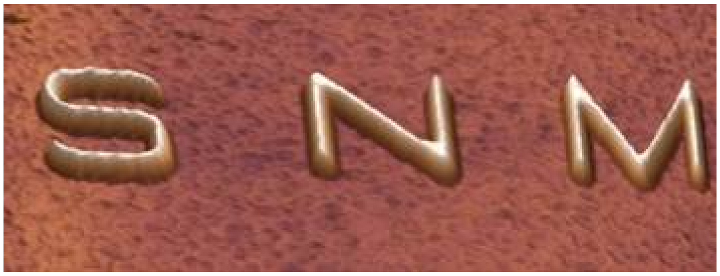

Collaborative project*

Project acronym: SNM

Project full title: "**Single Nanometer Manufacturing for beyond CMOS devices**"

Grant agreement no: 318804

Deliverable: D2.7 (“Parallel operation of cantilever arrays”)

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3	IMEC	**IMEC**	RES	Belgium
4	Mikrosistemi Ltd	**µS**	SME; End-User	Bulgaria
5	Universität Bayreuth	**UBT**	HER	Germany
6	Technische Universiteit Delft	**TUD**	HER	Netherlands
7	Spanish National Research Council	**CSIC**	RES	Spain
8	IBM Research GmbH	**IBM**	IND; End-user	Switzerland
9	École polytechnique fédérale de Lausanne	**EPFL**	HER	Switzerland
10	SwissLitho AG	**SL**	SME; End-User	Switzerland
11	Oxford Instruments Nanotechnology Tools Ltd	**OINT**	IND; End-user	UK
12	Imperial College London	**IMPERIAL**	HER	UK
13	The Open University	**OU**	HER	UK
14	Oxford Scientific Consultants Ltd	**OSC**	SME	UK
15	VSL Dutch Metrology Institute	**VSL**	IND	Netherlands
16	University of Liverpool	**ULIV**	HER	UK

SNM
Work Package WP2
Deliverable: D2.7 ("Parallel operation of small cantilever arrays")

Lead beneficiary number	10 (SL)	**Nature**	Report	**Dissemination level**	CO
Estimated Person-months	16				
Person-months by partner for the Deliverable	SL				
	16				
estimated Delivery Date	M48: 01/2017	**Delivery Date**	31/01/2017		
Author	Martin Spieser, Simon Bonanni, Felix Holzner, Philip Paul				
Reviewed by:	WP2 Leader: Urs Dürig WPG2 Leader: Armin Knoll Coordinator: Ivo W. Rangelow				
Criteria and Achieved Results	**Criteria**	**Achieved result**			
	Parallel operation of small cantilever arrays	Sequential operation of cantilever arrays achieved.			
	Roll angle adjustment: Height difference between Lever 1 and 10 better than 300 nm	Height difference better than 30 nm achieved, factor 10 better.			
	Multiplexing scheme reading	Dual synchronous ADCs for roll angle measurement.			
	Multiplexing scheme writing	Sequential writing with identical settings. Thus, MuX should write same pattern with multiple levers			

Description of the Deliverable

The goal of Deliverable **D2.7 “Parallel operation of small cantilever arrays”** is to design and make the hardware on the machine to operate the cantilever arrays. This work is the second part for accomplishing objective **O-2-3: ”Development of a new scan-head for a tip scanning system: Allow to address large samples of up to wafer scale with increased throughput using small tip arrays”**.

For this purpose a new generation of cantilever array has been developed and fabricated, and an electro/mechanical interface has been developed to use the cantilever arrays on the tip scanning system described in the **D2.6 report**.

Cantilever arrays

While the first batch of array cantilevers was operational, it was also found that performance could be improved in some areas, most prominently with the approach sensitivity. Compared to the original design, the holder chip was also re-sized to give the cantilevers more angular tolerance or allow higher bond heights (improved yield during bonding).

The overall configuration of the 10-lever chip is unchanged. Figure 1a shows a SEM image of the cantilevers in the array, and Figure 2b the CAD drawing of the cantilevers. These form the front-most part of the chip/carrier board combination.

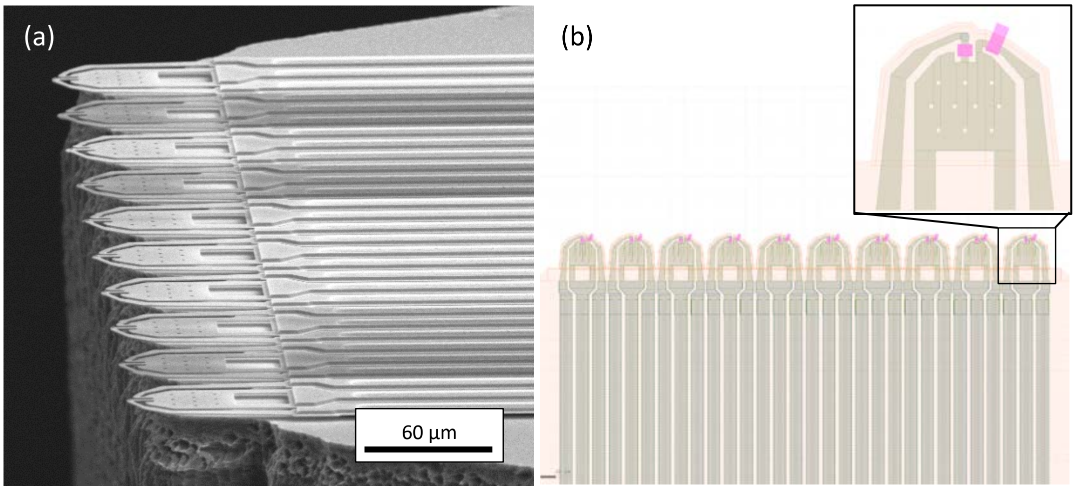


Figure 1: (a) SEM image of a tSPL chip with an array of 10 cantilevers. (b) GDSII design of the array (single cantilever magnified)

Carrier board for cantilever array chip

Each cantilever array chip features 10 cantilevers. To control the cantilevers 30 independent electric contacts are necessary, plus contacts for the electrostatic actuation of the levers by the backside electrode. To facilitate the replacement of the cantilever chips, a carrier board has been designed (Figure 2a). Carrier boards made of silicon and alumina have been tested. Because of its low cost and its good mechanical properties, alumina has been chosen as material for the carrier board. The cantilever chip is glued on the carrier board. Different adhesives have been tested for gluing the chip to the carrier board. Adhesives H20E PFC, U300-2, H70-2 gives average angle error respect to the carrier board of 0.13°. The pads on the chip are wire bonded to pads on the carrier board.

Aluminum wedge-wedge bonds are used to achieve bonds with a height below 120 µm. The low height is crucial so that the bonds don't touch the sample even for the low contact angle of 4°. Figure 2b shows SEM images of a dummy cantilever chip glued and wire bonded to the carrier board. A 32-wire ribbon cable is glued onto a silicon carrier board with conductive adhesive (Figure 2a and 4a).

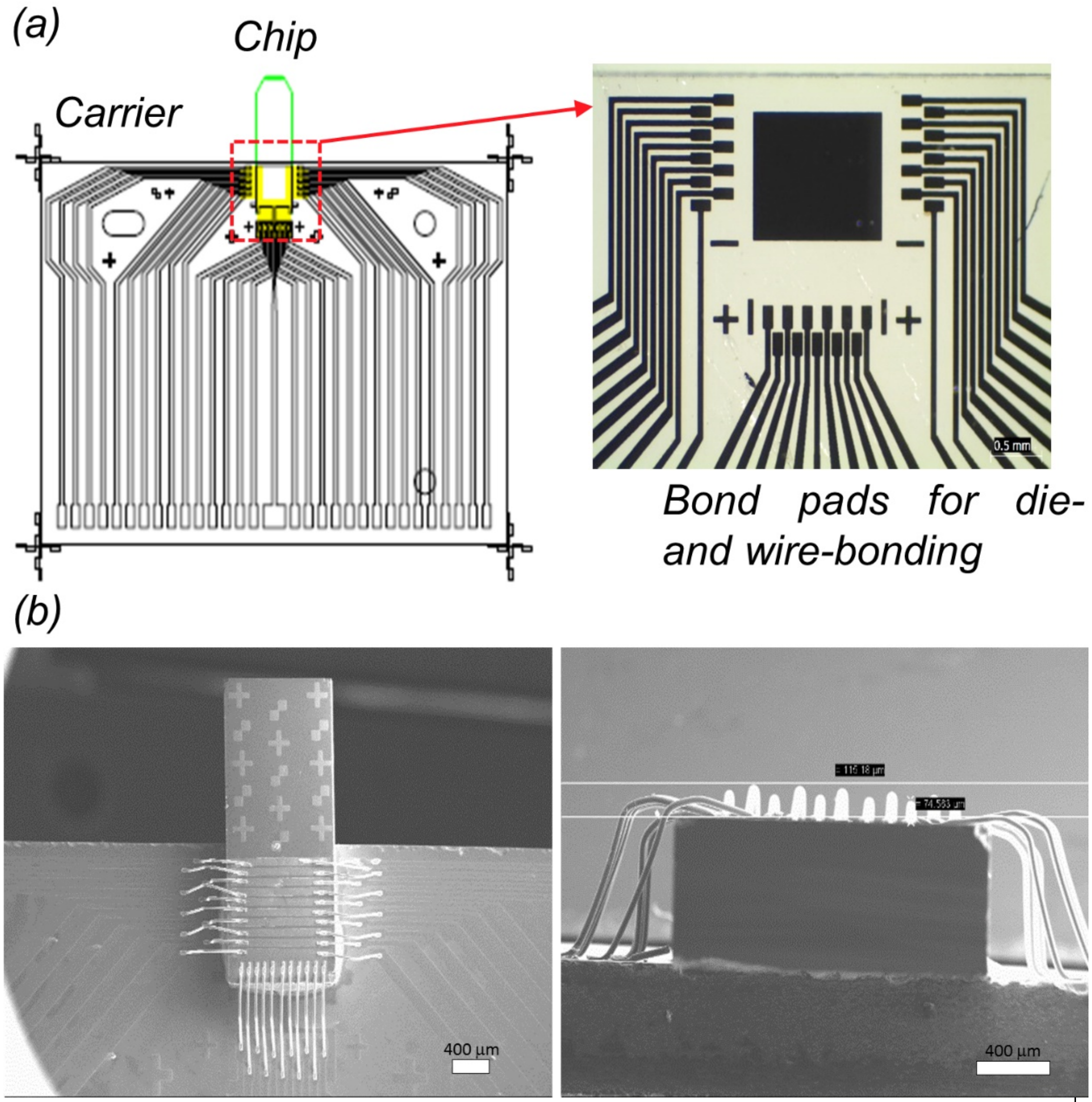


Figure 2: (a) Layout and picture of two of the tested carrier board designs. (b) SEM images of wire bonding of 30 contacts on a dummy cantilever chip. Highest point of the wires is less than 120 µm above the chip surface.

Read and write head / cantilever mounting

The self-actuated cantilevers have a maximum motion range of 300 nm. To bring all cantilevers sufficiently close to the surface for parallel operation, a roll angle of better than 0.06° was set as specification (illustrated in Figures 3a and b). The tolerances for the pitch and yaw angles are higher, in the order of 1°.

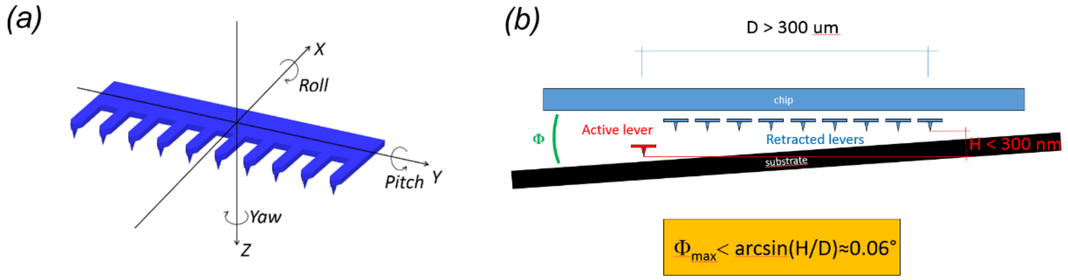


Figure 3: (a) Diagram of the angles of the cantilever array. (b) Diagram of the bigger acceptable error in the roll angle.

The first two versions of the tip holder are shown in Figures 4a and b. They feature micrometric screws and a wedge design to allow angular adjustment with a resolution of 0.001°.

The design was tested successfully on a sample scanning prototype. While the angle can be adjusted to the required precision, this adjustment is carried out manually, which is time consuming. Automation with a motorized micrometer screw adds around 100 g mass to the tip holder, either in front, or on the side. On the tip scanning system, the motorized screw is actuated together with the rest of the tip holder. With an ex-centric mass, the accelerations from scanning have a rotational component. High stiffness is required to absorb these forces and prevent out of plane vibrations. The angle adjustment mechanism is designed to translate motion of the motorized screw into a rotation. By definition it is the opposite of a stiff mounting.

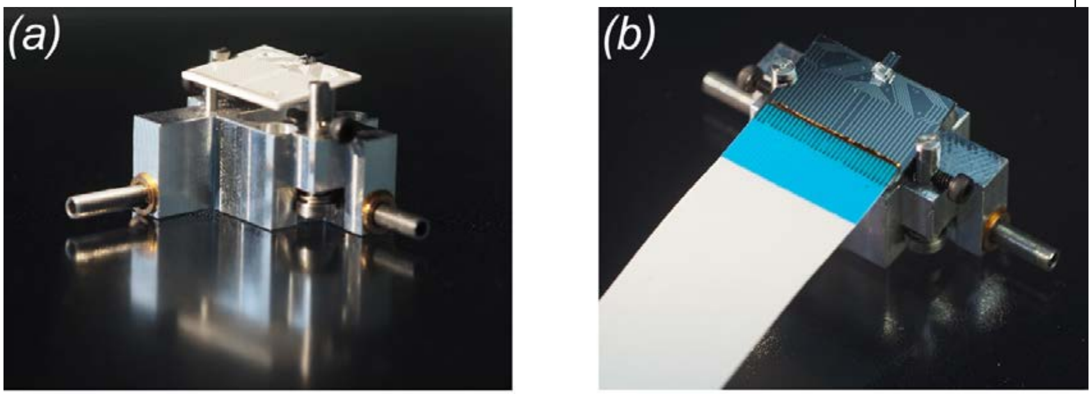


Figure 4: (a) and (b) pictures of the holder with mounted carrier board. The fine adjustment of the roll, pitch and yaw angle of the carrier board is possible by means of micrometric screws.

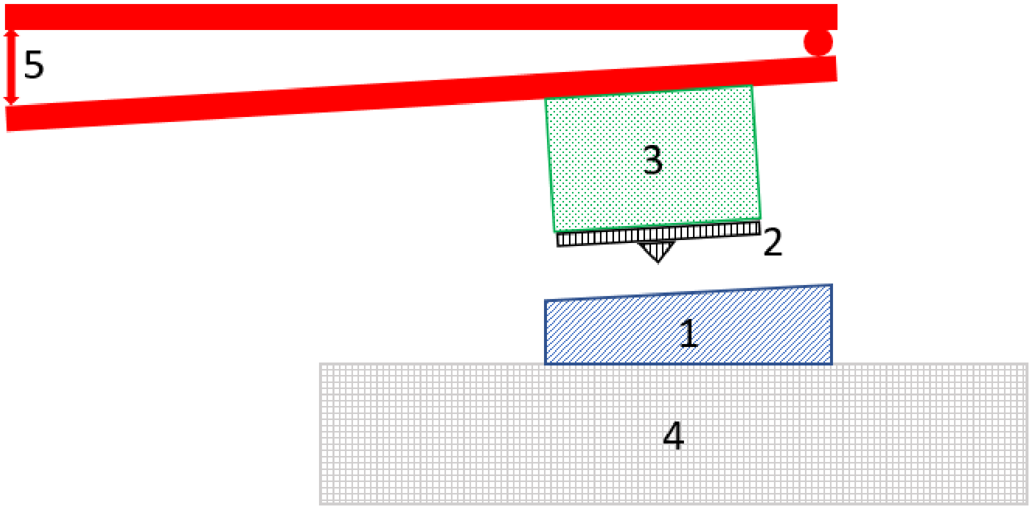


Figure 5: Angle adjustment schematic

Therefore, a completely new angle adjustment mechanism was developed to avoid the issue of placing ex-centric mass and translation mechanisms where the highest accelerations are found. Instead of placing a 3-angle adjustment mechanism on the read/write head, a single (roll) angle adjustment mechanism was found to be sufficient.

The schematic of the prototype is shown in Figure 5. Number 1 (blue diagonals) is the work piece, which is at an angle with respect to the cantilever mounting chip (2, black vertical lines), as well as the work piece holder (4, hatched grey). The tip holder (3, green dots) has been reduced to a fixed clamping mechanism. The roll angle adjustment mechanism (5, solid red) is placed under a non-moving part of the setup.

In the case of the sample scanning system, Figure 5 no 4 represents the work piece holder and fine piezo scanner. The mechanism (5) is mounted between the tip holder and the coarse positioning stage. In the case of a tip scanning system the placement of the mechanism (5) would be under the work piece holder (4), and the tip holder (3) would include the fine piezo scanner.

Figure 6 shows the completed third generation angle adjustment mechanism fitted to the NanoFrazor Explore mechanics. The manual micrometer screw has been replaced with a motorized one (red). The solid, ball-based hinge is placed under the Z Piezo motor to minimize vertical motion during angle adjustment.

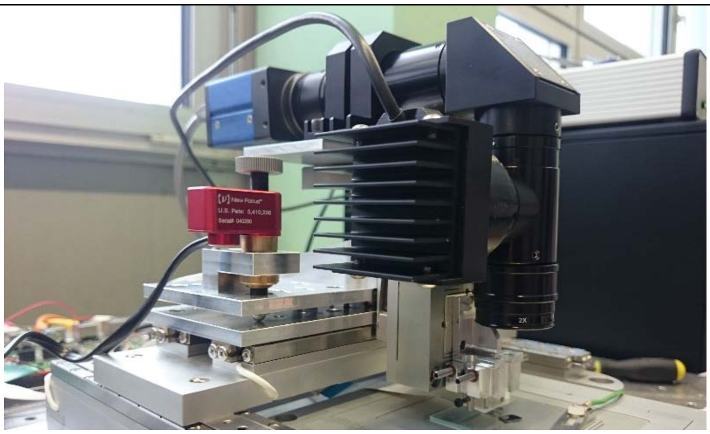


Figure 6:Third generation angle adjustment mechanism

The current tests are still being carried out with the second generation read/write head (below the microscope, right hand side of Figure 6), now only used for clamping the tip carrier board. A minor, non-functional geometry change is planned for the carrier board, at which point a new, smaller, and rigid clamping mechanism will be designed. Without adjustment mechanics, the stiffness will be higher, and the mass and size can be reduced dramatically. Both features naturally enhance the performance, especially in the tip scanning NanoFrazor.

Multiplexing

The first version multiplexing circuit was designed as an add-on to the current electronics. The schematic is shown in Figure 7. Two voltages are fed from the ADC-DAC board to the analog board. In the non-multiplexed board these are the reader and writer voltages. The first element in each signal chain is a current measurement amplifier. Both amplifiers can be used simultaneously. After the amplifiers, there are "enable" switches to operate the cantilevers in different modes.

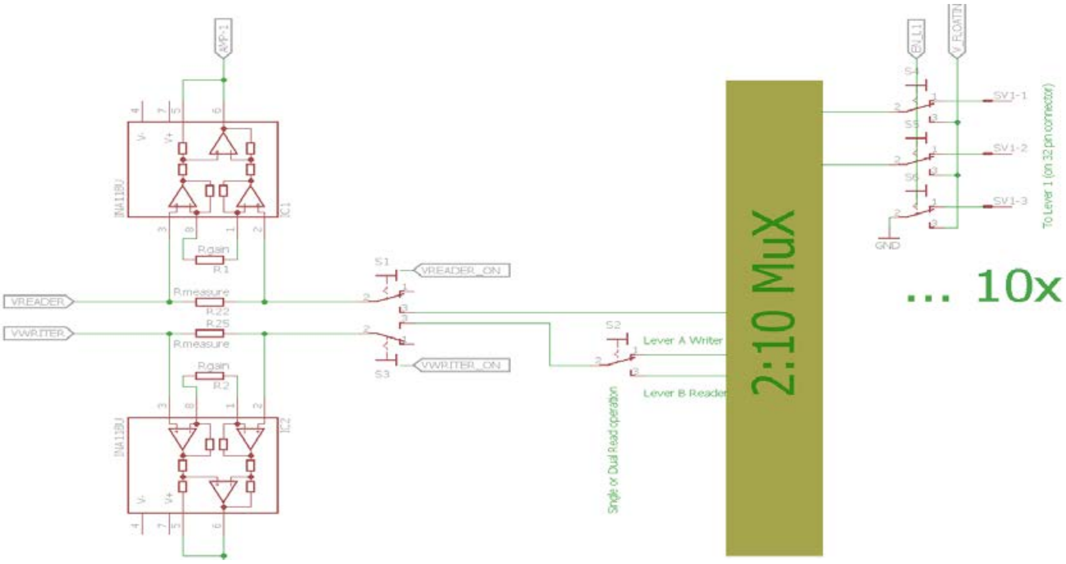


Figure 7:First version multiplexing circuit

The next element is a selector for the operating mode. Single cantilever operating mode essentially allows each cantilever to operate as if it were independent. Dual cantilever mode connects the “writer” signal chain to a second cantilever, to enable dual approaching and reading etc. This element essentially disables the writers of the dual cantilevers, however, readers and writers do not operate at the same time, so this is not a fundamental problem.

The 2:10 MuX is shown as a block for simplicity. Finally, a “cantilever enable” switch allows any cantilever not in use to be floated to a “retract” potential to retract it.

This multiplexing configuration works well for all purposes of sequential cantilever operation. The dual amplifier channels can be used for leveling the array with respect to the sample, and even for simultaneous read operations on two cantilevers.

However, the order of elements does not usefully allow simultaneous writing. The problem is that the resistor across which the current is measured also serves the purpose of limiting the current when the writer is above the intrinsic temperature (negative differential resistance).

The operation of multiple writers above the intrinsic temperature requires a separate current limiter for each writer, as the negative differential resistance causes oscillations and destructive overheating due to the mutual feedback. With the enable/ disable switch after the resistor, it is not possible to add the fan-out for parallel multiplexing before the measurement resistor without losing the ability to disable the writer. This issue requires a re-design of the multiplexer.

A new, manual multiplexer was designed to avoid the current runaway and oscillation issues above the intrinsic temperature. A photo of the fabricated multiplexer is shown in Figure 8. The design allows maximum flexibility in addressing the cantilevers. The new element in this multiplexer design are three 10-channel three-state switches. Each pin of the 10 cantilevers is connected to one of the three-state switch according to its designation (reader, writer, or common). The reader and writer connections have an additional series resistor to limit the current above the intrinsic temperature, as visible in Figure 8.

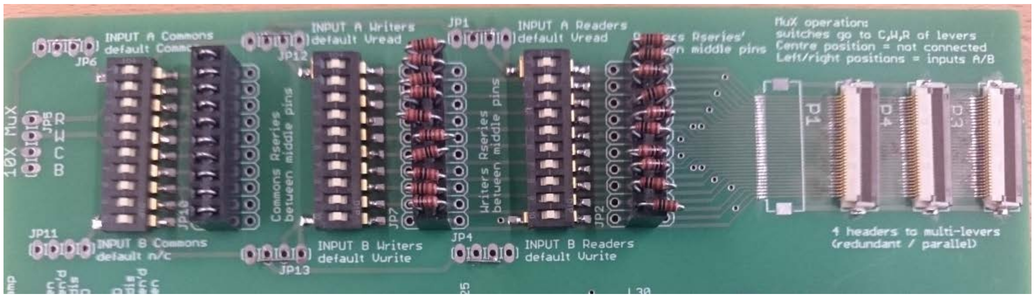


Figure 8: Second generation multiplexer

The multiplexer board is connected after the current sense amplifiers and enable switches. The input is shown on the left of Figure 8. The switches are located in the central part of the PCB, and a set of 0.5 mm ribbon connectors are located on the right edge of the PCB. Due to the small size and relative susceptibility to damage, four redundant connectors are added in parallel (with three soldered onto the PCB).

Parallel reader operation

Two independent hardware channels for reading are implemented in the electronics. Read bias generation, amplifiers and ADC channels are independent copies of each other, so issues such as cross-talk are avoided. Using the multiplexer in Figure 8, reader pins of cantilevers can either be disabled, or connected to one of the two read channels corresponding to the three states of the 10-channel switch.

Tests with the earlier multiplexer version showed that the most important issue for operating the cantilever array is the roll-angle alignment of the cantilevers with respect to the surface. When reading, any angular difference directly maps to a contact force differential, and thus to surface damage. During reading, the tips obviously need to come into contact, so the cantilever that comes into contact first needs to be deflected until the other cantilever also comes into contact. This results in an additional force of the spring constant of the cantilever times the deflection. Details are described in the roll-angle adjustment section.

While the hardware channels are fully operational, the current version of the SwissLitho software, still implements reading as a sequential operation. The reason for this is the commercial nature of SwissLitho's software base. Duplicating the read data flow from the controller to the controlling PC requires careful planning, as data integrity and operational robustness need to be ensured. Forking software versions ("main" and "test") yields significant management overhead, as improvements to the "main" software also requires an integration effort to the second "test" software fork, which overloads SwissLitho's software man power.

We do not expect any physical issues with simultaneous reading. SwissLitho's read scheme is equivalent to an AFM "contact mode" operation. The cantilevers are brought into contact, and scanned across the surface, with the topography imaged via the reader sensor. The topography signal is derived from a small resistance change under a D.C. bias. There is no oscillation of the cantilevers (neither through physical actuation nor via electrostatic actuation), so there are no frequencies coupling into the reader signal. The cantilevers themselves are completely isolated from each other with trenches through the entire silicon layer. The handling silicon and back-side actuation electrode are connected to low-impedance ground to prevent capacitive coupling.

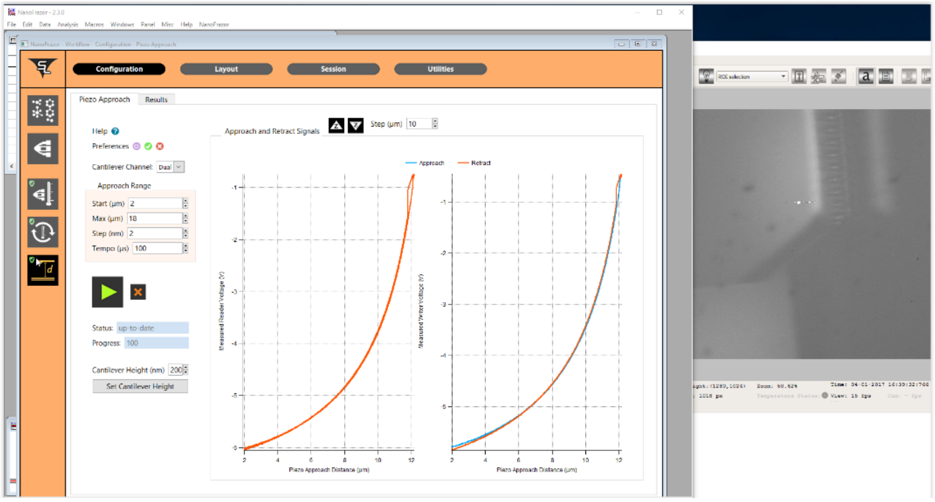
The read procedure for multi-levers is identical to reading standard single levers. While only one channel is recorded during a read operation due to the software implementation, the multi-lever array was physically operated as if it were reading with multiple channels simultaneously – For easy switching between the channels, the reader bias was applied to the inactive reader, so all signals were applied in the same way, but not recorded. No difference in noise levels or cross talk were seen between single lever operation and operating the multi-lever array. Therefore, activating the second ADC channel is not expected to reveal anything different.

Roll-angle adjustment

The roll angle adjustment procedure is based on the dual tip-sample approach procedure. Essentially, two cantilever channels are monitored for contact as they approach the substrate. The approach is stopped as soon as the surface is found with any of the levers. The cantilevers on either edge of the chip have the largest height difference, so these are used preferentially.

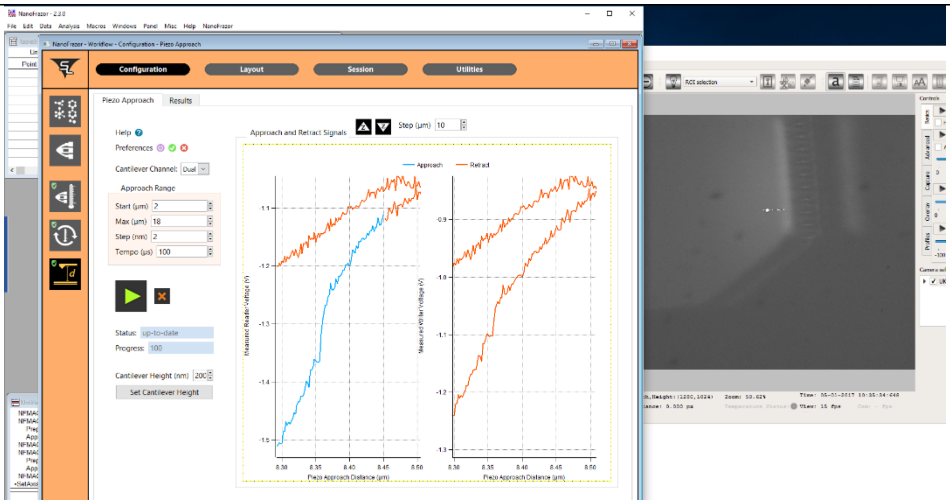
Figures ~~8~~ 9 and ~~9~~ 10 show the output of the approach after angle adjustment. The two data sets are taken with the two read channels, and they are for all purposes identical to single lever operation, and no cross-talk was observed. The black and white image on the right is the microscope view of the cantilevers. Figure ~~8~~ 9 shows the full approach curves of the two outer-most cantilevers, while Figure ~~9~~ 10 shows a zoom on the contact diamond. As the entire read/write head was removed to mount the chips, the roll angle before adjustment was several degrees. In this case, the contact diamond is only seen in one of the two channels.

From the blue and red (as opposed to all red) curves on the graph, surface contact was detected with the right cantilever channel in Figure ~~8~~9, and left channel in Figure ~~9~~10. The contact point is defined by a jump into contact, the so-called snap-in, followed by a change in slope of the approach curve. In Figure ~~9~~ 10 the snap-in is located just after 8.35 um of approach in both channels, the software simply recognized the left channel first.



Cantilever Channel: Dual
Start (µm) 2
Max (µm) 18
Step (nm) 2
Tempo (µs) 100
Status: up-to-date
Progress: 100
Cantilever Height (nm) 200
Step (µm) 10

Figure 9: Dual approach after angle adjustment (full approach)



Step (µm): 10
Cantilever Channel: Dual
Approach Range
Start (µm): 2
Max (µm): 18
Step (nm): 2
Tempo (µs): 100
Status: up-to-date
Progress: 100
Cantilever Height (nm): 200

Figure 10: Dual approach after angle adjustment (zoom)

The levelling procedure is carried out by monitoring both approaches, and varying the angle until the channel at which the approach is detected changes. The current third generation angle adjustment mechanism allows the roll angle to be set so finely that the relative height difference between the edge cantilevers is of the order of 10 nm over a distance of 300 um.

This super-fine angular alignment capability simplifies cantilever and writing force controls, as the force offsets between different cantilevers will be small compared to the original 300 nm specification.

This very successful angle adjustment mechanism will be ported to the wafer scale system with the next prototype. The current mechanics does not allow the insertion of home-built elements without voiding the warranty and calibrations.

Multi-cantilever writing

The goal for multi-lever writing in this project is to write an identical copy of a pattern with each cantilever. This approach requires the cantilevers of the array to have very similar properties, as identical voltages and settings are applied to all cantilevers in the operation. The most important properties are the electrical resistances of the lever sections (determines writer temperature), as well as the geometry and stresses which determine the actuation properties (spring constant, heat confinement, deflection with voltage). Furthermore, the roll angle alignment also maps into a difference in written depth.

Simultaneous independent patterning of each cantilever is beyond the scope of this first implementation. As each written pattern may have different characteristics (resolution and depth), the optimum writing conditions may vary significantly. Thus, for an implementation useful to customers, simultaneous depth-control feedback loops would be required. This in turn requires completely new control hardware with more ADC/DAC channels and computation performance. Such a major re-design should be made after the first evaluation, when all requirements and effects are known.

Due to the issues described in the multiplexing section, successful writing could only be carried out sequentially. The above criteria were evaluated during sequential operation. The results are most easily summarized in the writing results shown in Figures 1~~0~~1 and 1~~1~~2. Te outer most cantilevers were used for writing, with the same settings (voltages, temperature, roll angle etc). This represents the most difficult case for writing, as mismatch in angular alignment has the greatest effect.

As visible in the scale bars, the written depths (blue is written depth) are similar in both written patterns. The yellow rims are related to pile-ups. Comparing the written patterns in Figures 1~~0~~1 and 1~~1~~2, one can observe that Cantilever 1 (Fig. ~~10~~11) yields higher resolution than Cantilever 10 (Fig. ~~11~~12). The reason for this is Cantilever 10 was previously used for other trials and for finding optimal settings.

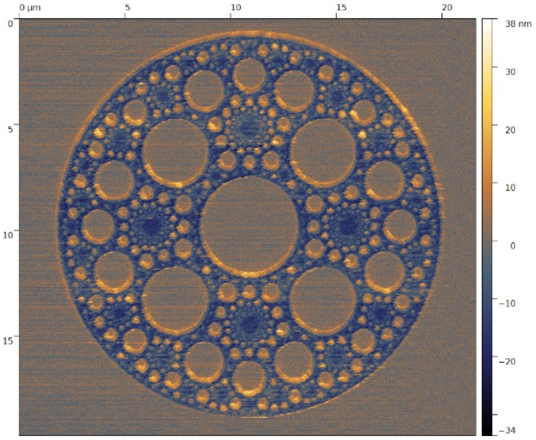


Figure 11: Write result of cantilever 1

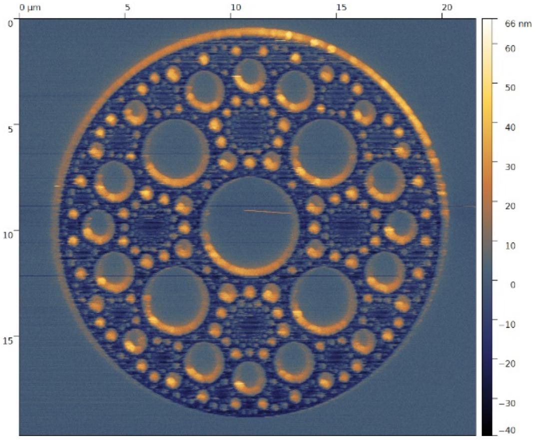


Figure 12: Write results cantilever 10

All cantilevers are fabricated on a single SOI silicon on insulator chip. Electrical separation (elimination of cross-talk during reading) between levers is achieved by etching trenches through the top silicon layer. The SOI layers are sufficiently thick to prevent mechanical cross-talk between levers.

For simultaneous writing of identical copy of a pattern, the multiplexer fans out the same

	signals to multiple cantilevers, so we do no~~’~~t expect any major complications for parallel writing. **Future work** The parallel writing operation of the cantilever arrays is still outstanding for the deliverable. The new multiplexer needs to be tested and the resistances tuned to achieve parallel operation above the intrinsic temperature. It is expected that we deliver the promised parallel operation before the end of the project.
Explanation of Differences between Estimation and Realisation	Delays were incurred with needing to re-design both the roll angle adjustment mechanism as well as the multiplexer. However, we are confident to have solved these problems and do not expect other major delays. Experience parallel read operation, and evidence that there is no cross-talk, was gathered with the standard sequential operation of the cantilevers. The full integration of simultaneous multi-channel reading into SwissLitho’s commercial software requires careful and conservative planning, to avoid increasing the overhead from managing multiple software forks, and from implementing the same functionality twice (once for testing, once for commercial release).
Metrology comments	The depths of the written patterns were determined using the standard NanoFrazor imaging method. Only relative height and depth differences are of concern, i.e. repeatable values are required, not absolute calibrated values.