

Individually addressable Cantilever Arrays for Parallel Atomic Force Microscope

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ABSTRACT

Cantilever arrays probes with self-sensing and self-actuating cantilevers and integrated sharp silicon tips for parallel surface scanning were realized. Each cantilever is equipped with a piezoresistive deflection sensor and a thermal bimorph actuator enabling an individual tip-sample distance control. The probe concept and fabrication is explained as well as the probe characteristics.

1. INTRODUCTION

Since the invention of atomic force microscopy by Binnig et al. in 1986 [1] surface imaging at the nanometer scale by means of microcantilever probes has become a routine surface analysis method. The development of mass fabricated silicon cantilevers with integrated sharp tip and adequate force constants by Wolter et al. [2] enabled the establishment of non-contact or intermediate contact measurement schemes with drastically reduced tip wear and fostered the further establishment of atomic force microscopy.

Although, integration of the beam deflection detector into the cantilever beam in form of piezoresistive stress gauges was realized by Tortonesi et al. already in 1993 [3], the fundamental obstacle of slowness has not been addressed for years.

The idea of solving the slowness problem by parallel scanning of multi-cantilever arrays has been demonstrated by Minne et al. [4]. By use of piezoresistive deflection sensors and piezoelectric actuators in each cantilever the parallel operation of up to 50 cantilevers could be shown. Despite of the successful demonstration the major obstacles of complex probe fabrication and internal electrical cross-talk remained and prevented an establishment of the parallelization.

2. CONCEPT

The presented work follows the approach of parallel surface scanning with multi-cantilever arrays but replaces the complex piezoelectric actuator by a thermal bimorph actuator as proposed by Ivanow et al. [5]. One major advantage of this actuator scheme is its rather simple integration into the fabrication

procedure for cantilever probes with piezoresistive beam deflection according to the fabrication scheme of Jumpertz et al. [6]. The formation of an adequate heater element can be performed together with the realization of the piezoresistor wiring.

A second major advantage arises from the actuation mechanism itself. As the deflection is actuated by temperature modulations in the cantilever which are induced by via an electric heater element, the deflection of the cantilever is proportional to the square of the driving voltage (or current). Therefore, for a sinusoidal voltage (or current) signal, the resulting cantilever deflection will be an oscillation at twice the frequency of electrical actuation:

$$P_{heat} = \frac{V_{ac}^2}{R_{heater}} \left(1 - \frac{1}{2} \cos(2\omega_{drive} t) \right)$$

For the suppression of electrical cross-talk between driving and sensing signals this "frequency doubling" is invaluable. Any electrical cross-talk of the driving signal $V_{ac} \cdot \sin(\omega_{drive} \cdot t)$ into the sensing path of the electronics can be easily filtered out by a high pass or band pass filter.

In practical application, an ac-signal with a frequency of half of the cantilever resonance is used to drive the cantilever oscillation whereas a dc-signal is used to follow the surface topography while scanning.

3. PROBE DESIGN

In the described implementation the cantilevers are fabricated from single crystalline silicon with integrated monolithic tip. The bimorph is completed by an aluminum layer at the backside of the cantilever (opposite to the integrated tip). The heater elements of the actuator as well as the piezoresistors of the deflection sensors are formed by local doping inversion. Electrical contact is realized by aluminum lines at the probes chip and wire bonding to a polymer carrier.

3.1. Tip

The cantilever array probe is manufactured from the single crystalline silicon wafer by well-established etching techniques of a commercial AFM probe fabrication [7]. A sufficient tip height is necessary to reduce squeezed air-film damping between cantilever

and sample surface whereas huge tips infringe subsequent processing. Therefore, a tip height of 5-10 μm was chosen as compromise but in latest implementations an increased tip height of well above 10 μm could also be demonstrated successfully.

3.2. Cantilever

For application in non-contact atomic force microscopy the force constant of the cantilevers has to be in the range of a few tens of N/m. The first eigenmode resonance frequency of the cantilevers should be as large as possible in order to enable fast surface scanning. For given force constant this can be achieved by decrease of cantilever size. On the other hand, the minimum size of cantilever is limited by the necessary integration of actuator and sensor elements with accessible fabrication technologies. Therefore, the width of cantilever has to be at least 50 μm . Moreover, the actuation range is linked to the length of the cantilevers. In order to compensate tolerances in tip height, initial cantilever bending and potential topography of the sample surface a minimum actuation range of 2 μm is required.

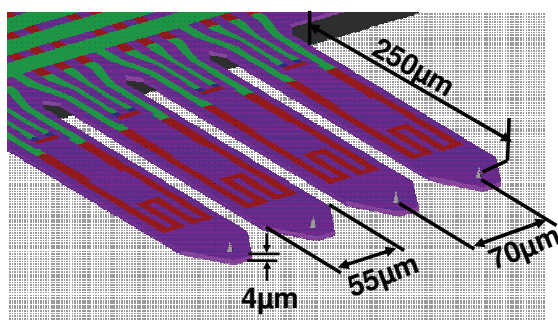


Figure 1 Cantilever layout

According to these requirements a length of 250 μm , width of 70 μm and thickness of 4 μm has been chosen as final design. The resulting nominal force constant is 12N/m, the calculated resonance frequency of the first eigenmode 90kHz.

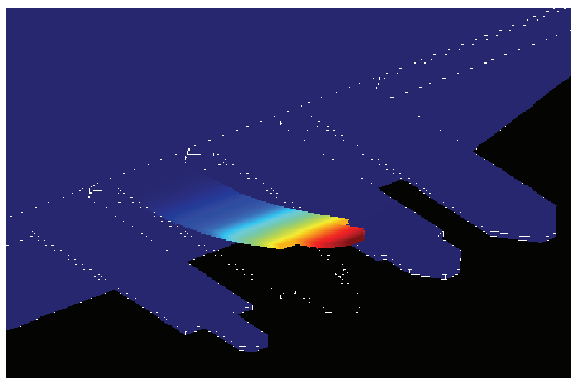


Figure 2 FEM simulation of cantilevers with varied shape

For suppressing of mechanical cross-talk between neighbor cantilevers their shape is varied in groups of four cantilevers. Each cantilever has a different width at its free end portion. Thus, the frequency of neighbor cantilevers differs about more than 3kHz without significant changes in cantilever stiffness and actuation efficiency. Moreover, the tip position remains identical as the length of cantilever is not modified.

3.3. Actuator

The cantilevers are realized as composite of single crystalline silicon and aluminum forming a bimorph of materials with rather different thermal expansion coefficients. The realized bimorph cantilevers consist of an about 3 μm thick silicon layer and a 1 μm thick aluminum layer. The heater elements are realized as meander shaped resistors within silicon at the free end of the cantilever. The resistors are semi-isolated from the surrounding silicon by a pn-junction which is reversely biased under operation conditions.

3.4. Sensors

The beam deflection sensors are formed by two parallel piezoresistors integrated into the cantilever close to the fixture point. The sensor location coincides with the area of maximum surface stress and minimum temperature increase. The piezoresistors are realized by local doping inversion with shallow junctions for optimized sensitivity. The change of resistance due to strained piezomaterial is determined as measure for the cantilever bending. For that, a defined current is supplied to the sensor whereas the voltage is measured.

4. FABRICATION TECHNIQUES

The fabrication of cantilever array probes is similar to previously described approaches of Wolter et al. [2] for the probes and Jumpertz et al. for sensors integration [6]. The main steps are:

1. Realization of tip and support chip by anisotropic wet chemical etching
2. Local Boron implantation for formation of heater elements and piezoresistors
3. Deposition and patterning of isolation and metal layers
4. Cantilever release by reactive ion etching
5. Deposition of backside metallization by evaporation
6. Mounting of probe onto the PCB carrier and wire bonding

Crucial for the final result is an adequate protection of the early formed tip during the subsequent processing because a final refinement the tip shape is almost impossible due to the presence of a variety of materials and susceptible patterns as the shallow junction piezoresistors.

5. RESULTS

Several cantilever array sizes were realized starting with single cantilever probes to arrays of 4, 16, 32 and 128 cantilevers. Nevertheless, due to restrictions of packaging technology and limits of currently available electronics the recent focus was on cantilever arrays of 32 cantilevers.

5.1. Cantilever array probes

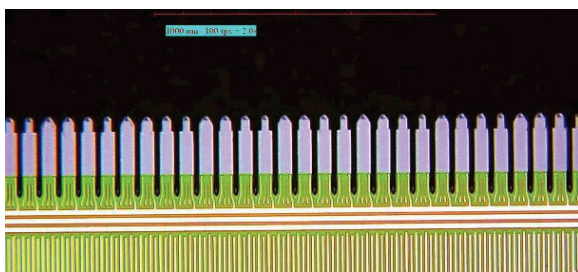


Figure 3 Microscope image of fabricated individually addressable array of 32 cantilevers with sharp tips

The cantilever array probes have been realized successfully. The tip radii are typically better than 20nm for both, the version with tip height of 12μm and the one with 6μm tall tips. The thickness of the initial silicon cantilever has been varied from 2 to 5μm supplemented by a 1μm thick aluminum layer.

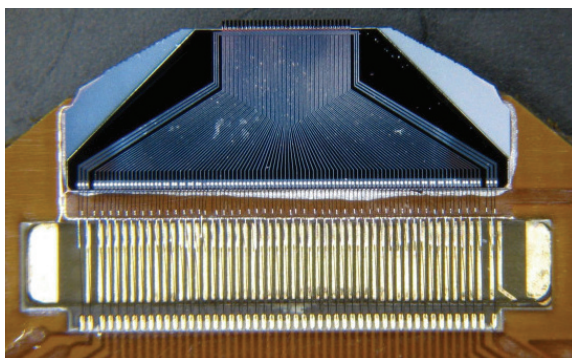


Figure 4 Array of 32 cantilevers mounted onto PCB carrier with 2-lever staggered bond pads

5.2. Electrical characteristics

Under operation conditions the pn-junctions between piezoresistors and substrate, on the one hand, as well as between the heaters and substrate, on the other hand, must be reversely biased in order to avoid current leakage via the substrate. Therefore, the substrate is biased with a positive voltage of 10V which is well above any other electrical potential within the chip. By that, implanted resistors are effectively isolated from the substrate.

5.2.1. Piezoresistors

The mean measured resistance of the piezoresistive stress gauges is 12kΩ with a small variation of 0,5kΩ. For determination of deflection sensor performance, the cantilevers were accelerated in resonance by means of an external piezoceramics whereas sensor signal and real deflection amplitudes are measured. During these experiments the piezoresistors were supplied with a constant current of 200μA while the variation of voltage is recorded as measure for the beam deflection. The independent measurement of real beam deflection has been carried out by a laser vibrometer system. The determined sensitivity of the integrated piezoresistive sensors is about 0.075Ω/nm which corresponds to an overall piezoresistive K-factor of 74.

5.2.2. Thermal bimorph actuators

The measured resistance of the heating elements is 4.1kΩ. The variation of resistance is as low as for the piezoresistors. Sufficient actuation efficiency has been achieved and actuation ranges of up to several microns were measured for moderate voltage signals of up to 10V. The actuation efficiency is frequency dependant with maximum efficiency for dc-signals and significantly reduced efficiency for frequencies in the kHz-regime but rising again in the resonance case. The measured dc-actuation efficiency is 200nm/mW for cantilever of 4μm thickness and drops to less than 2nm/mW at 60kHz. In resonance, the efficiency is about 100nm/mW. As expected, the actuation efficiency increases drastically with reduced cantilever thickness. For 2μm thin cantilevers the actuation efficiency was about 400nm/mW.

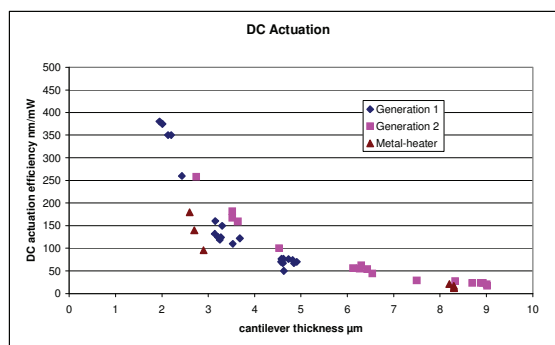


Figure 5 Measured DC actuation efficiencies for varied cantilever thickness

5.2.3. Electrical cross-talk

One of the fundamental problems of self-actuating and self-sensing cantilevers is caused by electrical cross-talk between the driving signal supplied to the probe and the measurement signal of the piezoresistor. In the realized probes the dominating effect for cross-talk is capacitive coupling via the probe substrate. The introduction of additional shielding patterns has dramatically reduced this effect but, in particular for the large arrays it could not be avoided completely.

If in the feed-back loop for controlling the amplitude of oscillation the deflection signal is converted by a simple RMS-detector, the cross-coupled actuation signal is visible as constant offset and, thus, reduces the system sensitivity. Therefore, the remaining electrical cross-talk is filtered by an adequate band-pass filter within the amplifier stage of the electronics.

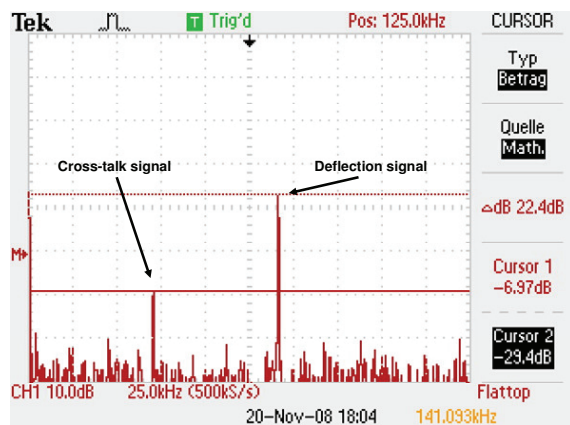


Figure 6 Measured signal of piezoresistive deflection sensor under operation conditions

5.2.4. Mechanical cross-talk

A fundamental aim in the development of cantilever array probes for parallel surface scanning is the realization of smallest possible distance between neighbor cantilevers in order to enable overlapping images with a minimum scan area size. As consequence of cantilever pitches of 100 μ m and 70 μ m the mechanical motion of an individual cantilever is transmitted to the neighbor cantilever if the cantilevers have identical resonance frequencies. This characteristic indicates a mechanical coupling via the support chip. Even additional grooves between the fixture points of neighbor cantilevers did not improve the situation significantly. Therefore, the cantilevers were designed with varied shape for intentionally differing resonance frequencies of neighbor cantilevers. As modification, the width of cantilever was locally reduced at the free end of the beam leading to a noticeable variation of cantilever mass. Due to the nature of shape modification the force constant of the cantilevers is kept almost constant as well as actuation efficiency and deflection sensitivity. The variation of probe shape has been carried out in groups of four cantilevers with intentionally differing resonance frequencies. The group is repeated 8 times for the full array of 32 cantilevers. In this arrangement the distance between identically shaped cantilevers is large enough to avoid any noticeable mechanical cross-talk.

In the realized cantilever probes a difference of more than 3kHz in the resonance frequency of neighbor cantilevers was achieved. With this layout a mechanical cross-talk could not be measured - neither for neighbor cantilevers nor for cantilevers of identical shape (forth cantilever).

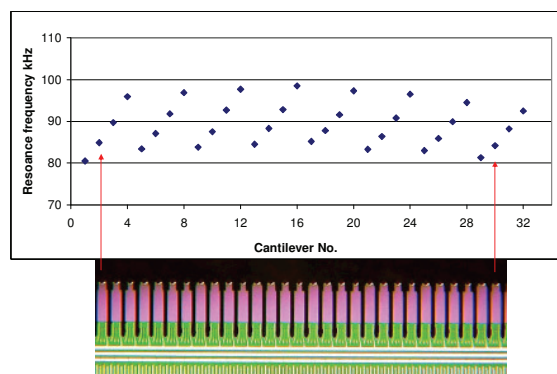


Figure 7 Resonance frequencies of all cantilevers within an array of 32 cantilevers

6. CONCLUSIONS

Cantilever array probes of with up to 32 cantilevers for parallel surface imaging has been successfully realized. Sharp silicon tips are integrated into the cantilevers for high lateral resolution. Each cantilever is self-sensing and self-actuating enabling individual tip-sample control. The height sensitivity is comparable to that of conventional AFM probes. The integrated actuators are used for cantilever oscillation excitation and for individual adjustment of tip-surface distance. Electrical and mechanical cross-talk has been reduced to a minimum.

7. ACKNOWLEDGEMENT

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