of the oscillation period, often averaged over many cycles. The uncertainty in the resonant frequency can be measured and quantified by its root-Allen variance, but with the exception of low frequency drift, the sources of the error in this detection scheme are not 4 T 0.0 /ati/FMMM M Q BT 36 210.36 TD /F0 9 Tf 0.001 Tc 0.017 Tw (Figure 3. Amplitude detection of r plane element. An approximation of this design was achieved by a tether at the end of the resonator which was stiff in the out of plane direction, but compliant to forces applied in the plane. The fundamental mode of oscillation from an Ansys model is shown in figure 4. As long as the stiffness in the plane is considerably less than the axial stiffness of the oscillator the tether should not seriously impact the force transmission. For the dimensions chosen, the tether has a spring constant of about 1N/m in plane (vertically), as compared to the axial spring constant of several hundred Newtons per meter for the resonator in tension or compression.

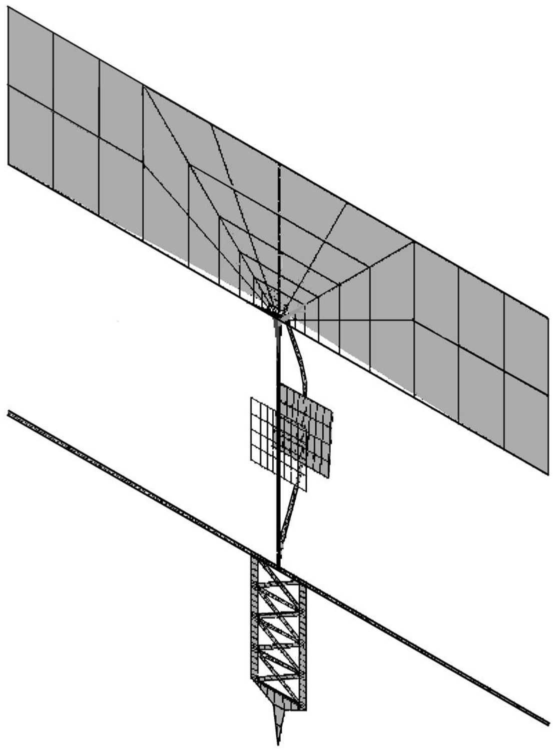

Figure 4. Ansys model showing fundamental mode.

The tip needs clearance from the corners of the chip to access a surface, so a stiff beam of trusses extends out beyond the tether. A paddle was added at the center of the beam, with an electrode running out to it to enable capacitive drive (this would require another plate not shown). However, for initial testing this approach has been set aside in favor of oscillating the entire chip on a piezo pellet. Such a shaking of the chip might be expected to result in a loss of lateral imaging resolution, since the tip would be moving. However the tip extension on the tether is massive enough compared to the torsional stiffness of the tether, that the fundamental oscillation frequency of the tip is well below the drive frequency, and any resulting tip motion is greatly attenuated.

Since all of the geometric design guidelines for the resonator are monotonic, the dimensions chosen were limited by the fabrication technology. Without excessively pushing the lithography capabilities of our system, 2μm line widths were the smallest achievable limit for the width. Since the beam is mounted vertically, it is difficult to get a laser reflected off the surface in an AFM, so a piezoresistive detector was integrated at the base of the oscillator. The thickness of the resonator, which is the most important parameter, is set by our ability to make functional piezoresistors, and the ability to release fragile structures. The thinnest piezoresistors to date were fabricated by Ried et al[10], and are 300nm thick. We have successfully constructed 200nm thick piezoresistors, but they did not achieve the Johnson noise limit, so their performance is not optimal. At 60kHz, our noise was 7 times the Johnson limit, due to lack of a forming gas anneal. Steps will be taken in future runs which should further improve the noise.

The piezoresistor current path is confined to the very base of the cantilever in order to maximize the ΔR/R seen by a wheatstone bridge circuit. The stress in the beam is maximum near the base, and decreases linearly with distance from the base, so running the resistor further out on the beam increases the overall resistance more than the total stress increases, resulting in lower sensitivity to deflections.

FABRICATION

The cantilever procedure is similar to that of Tortonese et al[11], and modified by Chui et al[12], with a slightly different release step in this case. The tether and side support structure were defined in a 2μm thick SOI wafer, and the remaining surface area thinned to 0.2μm. Next, the oscillator was defined and etched down to the buried oxide. 30nm of oxide was thermally grown to passivate the piezoresistor. The oxide thickness must be minimized since at these dimensions it is a significant contributor to the resonator thickness. Following the oxide growth the piezoresistor was implanted with Boron at 1E13, 10keV, and then activated at 1025C for 10 seconds using a rapid thermal anneal. Another important reason to have a thin oxide is that lower implant energies can be used, thus giving a shallower implant. Aluminum was then deposited on the wafer end wet etched to form the electrical contacts, completing the front side fabrication. The cantilevers were the protected with 8μm of PIQ L-100 polyimide, and then released from the back using an STS deep reactive ion etcher. The chips were then scribed on a dicing saw, and the polyimide finally stripped in an O_2 plasma with 5% CF_4.

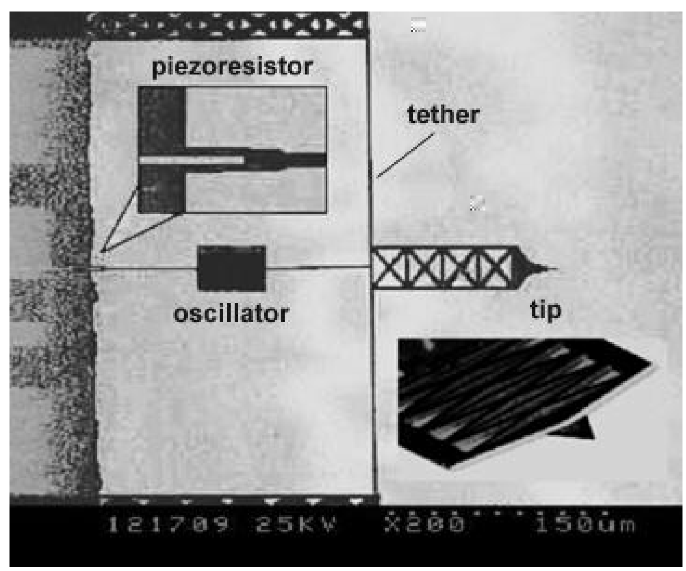

Figure 5. SEM image of force probe. Tether is 2μm thick by 2μm wide. Oscillator is 0.2μm thick, 3μm wide and 200μm long.

RESULTS

In order to test the force resolution of the devices it was necessary to apply a known force load to the tip. To do this, the resonant force probes were placed upside down as a sample in an atomic force microscope, as shown in figure 6. Then, using commercially available cantilevers in a Park Bioprobe AFM, known loads were applied to the resonant force probes. The sample in this case was several hundred times stiffer than the loading cantilever, so it was assumed that all deflection was in the AFM cantilever. In this way lowering a 0.6N/m AFM cantilever by 1µm applied a reliable 0.6µN load.

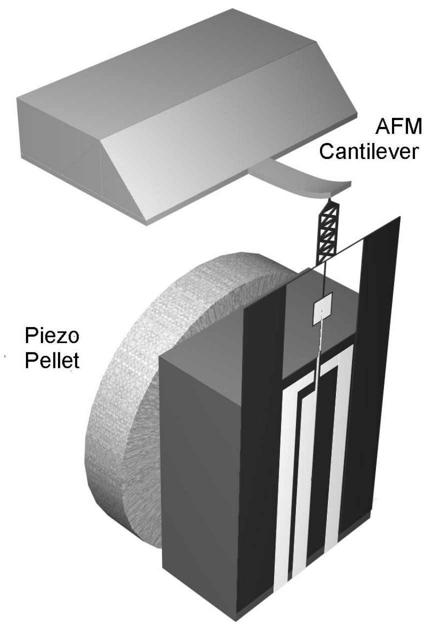

Figure 6. Sketch of experimental set-up.

The amplitude of the resonant peak was measured using a spectrum analyzer averaged 50 times with a 16 Hz bin size and a Hanning window. The amplitude was recorded, and the AFM cantilever lowered another step. A plot of the amplitude vs. loading force is shown in figure 7. The plot starts driven on resonance, at which point the force sensitivity is very poor. As the frequency response shifts, the drive frequency becomes closer to point of maximum slope on the frequency response curve. This occurs near a 250nN load. Finally, at the far left of the plot, there is a second rise in the amplitude. At this point the frequency response has been shifted to the point where another mode of oscillation is influencing the response. The maximum slope of this curve, is 753nm/µN, which corresponds to a frequency shift of about 30kHz/µN.

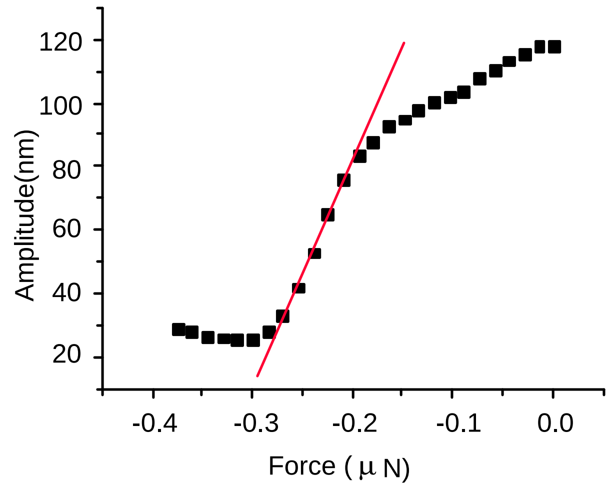

Figure 7. Amplitude shift vs. loading.

The piezoresistor was calibrated by measuring the amplitude of the paddle oscillations with a Polytech vibrometer. Driving the piezo pellet with a 5V sine wave resulted in approximately 100nm oscillations of the paddle, and 60nm oscillations where the maximum sensitivity is achieved. A noise spectrum of the piezoresistor while driven is shown below (Figure 8). Although the fundamental resonant frequency is around 13kHz, due to the unusually high frequency knee of the 1/f noise in these devices measurements were made on a higher frequency mode of oscillation at 59kHz.

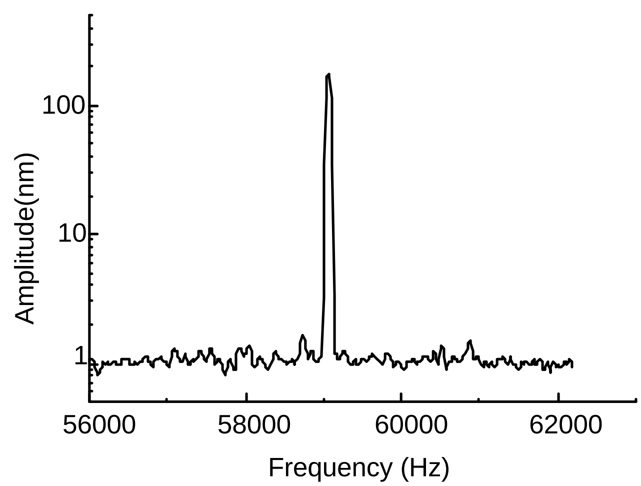

Figure 8. Spectrum of driven oscillator.

By integrating the noise in figure 8 over a 1kHz bandwidth, and using the sensitivity measurements of figure 7, the ultimate force resolution of this device is computed to be 8nN in a 1kHz bandwidth in air. Measurements of the Q of this resonator in air using the vibrometer show it to be only around 15. In a moderate vacuum, this improves to 1200. Since the sensitivity improves as Q, and the piezoresistor noise is unrelated to Q, the performance of this sensor is therefore expected to improve by two orders of magnitude if the resonator could be encapsulated in a vacuum, or if the measurement took place in a vacuum environment.

The oscillation amplitudes are currently limited by ability to drive the chip with a piezo pellet. Future measurements will use an electrostatic drive to oscillate the paddle. Between increased oscillation amplitude and improved piezoresistor noise, we believe another order of magnitude improvement is possible. In this case the force resolution in vacuum would be 10pN in a 1kHz bandwidth. Such a force sensitivity would be equal to the best force resolution capabilities of a commercial AFM using extremely soft cantilevers. Commercial piezoresistive cantilevers can typically detect 0.4 nN forces in the same bandwidth[13]. Since micromachined resonators with Q as large as 600 000 have been constructed [14], there is room for even more improvement in resonant AFM force probes.

CONCLUSIONS

A sensitivity analysis has been presented which is broadly applicable to resonant sensors. Using the theoretical developments in this paper, the performance limits of resonant sensing can be expanded through improved mechanical design.

Based on this analysis a resonant based axial AFM probe has been created which has good force resolution and high stiffness. As a result of its stiffness, the probe is not susceptible to the snap-down instabilities which limit conventional cantilever techniques. Even with high stiffness, this device has the potential rival the force resolution capabilities of commercial cantilever-based force measurement techniques.

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