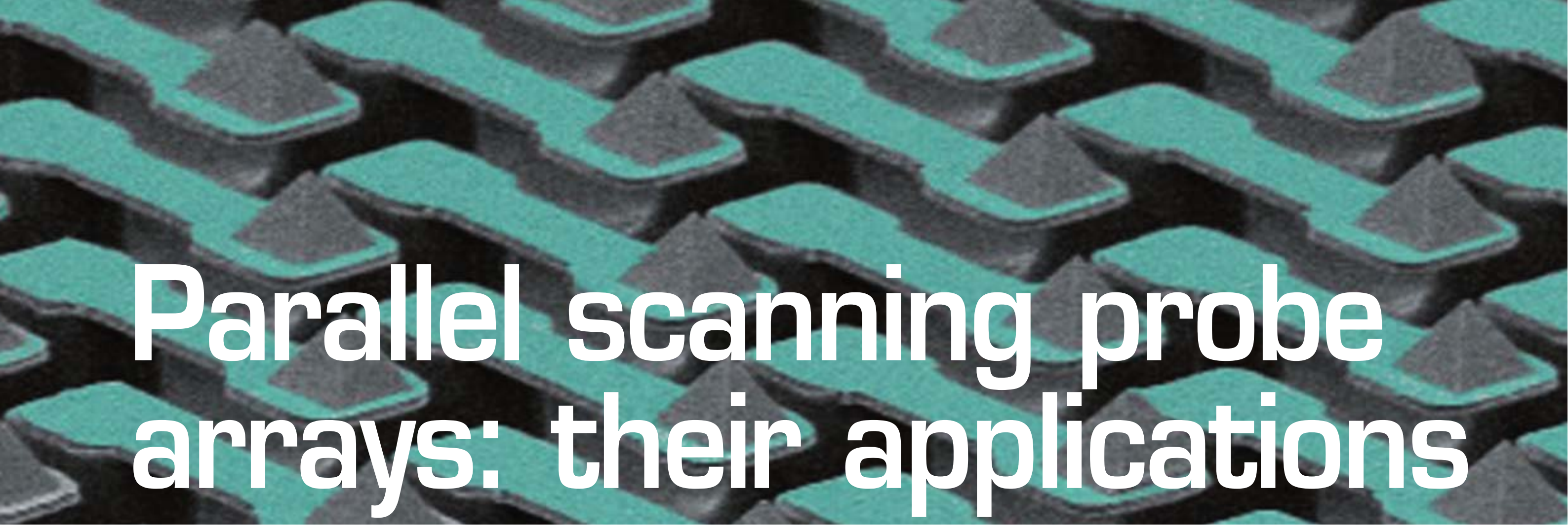

# Parallel scanning probe arrays: their applications

**Since the invention of the scanning tunneling microscope (STM)[1] and the atomic force microscope (AFM)[2], the field of scanning probe microscopy (SPM) instruments has grown steadily and has had a profound influence in materials research, chemistry, biology, nanotechnology, and electronics[3,4]. Today, scanning probe instruments are used for metrology, characterization[5], detection[6], manipulation[7], patterning[8,9], and material modification. A wide range of scanning probe applications are available, taking advantage of various modes of tip–substrate interactions, including force, optics[10,11], electrochemistry[12], electromagnetics, electrostatics, thermal and mass transfer[13,14], and vibration[15,16].**

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The scanning probe instrument family includes various surface characterization tools that measure surface force interactions; these ‘force microscopy’ tools include AFMs[2], magnetic force microscopes[17,18], electrostatic force microscopes[19], lateral force microscopy[20,21], and so on. The AFM has been used to characterize surfaces of inorganic materials, organic materials, and biological entities.

Scanning probes can also be used to produce high-resolution spatial mapping of topography, hardness, temperature, emitted or reflected light, charge distribution[22], and vibration magnitude[16]. SPM probes have also been widely used in surface modification, in either additive mode[23], subtractive mode, electrochemical reaction mode[12], or thermal phase change mode[24]. Since scanning probes are essentially nanoeffectors connected to high-precision mechanical movement controllers, they have been used as manipulators[7].

Today, advancements in nanoscience and nanotechnology are being pursued in a multidisciplinary fashion and on a global scale[25]. An SPM has broad technical appeal because it embodies a number of powerful and yet turnkey features: sharp end effectors, a computer-programmable mechanical motion stage, a calibrated precision force actuator, and a high-sensitivity motion detector[26]. The scanning probe instruments play a key role in facilitating the top-down as well as bottom-up agendas of nanomanufacturing. SPMs will be increasingly used to address needs beyond laboratory research. Examples of future needs include large area metrology, high throughput characterization and detection[6], high density data storage[27], and large area nanolithography.

Traditional scanning probes use a singular tip/cantilever entity. This poses a limit on the throughput of imaging and manipulation tasks. Linear scan rates are typically of the order of 1–10 μm/s. At 10 μm/s, it would take or 2.4 h to cover a distance of 10 cm, the

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**diameter of a typical wafer. In order to increase the throughput and area coverage, it is important to use parallel arrayed probes, preferably high-density and large-area arrays. The parallel scanning probe array, which is a chip or substrate containing at least two scanning probes engaged in a serial or parallel operation, is crucial for satisfying future research and industry needs. This paper will illustrate fundamentals of parallel scanning probe microscopy – including design and fabrication of probes, integration of functions, and operations. Further, it will use a few cases to exemplify how parallel scanning probes are designed, made, and used.**

## Basics of scanning probes

The probes in an SPM system are one of the crucial elements affecting performance, functionality, and speed. An SPM generally consists of a cantilever with a tip located at the distal end (Fig. 1). The cantilever is in turn connected to a handle for handling and mounting in instruments.

Today, SPMs are often made of microelectromechanical systems (MEMS) technology, which is uniquely capable of miniaturization (giving rise to low force constant and high resonant frequency), precision (giving rise to repeatability and uniformity), mass production on a wafer scale (giving rise to low cost), and electromechanical functional integration[28].

The flexural displacement of cantilevers in force-microscopy measurements is often sensed optically with an external light source and detector. (Alternatively, the torsional displacement of the beam along its longitudinal axis may be used[29].) A laser beam is reflected off the cantilever to a light detector; movement of the reflected spot indicates the extent of flexural bending. The displacement of the cantilever can be measured by using other methods, such as light interference[30] or surface-stress sensing elements (including piezoresistors, piezoelectric sensors, and stress-sensitive transistors[31,32]). Piezoresistors may be realized using doped silicon, whereas piezoelectric sensors are made by depositing and patterning piezoelectric materials including lead zirconate titanate (PZT) and ZnO.

The flexural bending mode of the cantilever is most commonly encountered. When a force F acts on the end of a cantilever with a length of l, a cross-section of w × t, and a material Young's modulus of *E*, it produces a tip displacement *d* and a surface stress *s*. The magnitude of d and s are $\frac{4Fl^3}{Ewt^3}$ and $\frac{6Fl}{Ewt^2}$, respectively[28]. The equivalent spring constant of the beam is $k=\frac{F}{d}=\frac{Ewt^3}{4l^3}$. The first-order natural frequency of the cantilever is $3.57\sqrt{\frac{Et^2}{\rho l^4}}$, with ρ being the density of the cantilever material.

Design compromises are necessary in many cases. Certain applications demand probes with low force constant (for high sensitivity) and high mechanical resonant frequency (for high speed). Increasing the length of the cantilever, for example, would tend to reduce the force constant, increase the surface-induced stress (thus increasing sensitivity if integrated sensing is used), and reducing the resonant frequency. Reducing the thickness would make the cantilever more compliant, reduce the resonant frequency, and increase the force sensitivity. One must carefully select the design and materials to obtain the desired performance characteristics.

## Basics of SPM probe fabrication

The art of realizing an individual cantilever, without the tip attachment, is relatively well established in the MEMS area. Cantilevers may be made of a variety of materials, including silicon nitride ($Si_3N_4$), single-crystalline Si, polymer, and metal[28].

SPM probes are more complex compared with bare cantilevers. The need to incorporate tips, especially sharp or high-aspect ratio tips, increases the degree of difficulty of processing beyond that for plain cantilevers. Namely, the process must yield sharp tips first, preserve the tip sharpness throughout the process and accomplish high process yield, while allowing a broad choice of tip and cantilever materials. There are other areas of complication. For example, certain probes may require integration of sensors and actuators.

Tips made of Si and $Si_3N_4$ (by chemical vapor deposition) are most common today. Some applications may demand tip materials that are unconventional, i.e. not compatible with traditional MEMS and

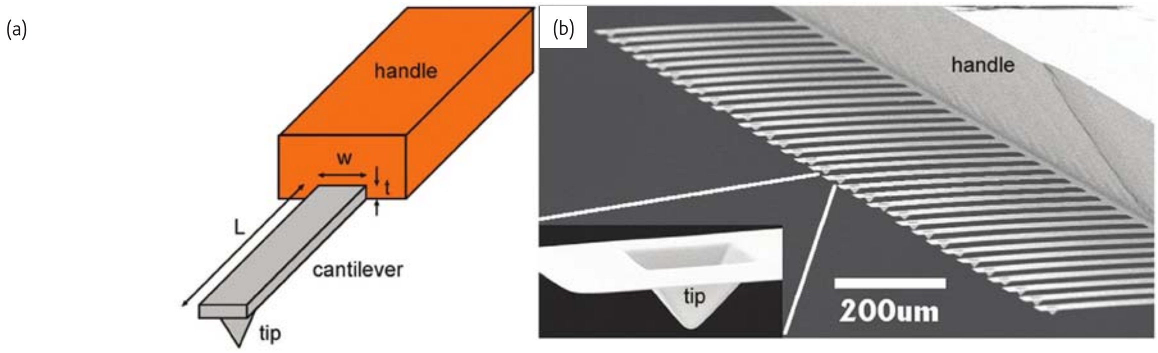


*Fig. 1 SPM design. (a) A schematic diagram of a representative probe. (b) Scanning electron micrographs of an array of scanning probes.*

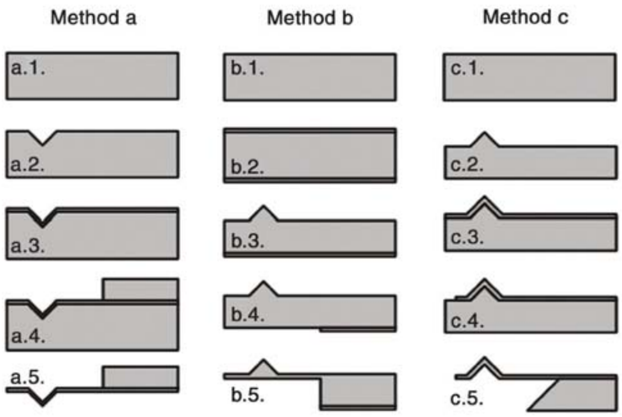


*Figure 2: Representative SPM fabrication methods.*

microelectronics processes. Other demonstrated materials for tips include metal[33], elastomer[34], and diamond[35].

There are a number of important technical issues that may seem easy to solve. The cantilever needs to have sufficient optical reflectivity (if optical sensing is used) and controlled intrinsic bending. Intrinsic bending is due to stress mismatch between layers at different thicknesses. It is undesirable for a number of reasons: (1) If the bending is not controllable or repeatable, the implementation may require tedious optical alignment. (2) Intrinsic bending causes the force–displacement characteristics of the probe to change, altering the effective force constant and enhancing the transverse displacement.

For many applications, it is desirable for the tip to face in the opposite direction to the handle, such that the handle does not impede the operation of the SPM. Another challenge is the packaging of such devices – the release of individual elements and drying of finished MEMS devices, which contain delicate cantilevers, are often nontrivial tasks.

Processes can be categorized according to a number of criteria. Processes may be discrete or monolithic. A discrete process involves precision assembly of various discrete elements (e.g. tips or cantilevers) into a joint device. A monolithic process is defined by the fact that all elements are made from a contiguous material, without needing delicate assembly or attachment. Monolithic processes are preferred for their uniformity and efficiency. Discrete processes may offer certain flexibility but are difficult to achieve due to the small sizes of the elements.

Monolithic fabrication processes can be categorized in many ways. The processes fall into two major categories according to the method of tip fabrication. In the first category, tips are made by etching. In the second category, tips are made by molding.

Tip etching can be accomplished by both dry and wet chemistry. This typically results in very sharp tips; however, the uniformity and repeatability is questionable. Tip formation by molding can result in greater uniformity of geometry and sharpness. However, tip molding is accomplished by etching away the substrate, which is wasteful and time consuming, or by removal of a sacrificial space layer, which increases the radius of curvature of the tips.

Tips may be sharpened by a variety of methods, including oxidation followed by subsequent oxide removal, by ion beam etching, or by growth of high-aspect-ratio nanostructures. For example, C nanotubes may be grown at the end of tips using chemical vapor deposition[36].

The available processes can also be categorized by the material of the cantilevers (insulator or conductor).

Commonly used routes for the fabrication of nonsensorized scanning probe cantilevers are summarized in Fig. 2. General method (a) starts with a single-crystal silicon wafer (often <100> oriented) (Fig. 2a.1). Cavities for molding tips are made by anisotropic etching of Si (Fig. 2a.2); common etchants include KOH and EDP[28,33]. The materials for tips and cantilevers are then deposited and patterned (Fig. 2a.3), followed by the attachment of a handle piece (Fig. 2a.4). Finally, the mold material is removed (Fig. 2a.5). General method (b) also starts with a single-crystal Si piece (Fig. 2b.1). A convex tip is formed by etching (e.g. anisotropic chemical etching, plasma etching) (Fig. 2b.3). The back side of the wafer is patterned in preparation for a bulk etch (Fig. 2b.4), after which a cantilever with controlled thickness is left standing (Fig. 2b.5). Method (c) is similar to method (b) in the first two steps. The material is coated with a thin film (Fig. 2c.3), which serves as the tip and cantilever. Bulk etching is completed by chemical etching from the front side of the wafer (Fig. 2c.5).

The relative advantages and disadvantages of these three methods are discussed in Table 1.

## Parallel probes: design, materials, and fabrication

MEMS technology is uniquely suited for fabricating parallel scanning probes. If MEMS and photolithography are used, making an array of n probes does not take n times the efforts of making a single probe. In addition, MEMS can increase the degree of uniformity of device geometries. However, there are unique challenges for parallel arrays, in

**Table 1: Pros and cons of the three general SPM fabrication methods shown in Fig. 1.**

| | Method a | Method b | Method c |
|---|---|---|---|
| Advantages | Can form tips with uniform sharpness and dimensions. | May result in very sharp tips. | Requires only one-sided lithography and etching.<br>Tips are dulled by the blanket deposition of the thin film. |
| Disadvantages | If the bulk substrate is removed by chemical etching, the process is time consuming. | Controlling the cantilever thickness and retaining sharpness of tips during the process is difficult.<br>Narrow choices of tip materials.<br>Difficulty of controlling the uniformity of tips. | Retaining sharpness of the tips is difficult.<br>Narrow choice of tip materials. |

addition to those encountered for individual probes. (1) The maximum density of tips is dictated by the minimal distance between probes. The decision of minimal distance is affected by cantilever geometries, footprint for wiring, and cross-talks among neighboring probes. (2) The uniformity of tip and cantilever dimensions, of mechanical properties, and of tip height is of the utmost importance and must be carefully controlled through design, processing, and materials selection. The degree of intrinsic bending is related to the dimensions of the cantilever, the stress level of various layers, and the thickness (Fig. 3). (3) The processing yield must be extremely high. If the chance of process failure for an individual probe is x, with x being a number between 0 and 1, the chance of process failure for an array of n probes is $1-(1-x)^n$.

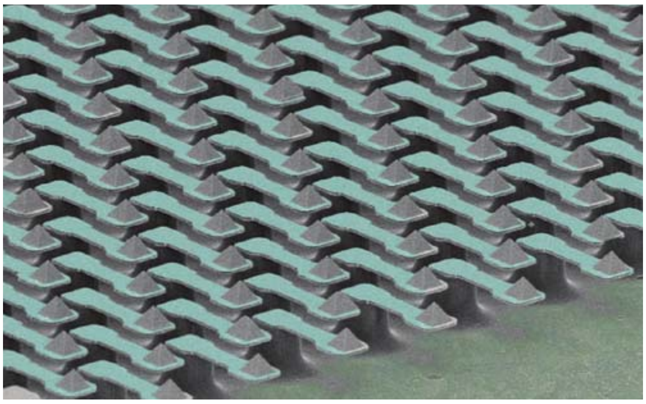

*Fig. 3 Scanning probes with undesirable intrinsic bending.*

A fabrication process called the mold and transfer process has been developed to allow an extensive choice of tip materials, a high degree of tip sharpness, and a high uniformity of tip dimensions (Fig. 4)[33]. First, a single-crystalline Si wafer is patterned to define rectangular open windows on the front surface. Then, anisotropic Si etching is performed to create inverted cavities bound by four[37] crystalline surfaces, ending at a sharp tip. A thin layer of sacrificial material is deposited next, followed by the deposition of the patterning for the tip and cantilevers. A handle is bonded to the wafer. After this, the sacrificial layer is removed, allowing the cantilever and the bottom substrate (mold) to be separated. The sequence for depositing the tip

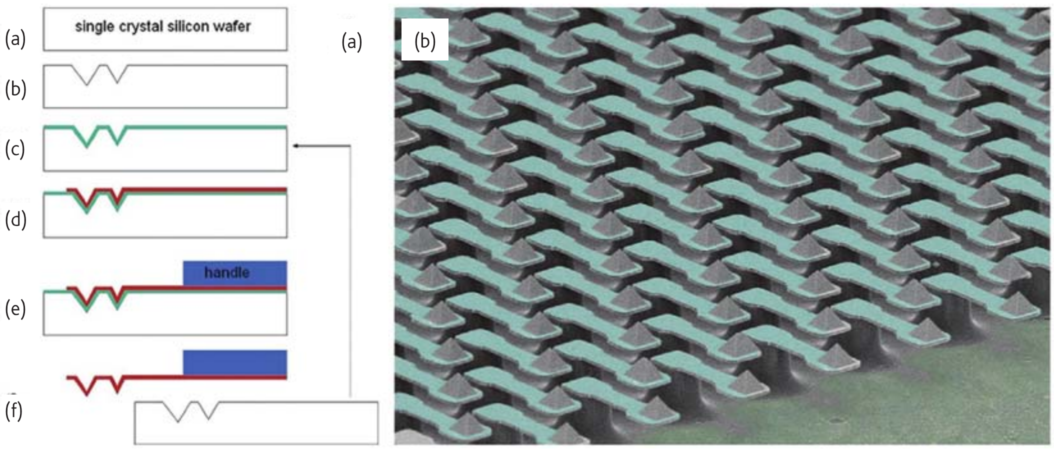


*Fig. 4 (a) Schematic diagram illustrating major steps of a mold and transfer process for fabricating scanning probe arrays. (b ) An array of probes with Al cantilever and tips.*

and cantilever material can be changed, to accommodate thermal, chemical, and material compatibility during processing. A wide variety of tip materials can be accommodated, including Si, $Si_3N_4$, elastomer, metal, and diamond. A wide range of cantilever materials can be used, including $Si_3N_4$, $SiO_2$, metal, and Si (by chemical vapor deposition). A large combinatorial matrix of tip–cantilever pairings can be accomplished.

## Applications

In this section, I will discuss a number of examples, including arrayed AFM devices, passive and active nanolithography arrays, and active arrays for data storage.

### Arrayed scanning probe

To increase the throughput and area coverage of AFM imaging, an array of such probes is needed. Whereas a single SPM probe is often exposed beyond the edge of the holder chip and is therefore accessible for optically based displacement sensing methods, it is difficult to measure the displacement of individual tips within an array of probes, because some probes may not be optically accessible. Even if the probes are optically accessible, the complexity of optical readout is daunting. Integrating displacement sensors onto the cantilevers has become a viable option. For example, piezoresistors can be integrated by selective doping of the cantilevers.

Parallel arrays of AFMs with sensorized cantilevers have been developed by Professor Calvin Quate's research group at Stanford University. A modular cantilever design was replicated to produce an array of 50 cantilevers with a 200 μm pitch[38]. Each probe contains a dedicated integrated sensor and an integrated actuator. Electrical shielding within the array is needed to eliminate coupling between sensors and actuators. The actuator is based on ZnO piezoelectric material. Piezoresistors, serving as position sensors, are defined by a patterned implant, allowing the cantilever to be actuated with a single pad of ZnO. Centimeter-scale AFM imaging and lithography was accomplished using such probes[31].

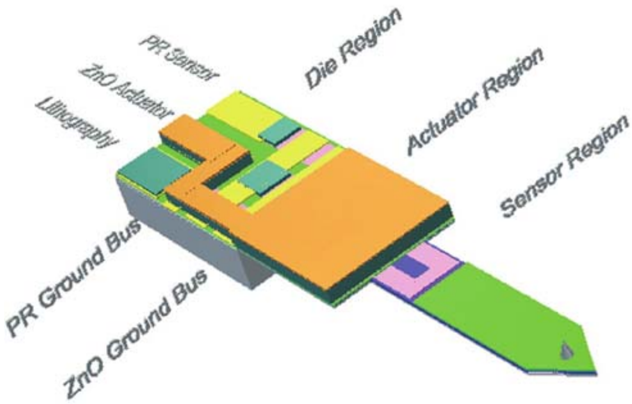


*Fig. 5 Schematic illustration of a design comprising integrated piezoresistors and an integrated ZnO actuator.*

### Passive DPN probe array

Dip pen nanolithography (DPN) technology involves the use of a scanning probe for direct deposition of chemical compounds with sub-100 nm resolution and high registration accuracy[39]. When a scanning probe tip, coated with chemicals, is placed in contact with a sample surface, a water meniscus is formed between the tip and the substrate. The meniscus facilitates the transport of chemicals from the tip to the sample surface, causing precise chemical deposition and patterning.

The DPN technique can be used to deposit a wide variety of materials, including organic (proteins, peptides, and oligonucleotide molecules[40]) and inorganic substances (magnetic particles, ceramics, and sol–gels[41]). When combined with subsequent fabrication steps, DPN technology can deposit and pattern a variety of structures.

With a single DPN probe, one can accomplish chemical patterning with high spatial resolution. However, single DPN probes encounter problems in two areas: (1) the throughput and area coverage is limited; (2) to perform complex surface patterning and subsequent characterization, tedious pen swapping and realignment is necessary.

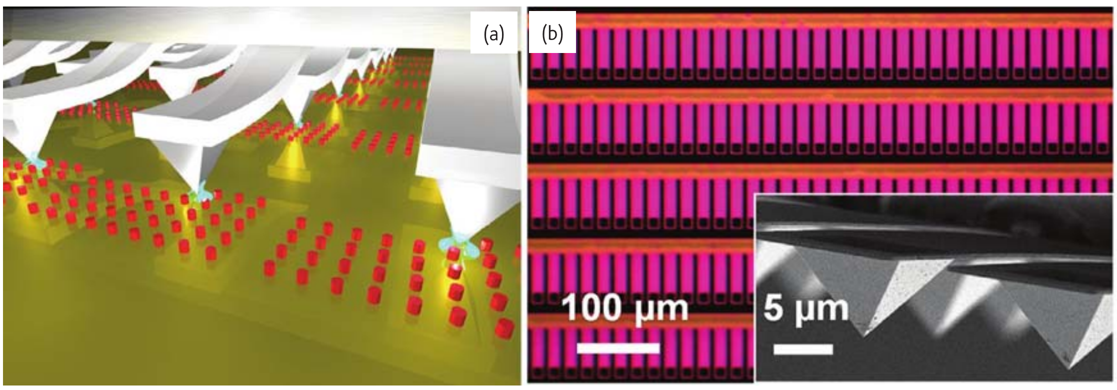


*Fig. A 6 55,000-pen DPN array. (a) Schematic diagram of arrayed writing. (b) Micrograph of a section of the array.*

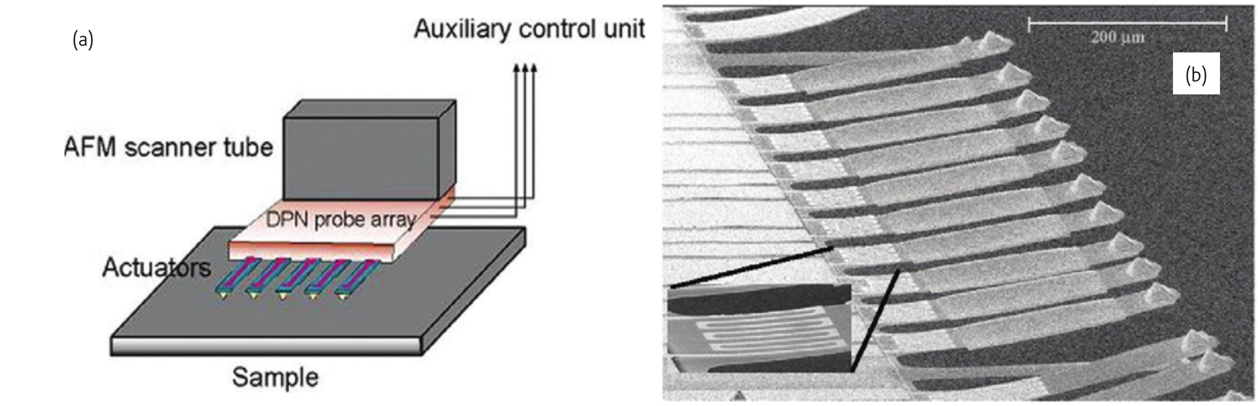


*Figure 7: Active parallel DPN actuation principles.*

An array of DPN probes could be used to address these issues. A passive array refers to an array of probes that do not have the ability to individually engage or disengage the surface. In other words, the probe array is often connected to a single mechanical motion stage to contact and disengage simultaneously.

Massively parallel DPN lithography with 55,000 pens has been demonstrated[42] to generate approximately 88 million dot features, each pen generating 1600 dots in a 40 × 40 array, with the size of each dot being 100 ± 20 nm in diameter and 30 nm in height. The average distance between dots is 400 nm. Million-pen probe arrays have been developed, using the mold and transfer process[33].

### Active DPN probe array

In an active DPN probe array, each probe is endowed with the ability to engage or disengage with the writing surface independent of others. Displacement of the tip may be accomplished by introducing

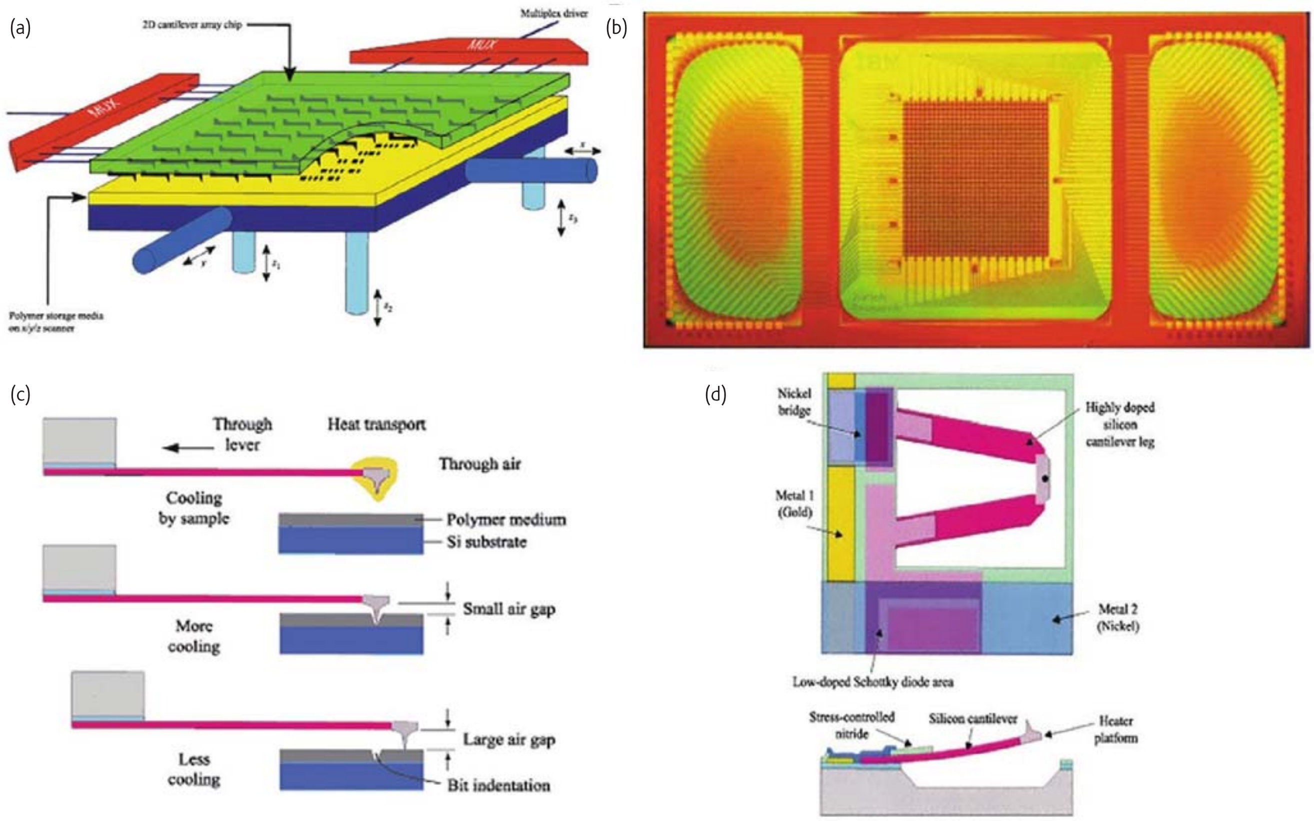


*Fig. 8 High-density scanning probe data storage concept. (a) Schematic diagram of the millipede system. (b) An optical micrograph of the chip array. (c) Concept of writing a single bit. (d) Top and side views of an individual probe.*

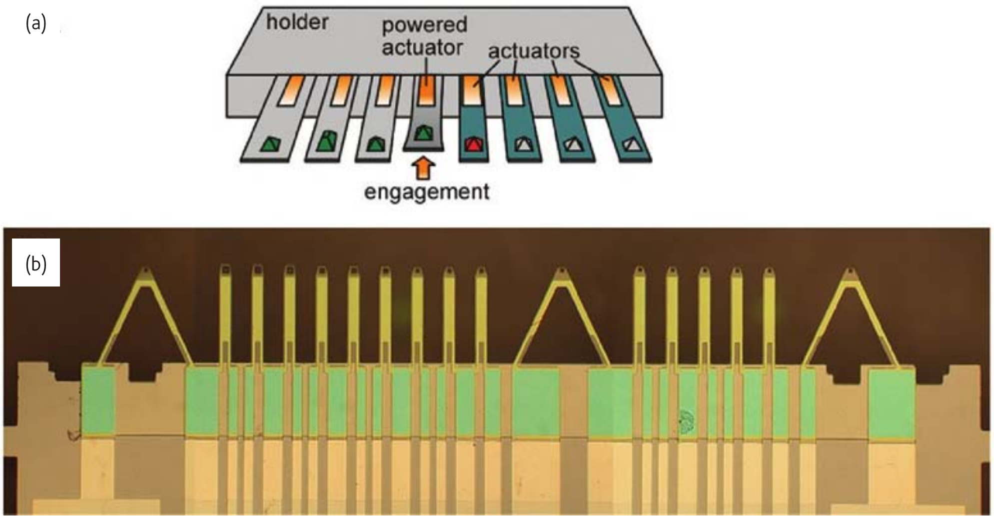


*Fig. 9 SAK probe diagram. (a) A schematic diagram. (b) An optical micrograph of a fabricated probe array.*

longitudinal stress in the cantilever (through thermal expansion[43] or piezoelectric conversion) or by introducing transverse force (through electrostatic force). If the displacement is produced by applying electric charge or current, each probe needs to be addressed by at least one conductive lead[44]. Among the common strategies of actuation (thermal, piezoelectric, capacitive), thermal actuation is one of the simplest, involving no special functional materials.

Compared with the passive probe array, there are additional challenges stemming from the need to integrate actuators on the probes and to control the motion of individual probes. The introduction of actuators sometimes introduces new issues concerning the chemical, thermal, and mechanical compatibility of processing.

The design of active probes for DPN must satisfy a number of criteria. (1) The probe must be sufficiently soft to avoid scratching and damaging the writing surface. (2) On the other hand, the probe must be sufficiently rigid to avoid being stuck to the surface by surface tension. (3) The cantilevers should have minimal actuation cross-talk. For thermally actuated probes, for example, thermal heating can be transferred from one probe to another. This limits the minimum distance between probes[43].

A thermally actuated active DPN array has been developed consisting of at least 10 individually addressable probes (Fig. 7)[44]. Each probe consists of a patterned resistive heater near its base (Fig. 7B). A modest temperature increase would introduce vertical displacement of the tip.

## Active array – data storage

IBM has developed a high-density data storage technology that uses an array of scanning probes (Fig. 8)[45]. Each scanning probe has a thermal heater allowing its temperature to be independently raised above the ambient. When a heated probe is placed near a polymer substrate, the intended memory media, the temperature causes localalized melting of the material. Imprinting action by the heated probe produces a dent, representing a binary bit. A high-density array of such thermal probes can be used to write large numbers of digital bits onto the media[45].

## Multifunctional array for nanofabrication

Difficulties arise when traditional single SPM probes are used for more than one purpose. For example, a DPN probe can accomplish both chemical writing and imaging of deposited chemicals, but it is unadvisable to use the same probe to perform both writing and reading due to concerns over contamination. Certainly, the probe can be cleaned or switched in between steps. However, this action generally calls the probe to be removed from the SPM machine and remounted. Careful and time-consuming realignment must then be done.

A parallel array of multifunctional probes would eliminate the need for such time-consuming operations and increase the functionality and efficiency. Fig. 9A is a schematic diagram of a multifunctional active probe, showing a number of notable features. (1) Each probe is attached to an actuator to allow individual engagement and disengagement with the sample surface. (2) Neighboring probes may have different tip materials or tip geometries. For example, two neighboring tips may be made of silicone elastomer and $Si_3N_4$, one for scanning probe contact printing[34] and one for lateral force imaging. (3) The distance between probes is precisely defined. (4) Neighboring probes may have different cantilever geometry and materials. (5) Selected probes may have position sensing capabilities. Some probes may be individually addressable thermally, electrically, and mechanically.

With multifunctional probes, the concept of a parallel array can be expanded. An array may contain multiple probes, each being able to engage or disengage individually to perform a cohort of complex nanomanufacturing tasks in a serial fashion without needing to remove, remount, and calibrate probes in between steps. For example, the design and fabrication of a multifunctional SPM probe array has been demonstrated (Fig. 9B)[46]. The array contains three cantilevers with A-frames and 14 straight cantilevers. The A-framed cantilevers have $Si_3N_4$ tips. They are used for imaging. Nine of the straight cantilevers have tips made of silicone elastomers. Within the nine, the dimensions of the tips change. The other five straight cantilevers have $Si_3N_4$ tips and are used for general DPN patterning.

## Challenges

The science, technology, and applications of scanning probe instruments will continue to be advanced in the future. However, future advancement will require close collaboration between scientists, engineers, and application experts. The path to commercial success or even laboratory success is not straightforward. The most significant barriers include the design and manufacturing of parallel probe systems, and high-throughput, nanometer-resolution imaging.

The development of SPM probes and instruments must be done in the face of competing technologies. In the commercial world, parallel probe technology must compete with existing methods. They must provide an order of magnitude improvement in performance and cost in order to displace existing techniques and to open new possibilities.

In the arena of pattern generation, scanning probes compete with electron-beam (ebeam) lithography and optical lithography. In the area of surface characterization, the scanning probe methods compete with scanning electron microscopy (SEM). In the area of nanofunctionalization, the DPN method competes with microcontact printing.

## Conclusions

The SPM is a powerful tool that has found many diverse and important applications in science and technology. Parallel scanning probes present an exciting and inevitable extension of single-probe scanning probe microscopy methods, which suffer from low throughput, inefficiency, and lack of functional richness. Parallel SPM instruments make possible new applications such as nanomanufacturing, high-density data storage, and high-throughput surface characterization, detection, and imaging. Future development of new parallel scanning probes will enable emerging applications and lead to industrial-scale application of SPM techniques. mt

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