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Realization of cantilever arrays for parallel proximity imaging

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Abstract. This paper reports on the fabrication and characterisation of self-actuating, and self-sensing cantilever arrays for large-scale parallel surface scanning. Each cantilever is integrated with a sharp silicon tip, a thermal-driven bimorph actuator, and a piezoresistive deflection sensor. Thus, the tip to the sample distance can be controlled individually for each cantilever. A radius of the tips below 10 nm is obtained, which enables nanometre in-plane surface imaging by Angstrom resolution in vertical direction. The fabricated cantilever probe arrays are also applicable for large-area manipulation, sub-10 nm metrology, bottom-up synthesis, high-speed gas analysis, for different bio-applications like recognition of DNA, RNA, or various biomarkers of a single disease, etc.

1. Introduction
During the last decade the surface imaging by atomic force microscopy (AFM) has become a routine surface analysis method providing Angstrom resolution [1]. The AFM systems are based on micro-cantilever probes with sharp tips brought to the vicinity of the sample surface as the interaction between them is localized in a nano-sized region. Unfortunately, the applications of the cantilever systems for large-area surface proximity scanning are limited by the low scanning speed [2]. Complete scanning of larger samples can be realized by a small fast cantilevers hold by a small light stage [3-4] or by introducing of large 2-dimensional (2-D) array of parallel working, independently addressed cantilevers [5-6]. The latter approach offers a new quantitative way for large-area simultaneous scanning or analysis, manipulation and bottom-up manufacturing. It is clear, that the classical AFM actuation and read-out are slightly applicable for such an array. The piezoelectric actuation of the array is in contradiction with the independent addressing of the cantilevers. In addition, the standard read-out based on a laser-reflection is slightly feasible for very large arrays.

The development and the application of large parallel 2-D cantilever arrays for large area surface proximity scanning is the purpose of the European Project "PRONANO- Technology for the Production of Massively Parallel Intelligent Cantilever Probe Platforms for Nanoscale Analysis and Synthesis" Recently, the fabrication of such NEMS-chip (Nano Electro Mechanical System), incorporating 4x32=128 fully addressable proximal probes has been reported [7-8] as a part of the PRONANO activities. Later, new generation of 8x64 cantilever array with electrical contacting from the back side of the chip and flip-chip packaging has been demonstrated [9]. PRONANO appeared as an alternative to the famous IBM's project Millipede, headed by P. Vettiger and G. Binnig (the latter is a Nobel price winner for the discovery of the scanning tunnelling microscope), the aim of which is the development of a 2-dimentional arrays for ultra-dense record of information [5, 10-11].
Main challenges at PRONANO are the development of new technology for realization of large, 2-dimensional, individually addressed, self-actuated, piezoresistive nanosystems for proximity scanning, the application of new solutions for their packaging, development of specialized dedicated driving and measurements electronics, real-time transfer and processing of information (~ TBs/sec) and integration of all components in a complete system for nanopositioning and large-area surface proximity scanning. In this work some of our recent results on fabrication of large 1-D and 2-D arrays of cantilevers with integrated sharp AFM tips, thermally driven actuators and piezoresistive deflection sensors are presented. The development and the fabrication of the AFM arrays is considered in connection with the physical principles and the requirements of the AFM scanning, self-actuation of the probes, piezoresistive sensing and of the imaging by large 2-dimensional arrays.

2. Fabrication of the cantilever arrays

The fabrication of the piezoresistive AFM probes is illustrated in figure 1. The source material are \(<100>\) phosphorous doped Si wafers with small total thickness variation \(< 1\mu m\) (1). First, the wafers are oxidized and the AFM tips are formed (2) by the under-etch technique [12] using and a double photoresist + silicon dioxide surface protection and an anisotropic plasma reactive ion etching (RIE) or by oxide mask and an anisotropic chemical etching in potassium hydroxide (KOH). It should be noted, that the formation of the AFM tips in the beginning requires their further protection during rest of the fabrication by a mask of thick photo-resist.

The wafers are oxidized again. With the next fabrication steps the electrical structures on the chip are formed by three consequent implantations with resist mask: a) highly doped phosphorous doped areas for electrical shielding and contact to the substrate (3), b) highly doped boron implantation for low-resistive on-chip connections and contacts areas (4) and c) boron implantation of the piezoresistor deflection sensors (5). Then, an appropriate annealing activates the implanted elements. As a next step, the wafers are passivated by plasma enhanced chemical vapor deposited (PECVD) layer of SiNx (6). Contacts to the implanted structures are lithographically defined and chemically (wet) etched by buffered hydrofluoric acid (HF) (7). In the same time the passivation is removed near the tips. Again, lithographically patterned end structured aluminum is employed to form planar wiring interconnections, creating contacts to the piezoresistors and forming metallic bimorph micro-heaters for a thermal actuation of the cantilevers (8). The cantilever membrane is realized by bulk micromachining of Si, obtained by anisotropic KOH etch step. To form the cantilever beam and to cut the single sensor chip, a RIE step is employed with a thick resist mask. Finally, the resist mask is removed using microwave plasma stripping and the cantilever arrays are separated mechanically (9).

\[
\begin{align*}
1 & \quad \text{<100> n-Si} \\
2 & \quad \text{n+ Si} \\
3 & \quad \text{p++Si} \\
4 & \quad \text{piezo} \\
5 & \quad \text{SiO}_2 \\
6 & \quad \text{SiN}_x \\
7 & \quad \text{Resist} \\
8 & \quad \text{Al} \\
\end{align*}
\]

Figure 1. Fabrication sequence
3. Results and discussion

Scanning electron microscopy (SEM) pictures of the fabricated 1-D (1x32) and a 2-D (2x32) arrays are shown in figure 2 a) and b), respectively. The cantilevers are 240 µm long, 90 µm bright and 3-5 µm thick. The probes transversal pitch is 150 µm. The largest 2-D array realized within PRONANO has 8x64 cantilevers, following the same basic design as the chips presented in figure 2.

Figure 2. Cantilever arrays for parallel scanning and analysis a) 1x32 array, b) 2x32 array.

A fundamental requirement for cantilever arrays is independent actuation and deflection readout of each cantilever, which is needed for parallel proximity scanning of large areas by all cantilevers. This can be realized by integration of each cantilever with its own actuator and deflection sensor. Such integration provides an elegant and compact solution for high speed non-contact AFM as an alternative to the commercial cumbersome AFMs with optically detected devices with piezotube z actuator [13-14]. Piezoresistors, applied as stress gauges are widely used as cantilever deflection sensors. Especially important by the cantilever design is the piezoresistors to be situated at the cantilever areas of highest stress by bending (figure 3). This place is at the base of the cantilever and can be precisely determined by simulating the cantilever behavior by finite elements methods (e.g. the computer program ANSIS) [14]. In addition, the independent driving of each cantilever requires fabrication of microactuators, compatible with CMOS processing. The microactuators described in this article are based on the bimorph effect and are realized by the thin film technology. They are heaters, microstructured from an Al film in a meander-shape (figure 3). Again, the ANSIS simulations show the best situation for them at the front side of the cantilever [14]. The actuators are driven electrically, as the electrical to thermal conversion there causes bending of the cantilever, since the aluminum has significantly higher thermal expansion coefficient then the silicon. In standard feedback operation, the integration of the thermal actuator with the cantilever is used for both exiting the cantilever at resonance as well as applying the feedback actuation signal directly to the cantilever in order to control the position of the AFM tip with respect to the surface. This causes the resonance frequency to be much increased compared to the normally used piezoelectric-actuator stage in commercial systems. The high resonance frequency of the cantilever, feedback loop with smaller time constants and bigger gain determine the surface scan speed by which the tip can accurately follow the topography features. In our setup the cantilever is thermal driven at its resonance frequency $f_{res}$ by an AC current with frequency $f_{res}/2$, while $z$ axis actuation in the $z$ axis is provided by applying a DC current. The magnitude of the latter determines the deflection of the cantilever, controlled by the proportional integral differential (PID) feedback loop. A fundamental requirement for cantilever arrays is independent actuation and deflection readout of each cantilever, which is needed for parallel surface scanning of all cantilevers. The phase signal shift of the driving voltage and voltage drop response of the piezoresistive sensor is monotonic, ensuring a stable and reproducible control over the full $z$ range of probe sample interaction.
The measured surface, obtained by proximity scanning is a conjunction between the real surface topography and the shape of the AFM tip. Hence, a sharper tip is required for better image. Figures 3 and 4 show cantilever arrays, which tips are microstructures by wet (chemical) and by dry (plasma) etching, respectively. The obtained tip's radius in the first case is below 100 nm, while by the second processing tips sharper than 10 nm are realized. On the other hand the chemical etching is easier to perform and results in a better prediction of the tip's shape since the KOH etching is defined by the <111> crystal planes of the silicon.

**Figure 3.** Array of thermal actuated, piezoresistive cantilevers with integrated tips.

**Figure 4.** Arrays with integrated sharp AFM tips obtained by plasma under-etching.

The surface by an array of scanning probes requires that every cantilever can independently approach and follow the topography of the sample. For 1-D array (a row of cantilevers) the chip can be tilted for free access of the tips to the surface. For the case of 2-D array this is obviously not possible. To have the ability to scan surfaces with “hills” and “valley” the cantilevers of such 2-D array have to be off-plane of the wafer, i.e. to be pre-deflected (bent) towards the sample surface [8]. Such out-of-plane deflection has been recently achieved by passivation of the cantilevers with a film of LPCVD Si3N4 [10]. Such a layer of silicon nitride possesses string tensile stress (~750MPa) which causes the released beams to bend. The homogeneity of the bending is excellent, as can be seen from the SEM picture in figure 5.

The non-contact AFM operation the cantilevers is driven by DC and AC current. When a large 2D array is brought in proximity to the surface and scanned over it, all cantilevers have to bend up and down in order to follow the surface topography. That can be realized by pre-heating (quasi-static deflection) of beams before scanning by applying of certain DC power to the heater. In such a case by individual control of the actuator DC current each cantilever can be either heated additionally in order to approach the surface or cooled down in order to retract from it. That is realized using a topography feedback from piezoresistive sensors through the PID controllers. The “DC” time constant is effectively the maximum imaging bandwidth of the cantilever defined as the maximal speed with which the cantilever and its holder to reach a thermal equilibrium with the ambient. This time is usually defined as the inverse of the frequency at which the peak-to-peak resistance decreases to 3 dB of the maximum. The “DC” time constant for 240 µm long cantilever with uniformly distributed Al-heater is estimated to be below 0.5 ms, which corresponds roughly to a bandwidth of 2 kHz. The “AC” time constant corresponds to the frequency and mode used in the non-contact mode. Usually choosing first eigenmode the AC frequency is about several tens kHz and going up to about 1 MHz for the third eigenmode.

The technique of the strong off-plane bent cantilevers allows a simple way to fabricate AFM arrays. The tips can be just situated in the plane of the chip (figure 6) and formed during the last fabrication step (9) from figure 1- release of the cantilevers. In such a case the processing step (3) is
skipped and all fabrication is made much simpler using standard a thin photo-resist, since there are no
tips to protect. After the release of the cantilever it bends away of the wafer plane and the upper end of
the tip forms a 3-dimentional AFM apex. Its radius is determined mainly by the narrower line, which
can be created lithographically. In our case, although additionally sharpen by a short isotropic plasma
etching before releasing of the cantilever, the tips curvature is between 200 and 250 nm. Despite,
when no superior X-Y scanning resolution is required, such arrays are sometimes preferable due to the
significantly simplified and faster fabrication. Moreover, shear-force surface scanning is possible
when the cantilevers are strongly off-plane bend and the tips are directed orthogonal to the plane of the
chip and to the surface of the sample [15]. In this configuration the oscillation of the tip is parallel to
the surface and some parasitic effects like the air duping or sticking to the sample due to the surface
dew are avoided.

![Figure 5.](image1.png)  ![Figure 6.](image2.png)

**Figure 5.** Arrays of of-plane bent cantilevers. **Figure 6.** Array with in-plane tips and strongly
off-plane bent cantilevers.

Figure 7 shows a typical resonance curve of a thermally driven cantilever. The detection is from the
piezoresistive sensors. The main eigene modes up to the third resonance are clearly resolved. The
 corresponding resonance frequencies $f_{res}$, the peak's width $\Delta f_{res}$ and Q-factor of the resonances are
presented in Table 1. All measurements are performed by room conditions. The clear readability of the
resonance spectrum determines such cantilevers applicable for parallel proximity imaging.

![Figure 7.](image3.png)

**Figure 7.** Resonance spectrum of a thermal actuated
piezoresistive cantilever.
Table 1. Resonance frequencies $f_{res}$, width $\Delta f_{res}$ and Q-factor of the peaks for figure 7.

<table>
<thead>
<tr>
<th>$f_{res}$ [kHz]</th>
<th>$\Delta f_{res}$ [Hz]</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>67.72</td>
<td>428.92</td>
<td>157.9</td>
</tr>
<tr>
<td>135.40</td>
<td>775.44</td>
<td>174.6</td>
</tr>
<tr>
<td>362.28</td>
<td>1170.42</td>
<td>309.5</td>
</tr>
<tr>
<td>724.163</td>
<td>2231.07</td>
<td>324.8</td>
</tr>
</tbody>
</table>

4. Conclusion

This work describes the physical principles of the parallel surface proximity scanning. The requirements of the large-area fast AFM imaging by 2-dimensional cantilever arrays are shown and are related with the basics of the classical AFM scanning, self-actuation of the probes, piezoresistive deflection sensing. To realize that task, large 1-D and 2-D arrays of cantilevers with integrated sharp AFM tips, thermally driven actuators and piezoresistive deflection sensors are designed and successfully fabricated. The biggest microstructured AFM array up to the moment has 8x64 cantilevers. The successful realization of parallel fast AFM systems is crucial for development of future commercial nanotechnology products with an unprecedented throughput, for highly effective tools for analysis, manipulation and for synthesis (both top-down and bottom-up). Besides, an array of controllable proximal probes can also be used for the determination of large numbers of analytes such as various biomarkers of a single disease, for high-speed analysis, and the detection of explosive, combustible, and toxic components. Multi-parameter analysis of liquid or gas can also be done (e.g. simultaneous determination of temperature, pressure, humidity, concentration) if the cantilevers of an array are differently functionalized. The techniques presented in this paper are a part of a technology platform that can be used for the next generation of highly sensitive controllable proximal probes.

Acknowledgements

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