DESIGN AND TEST OF A NOVEL HIGHER HARMONIC IMAGING AFM PROBE WITH A DEDICATED SECOND CANTILEVER FOR HARMONIC AMPLIFICATION

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Abstract: We report on design, fabrication and initial testing of a new higher harmonic imaging atomic force microscopy (AFM) probe for the characterization of materials at the nanoscale. In contrast to previous designs [3],[4], this probe employs a dedicated second cantilever not only to amplify the desired higher harmonic, but also to suppress the actuation movement. With these measures the amplitudes of the actuation and the higher harmonic are brought closer together on the second cantilever, which is very advantageous for single- channel readout applications.

Keywords: AFM, Higher Harmonics, Nonlinear Dynamics

1. INTRODUCTION

A number of studies have been conducted on the higher harmonic response of an AFM cantilever operated in tapping mode [1],[2],[3] with a first upcoming commercialisation [6]. These higher harmonics can be mechanically preamplified with an appropriate construction [4] or excitation [5] of the system and be read out with the usual optical measurement methods.

However, in these previous designs, the Young's modulus- dependent amplitudes of the higher harmonics were orders of magnitude smaller than the actuation amplitude.

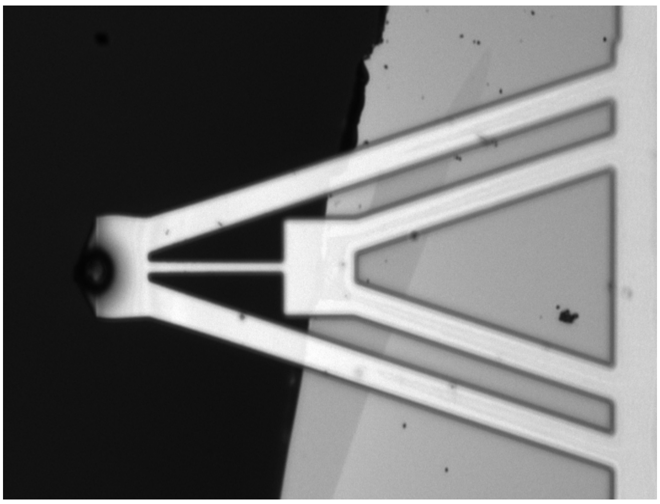


Fig. 1 Micrograph of the probe

We present a new design (fig. 1) with a second dedicated cantilever for the amplification of one desired higher harmonic. The outer cantilever represents a usual triangular AFM cantilever with the probe tip on its end (indenter). The second cascaded triangular cantilever functions as the sensor by harmonically amplifying one higher harmonic (sensor). Kinetic energy between the indentor and the sensor cantilever are exchanged by a thin coupling spring.

With this separation of functions the amplitudes of the base oscillation, carrying topographical information, and of the higher harmonic, carrying material data, can be brought closer together even for relatively soft materials in the 100MPa-10GPa domain. Both items can be detected for example by optical means with a single channel readout.

2. THEORY

Fig. 2 shows the lumped mass model of the probe. The indenter with its spring k_1 represents a usual AFM cantilever. Kinetic energy of its movement is being extracted by a coupling spring k_{12} into a tuned sensor cantilever.

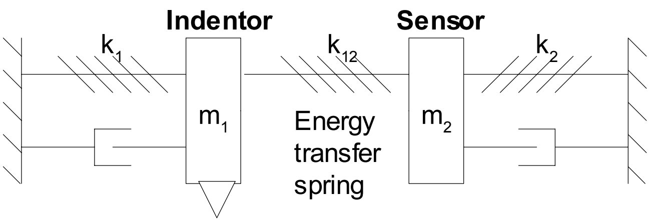


Fig. 2 Lumped mass model of the probe. The indentor mass can be understand as a regular AFM probe, the sensor cantilever as a tuned fork for the amplification of a desired higher harmonic

The governing equation for this system is

$$M\,\ddot{\boldsymbol{x}}+C\,\dot{\boldsymbol{x}}+K\,\boldsymbol{x}=\begin{pmatrix}F_{ext}\\0\end{pmatrix} \tag{1}$$

with

$$M=\begin{pmatrix}m_1 & 0\\ 0 & m_2\end{pmatrix}\ ,\ C=\begin{pmatrix}c_1 & 0\\ 0 & c_2\end{pmatrix}\ ,\ K=\begin{pmatrix}k_1 & k_{12}\\ k_{21} & k_2\end{pmatrix}$$

$$F_{ext}=F_i+A\sin\omega t \tag{2}$$

and m_1, m_2, c_1, c_2, k_1, k_2, $\{k_{12}, k_{21}\}$ being the indenter and sensor masses, damping- and spring constants and the directed constants for the coupling spring. Fig. 3 shows the amplification and suppression characteristics of this model.

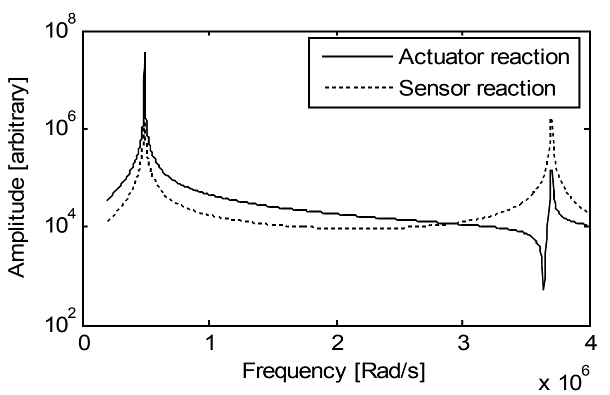


Fig. 3 Response of the actuator (indenter) and sensor to an excitation of the actuator

It can be assumed that the dominating tip-sample forces during the operation of this sensor are Hertzian indentation forces [3]; therefore

$$F_i=\frac{4}{3}E\sqrt{R}\{x_1-x_0\}^{3/2}\,\forall\,x_1>x_0 \tag{3}$$

with the reduced Young's modulus

$$\frac{1}{E}=\frac{1-\nu_t^2}{E_t}+\frac{1-\nu_s^2}{E_s} \tag{4}$$

and R the tip radius, x_0 the neutral tip-sample distance. When operated at a subharmonic of the sensor cantilever's resonance frequency, the sensor cantilever will amplify this higher harmonic of the actuation frequency. Fig. 4 shows the theoretical response of the sensor cantilever. A clear Young's Modulus- dependency of the higher harmonic and the similar amplitudes of the actuation frequency and higher harmonic on the sensor cantilever can be seen.

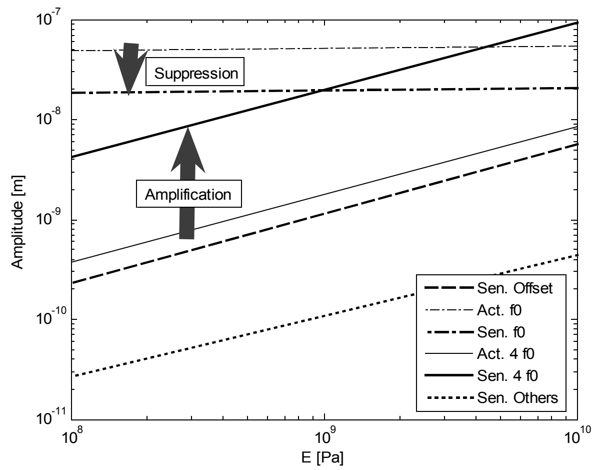


Fig. 4 E-Dependent response of the sensor

3. FABRICATION

The fabrication process for these probes is compatible to current AFM probe fabrication methods (fig. 5). Starting with an Silicon- On-

Insulator (SOI)- wafer, the tips can be etched with a single SF_6- based RIE etch [8]. With this robust method, strong tips with angles of 60-80° and radii of 5nm can be fabricated without subsequent oxidation. Afterwards the tips can be passified with a plasma enhanced chemical vapor deposited (PECVD) SiO_2 layer. In a next step, the overall contour of the sensor can be etched into the SiO_2 layer with a CHF_3 based RIE and into the silicon with a deep reactive ion etch (DRIE), finishing the front side processing of the wafer. After passivation of the front side with PECVD- SiO_2 and SiN_x, the backside can be etched with a KOH solution or an SF_6- based RIE- etch. Finally, the passivation layers can be removed with a CF_4-based RIE- etch to remove the SiN_x and HF to remove all SiO_2- layers on top of the device and on the insulator layer of the SOI wafer.

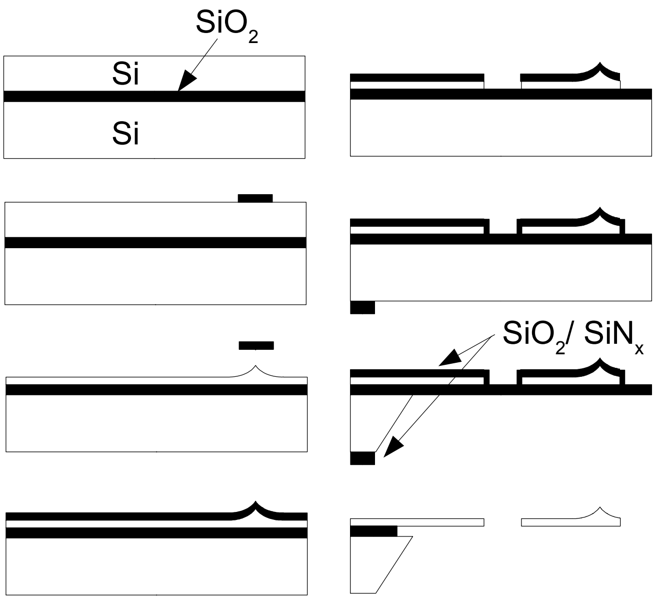


Fig. 5 Fabrication diagram for the probe

response. As the actuation force is not applied on the tip but the base, the resonant curve appears different than the one shown in fig. 3: The second resonant frequency is suppressed at base actuation as the indenter and sensor move in a 180° phase shift at this frequency. However, the results can be used to determine the two characteristic resonant frequencies and to estimate the quality factors of the probe for damping.

The results from the measurement with the vibrometer have been fed back into the numerical model together with estimates of the spring constants in order to predict the sensor's behavior as an AFM probe. The dynamic behavior of the sensor suggests an amplification of 10 for the higher harmonic and a suppression of 5 for the actuation movement.

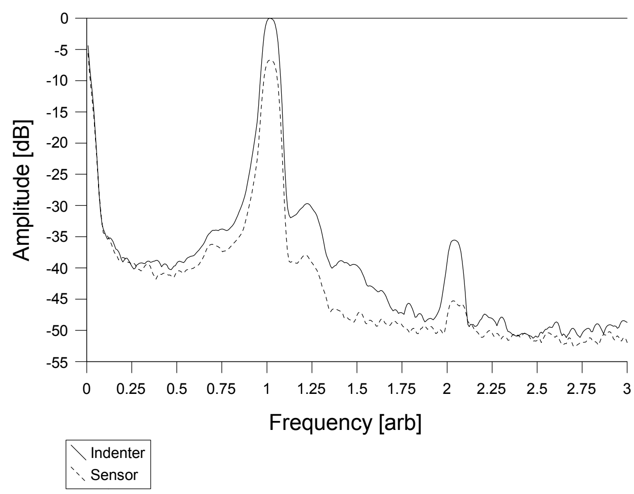


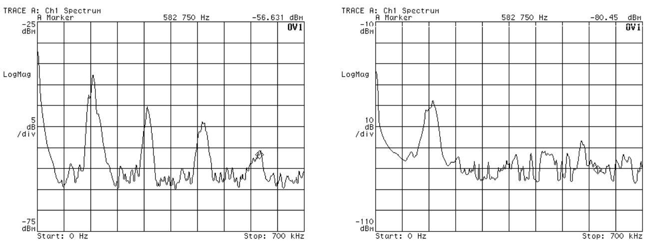
Fig. 6 Experimental results: Frequency dependent reaction of the indenter and sensor to base actuation in a laser doppler vibrometer

4. EXPERIMENTS

The dynamic behavior of the sensor has been measured by experiments with an optical laser doppler vibrometer (Polytec LDV, fig. 6). The probe has been base- actuated on a piezoelectric crystal to measure its frequency dependent

A first test has been conducted with a sensor head in a commercial AFM (Veeco Nanoscope 3). In this test the laser has been pointed onto the outer indenter mass- for fabrication reasons it was not possible to point on the sensor mass at this stage. The cantilever has been driven out of resonance at 1/4 of the sensor resonance frequency of 582KHz. The feedback signal of the

AFM carrying the information about the current cantilever's deflection has been probed and analyzed in a vector spectrum analyzer. A sample with thin patterned and developed/hardbaked photoresist (PR, SPR955CM0.9) on a piece of silicon has been used as a specimen for this experiment. The response of the indenter mass tapping on Si (a) and PR (b) is shown in fig 7.



(a) (b)

Fig. 7 Experimental results: Reaction of the indenter to (a) Si- Tapping; (b) PR- Tapping. Sensor movement is expected to suppress actuation movement (145kHz) by a factor of 5 and to amplify the movement in the sensor resonant frequency (582kHz) sensor movement by a factor of 10 as shown in fig 3.

5. CONCLUSIONS

A probe for higher harmonic imaging that is compatible to current AFM systems and AFM probe fabrication methods has been developed and fabricated. The aim to bring the base amplitude and the amplitude of one desired higher harmonic closer together has been validated by initial tests with both a vibrometer and a commercial AFM. We were able to amplify the 3rd higher harmonic by a factor of 10 and to suppress the base amplitude by a factor of 5.

6. ACKNOWLEDGEMENTS

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