# DESIGN AND FABRICATION OF A MULTIFUNCTIONAL SCANNING PROBE WITH INTEGRATED TIP CHANGER FOR FULLY AUTOMATED NANOFABRICATION

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## INTRODUCTION

The use of scanning probe microscope (SPM) tips as manufacturing tools for the fabrication of integrated microsystems, nanoelectromechanical (NEMS) systems, and nanoelectronic devices have been widely proposed and progress towards these goals was recently demonstrated, for example, by nanopatterning of 88 million nanofeatures in less than 20 minutes over 1 $cm^2$ using dip pen nanolithography [1]. However, in order to enable practical nanofabrication with probe tips for such applications as: (1) handheld replicators for nano rapid prototyping of nanoelectronics and NEMS, (2) printing and nanomachining of unique hybrid organic and inorganic material [2], (3) 3-D nanofabrication and assembly, and (4) complete desktop nanofactories [3]; it will be critical to address the issues of throughput, tip wear effects, chemical cross contamination, and scalability – all of which act to decrease the quality, reliability, and efficiency of probe-based fabrication.

To address these critical issues, a novel active cantilever probe is proposed with an automated ability to interchange probe tips (tools); for example, from nanotube tips for high resolution metrology to dynamic tips for nanomachining to chemically functionalized tips for cell biology, without the need for an operator to physically replace the cantilever as in traditional atomic force microscopy (AFM). The concept of the active cantilever system is shown in Figure 1. This novel design models macroscale computer numerical control (CNC) manufacturing in which CNC machines are fully automated allowing for rapid tool changes without operator interruption. Located at the distal end of an SPM cantilever is an electrically activated microgripper, which is designed to automatically load and unload tips from an array of available tools. Automation is achieved by exploiting the thermal properties of the microgripper to create a thermal-proximity sensor to determine the relative location between the microgripper and tool tip, similar to thermally activated cantilevers for AFM thermal imaging [4].

The ability to provide fully automated on-demand probe tip changes will improve the overall efficiency of a fabrication process, allow for multifunctional probe capabilities, and improve process reliability and quality by enabling the ability to replenish worn or chemically fouled tips in an efficient manner. This paper addresses the design aspects of the active cantilever probe and system automation, with preliminary experimental results to justify the design.

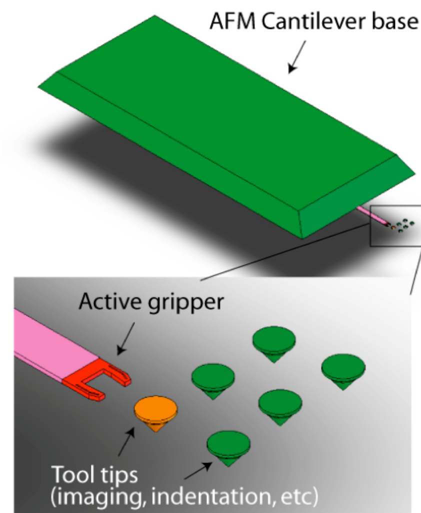


*FIGURE 1. Concept drawing showing active cantilever probe and modular tool tips.*

## CANTILEVER PROBE AND MODULAR-TIP DESIGN

The active cantilever probe design is based upon a thermally actuated microgripper that offers several advantages over other actuation techniques. In general, the available actuation mechanisms consist of: (1) electrostatic actuation [5], (2) thermal actuation [6], and (3) piezoelectric actuation, to name a few. Although piezoelectric actuators are the workhorse for positioning an SPM probe tip relative to a

sample surface, their use as microgrippers is rather limited because of their low percent strain (<0.5%). Micron-size electrostatic actuators have been developed to manipulate objects, such as a nanowire [7], with relatively large strain; however, they require large electric fields (as large as 100 V). A thermal-based actuator was developed that consumed 75 mW of power with an expansion of 35 μm [8]. Thermal actuators can provide a significant amount of force for gripping and holding a modular tool tip. Second, the fabrication process to create a micron-size thermal gripper is well established [9]. Thirdly, they occupy a relatively small foot print. Finally, the thermal behavior of the gripper can be exploited to create a sensor to detect the location of modular tips for loading/unloading. Therefore, no additional sensing mechanism is needed to determine the relative locations between the thermal gripper and tool tips for automated exchange.

A schematic of the active cantilever probe design is shown in Figure 2. Cantilevers with different geometries and dimensions were designed; in particular, the design in Figure 2 has approximate dimensions of 400 μm x 35 μm x 3 μm (*length;width;thickness*). The probe was designed to be compatible with existing commercial AFM systems; therefore the dimensions and mechanical performance were optimized within ranges of commercially available contact-mode probes. A 2 x 4 mm base (not shown) allows the probe to be handled relatively easy using tweezers. The chip base has metallic electrodes for electrically activating the microgripper at the distal end of the cantilever. The probe and modular tips (when attached) will function as a conventional AFM system using the optical lever mechanism for detection of tip deflection. A significant advantage of this design is that since only the modular tip is exchanged and not the entire cantilever, recalibration and alignment of the laser to the probe, as in replacement of conventional probes, is not needed. Additionally, the cantilever can be designed with integrated piezoelectric sensors for sensing of tip deflection thereby eliminating the need and associated complexities of an optical lever system.

Thermal actuation of the gripper is achieved by differential thermal expansion of the inner and outer arms of the gripper as shown in Figure 2. The current path through the gripper results in resistive Joule heating with higher temperature occurring in regions of smaller cross-sectional area. The smaller (hot) inner arm expands more than the (cold) outer arm resulting in bending or actuation of the gripper (Huang and Lee, 1999). The dimension and geometry of the gripping arms were designed to provide adequate gripping force to ensure a no slip condition of the secured modular tip and to ensure dynamic robustness during imaging and other functions. Thus the gripping force (> 17 μN) is passively maintained by making the modular tip dimensions greater than the equilibrium gripping dimensions—a compression fit is formed and is always maintained unless the gripping arms are actuated (opened). The U-shaped wedge design of the grips allows for mechanical interlocking and ensures non-rotation of the modular tip. The modular tips (not shown) are designed with a reverse geometry that locks into the gripper. The tips have a top gold coating to allow deflection of laser light as in conventional probes and will be stored for retrieval in a specially designed storage cassette. At present, modular tips are to be mass fabricated on a silicon wafer and attached via tabs similar to commercially fabricated cantilever probes.

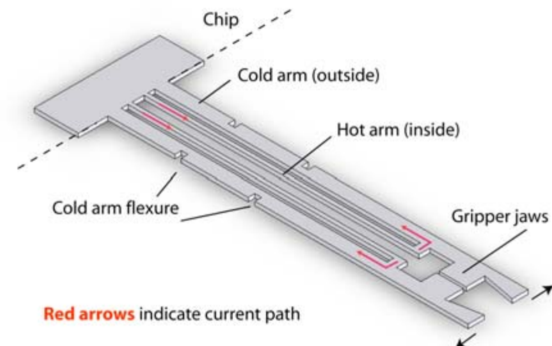


*FIGURE 2. Prototype design of cantilever probe with integrated thermally actuated gripper (electrodes and chip base not shown).*

The mechanical behavior of the cantilever probe was analyzed using finite element software (ANSYS FEA, Canonsburg, PA, USA). The cantilever material is polysilicon, with Young's modulus of 150 GPa, density of 2330 $kg/m^3$, Poisson's ratio of 0.28, and thermal expansion of $2.6\times10^{-6}$ $^{o}C^{-1}$. Using the temperature distribution given in [10], with low temperature value of 25 $^{o}C$ and maximum of 775 $^{o}C$, the maximum gripper opening, measured at the distal end of the gripper, was 7.08 μm. Assuming a boundary condition in which the base of the cantilever was fixed, the resonant

frequency of the first bending mode, without modular tool tip, was approximately 28 kHz.

## FABRICATION PROCESS

The active cantilever probe will be mass fabricated on a silicon-on-insulator (SOI) wafer. Si is widely used in conventional probe designs and offers flexibility in processing and tuning of mechanical and electrical properties. The fabrication process is shown in Figure 3. A n-type SOI wafer with a 3 μm Si device layer, 1 μm oxide ($SiO_2$) layer, and 350 μm Si handle layer is used. First, three Cr etch masks are made to transfer the top/bottom probe and electrode patterns to the SOI wafer for etching. A 25 nm Cr adhesion layer followed by a 150 nm Au layer is deposited on the Si device layer by electron beam evaporation. Next, photoresist is spun on top of the Au layer and patterned by photolithography to etch and form the Au electrode pads. After removal of the resist for the electrodes; a new layer of photoresist is deposited and patterned to form the probe and gripper geometries. The Au and Cr layers are etched through to the Si and the Si selectively etched using reactive ion etching (RIE) down to the $SiO_2$ layer. This completes the top-side (device layer) processing and the wafer is oriented for backside processing. Next, a 300 nm Al metal mask layer is deposited on the backside of the wafer by electron beam evaporation and a photoresist layer is deposited and patterned by photolithography to define the gripper and probe support chip. The Si handle layer is etched using reactive ion etching (RIE). Finally, the substrate is etched in a buffered oxide etch solution until the wafer has been completely etched through from the backside thereby releasing the cantilever. Modular tool tips are to be fabricated on Si using a similar microfabrication process.

## PROXIMITY SENSING AND AUTOMATION

Sensing the relative location (*x,y,z coordinates*) between the distal end of the gripper (jaws) and a tool tip will be achieved using an integrated thermal-proximity sensor [11]. This sensing scheme avoids the complexity of adding additional sensors to the cantilever probe. The junction will then be heated to a specific temperature and positioned relative to a calibration zone or tool tips until a noticeable change in thermal behavior is observed to indicate proximity (without physically touching the surface).

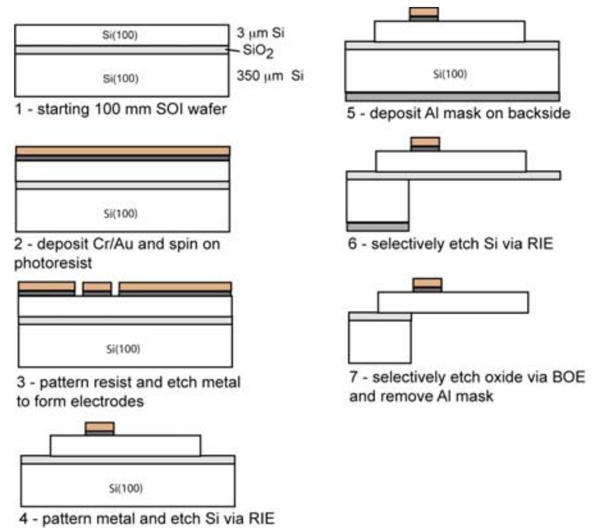


*FIGURE 3. Fabrication process of active cantilever probe.*

Figure 4 shows the layout of the envisioned workspace as well as the thermal-proximity concept. In particular, the heated gripper will be positioned over the calibration zone and slowly lowered until there is a noticeable change in thermal response due to conduction of thermal energy between the calibration feature and integrated sensor. By using the heated gripper as a thermal-proximity sensor, it can be rastered at constant height above the tool-tip array (x and y) to determine the approximate location of the tool tips relative to the jaws of the gripper. This information will be used to automatically position the AFM active cantilever at the correct location (x, y, and z) to enable loading/unloading of tips.

One significant design challenge is to ensure adequate resolution of the sensor within the framework of the three thermal resistances in series (i.e. the cold arm--sensor--hot arm). A coupled electro-thermo-mechanical model will be used to address this issue along with possibly tuning the resistivity via electrical doping of the gripper arms in order to achieve an adequate sensor signal.

## CONCLUSION

A novel system for automated exchange of multiple probe tip tools for nanoscale fabrication, metrology, and characterization has been presented. An active cantilever probe with a thermally actuated microgripper is used to sense and secure tool tips. The probe is compatible with commercially available AFM systems. A

working prototype of the active cantilever is currently being fabricated and tested.

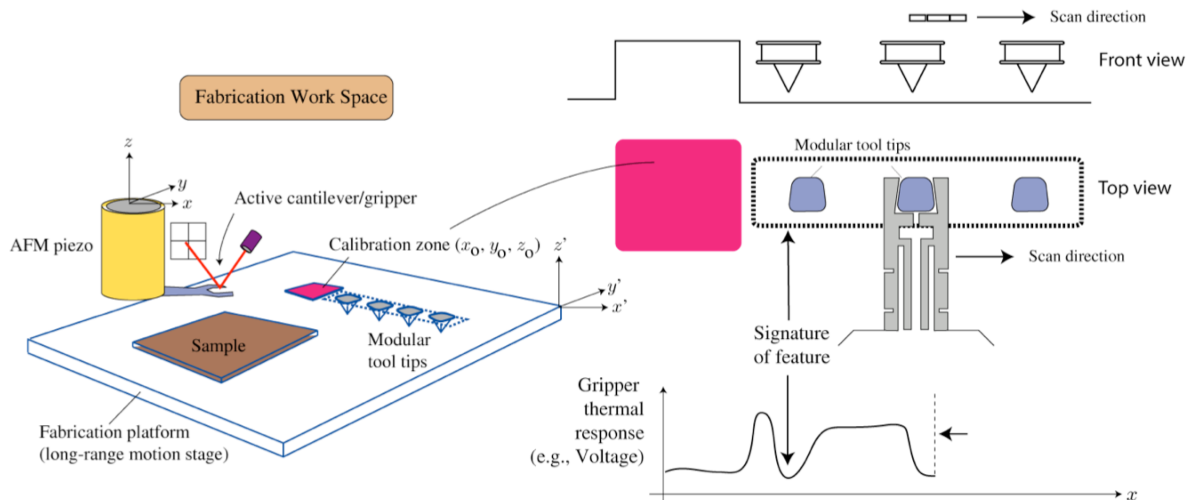


*FIGURE 4. (Left) Envisioned fabrication workspace, which consists of a platform containing sample and modular tool tips with a calibration zone (home position). The gripper is actuated by the AFM piezoactuator for scanning. (Right) Front and top view of thermal gripper hovering over tool tips. The relative location between gripper and tool tip is determined using thermal proximity sensing: monitoring the thermal behavior of the gripper as it moves over the calibration zone and tool tips.*

## REFERENCES


[1] Salaita, K., Y. Wang, J. Fragala, R.A. Vega, C. Liu, and C.A. Mirkin. Massively parallel dip-pen nanolithography with 55000-pen two-dimensional arrays. *Angew. Chem. Int. Ed.* 2006; 45: 7220-7223.

[2] Kentsch, J., M. D.urr, T. Schnelle, G. Gradl, T. Muller, M. Jager, A. Normann, and M. Stelzle. 2003. Microdevices for separation, accumulation, and analysis of biological micro- and nanoparticles. IEE Proceedings Nanobiotechnology. 150:82 -- 89.

[3] Johansson, S. 1995. Micromanipulation for micro- and nana- manufacturing. In INRIA/IEEE Symposium on Emerging Technologies and Factory Automation. 3-8.

[4] Lee, J., T. Beechem, T.L. Wright, B.A. Nelson, S. Graham, and W.P. King. 2006. Electrical, thermal, and mechanical characterization of silicon microcantilever heaters. Journal of Microelectromechanical Systems. 15:1644 -- 1655.

[5] Kim, C.-J., A.P. Pisano, and R.S. Muller. 1992. Silicon-processed overhanging microgripper. IEEE/ASME J. Microelectromechanical Systems. 1:31 -- 36.

[6] Jonsmann, J., O. Sigmund, and S. Bouwstra. 1999. Compliant electro-thermal microactuators. In 12th IEEE International Conference on Micro Electro Mechanical Systems. 588 -- 593.

[7] Molhave, K., T. Wich, A. Kortschack, and P. Boggled. 2006. Pick-and-place nanomanipulation using microfabricated grippers. Nanotechnology. 17:2434 -- 2441.

[8] Keller, C.G., and R.T. Howe. 1997. Hexsil tweezers for teleoperated micro-assembly. In IEEE 10th Annual International Workshop on Micro Electro Mechanical Systems. 72 -- 77.

[9] Liu, C. 2006. Foundations of MEMS. Prentice Hall, Upper Saddle River, New Jersey.

[10] Huang, Q-A. and Lee, N. K. S. Analysis and design of polysilicon thermal flexure actuator, J. Micromech. Micron.; 1999; 9; 64-70.

[11] Abraham, D.W., T.J. Chainer, K.F. Etzold, and H.K. Wickramasinghe. 2000. Thermal proximity imaging of hard-disk substrates. IEEE Trans. on Mathematics. 36:3997 -- 4004.