SCANNING PROBE MICROSCOPY (SPM) analysis of materials is reliant upon direct physical interaction between a scanning probe and a sample surface. This physical interaction provides a range of analysis and surface modification techniques that are unique in microscopy and offers particular advantages and limitations. Precise computer-controlled positioning capabilities of SPM instrumentation continues to improve and is being combined with new nanoengineered probe types to achieve long-sought nanotechnology goals and minimize some of the traditional limitations of scanning probe technology.

SPM is a nondestructive technique that does not require sectioning or fixation of a sample for analysis. By direct manipulation between the probe and sample, measurement of forces, heat, material properties, chemical information, and other data types as well as modification, deposition, and removal of material has been achieved. This wide range of applications has largely been accomplished by a small set of available probe tools. Scanning probes historically have been fabricated from silicon or silicon nitride using traditional lithographic techniques and are approximately pyramidal in

A New Generation of Scanning Probe Technology

State-of-the-art and novel applications.

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shape. The pyramid shape is the result of the probe fabrication approach, and the sharpness can be tailored, but because silicon is a brittle material there are tradeoffs between sharpness of the probe and the ability of the probe to withstand the imaging forces involved. Silicon structures fabricated using lithography are typically on the order of microns, but SPM works on scales of fractions of a nanometer, and so the functional shape of SPM tool needs to be precisely defined at the nanometer scale. Engineering structures out of silicon from 2 µm down to tens of nanometers becomes increasingly difficult. The material and techniques employed limit silicon technology versatility for SPM probe development. Probe structures made from silicon have thus far been rudimentary, but recent advances have the potential to drastically change that paradigm.

**CARBON NANOTUBES**

Carbon nanotubes (CNTs) have remarkable material properties and are thought of as the ideal material for everything from SPM probes to computer circuits. However, CNTs grown in chemical-vapor deposition (CVD) reactors naturally grow in every direction and have curvature on the order of tens of nanometers. To create a CNT probe, a single CNT from a bulk sample was manually attached to a cantilever in the early attempts [1], [2]. Then, researchers managed to grow CNTs directly on the cantilever using CVD [3]. Although these attempts have yielded CNT probes capable of atomic-scale imaging, the next step of engineering a useful device out of CNTs with controlled morphology was out of reach until recent breakthroughs by researchers at the NASA Ames Research Center in Mountain View, California, and its spinoff Carbon Design Innovations (CDI) in Burlingame, California. They used post-growth CNT-processing procedures to form and mold the CNT into almost any desired shape for advanced imaging applications [4].

CNTs can be a few nanometers in diameter and microns long. By using a focused ion beam-molding process, the CNTs can be transformed into a three-dimensional (3-D) shape, and then, the desirable properties such as high-electrical conductivity or high-tensile strength can be engineered in place to create a functional device. This CNT-shape control can be used to develop a new generation of scanning probes where the probe tool is designed specifically for the job, as shown in Figure 1.

**CDI-PROBE TECHNOLOGY**

CDI-probe technology uses multiwalled CNTs (MWCNTs) that naturally form in nanodimensions, essentially as a scaffold upon which other materials can be deposited or removed to create precise 3-D shapes that would be extremely difficult to make out of silicon alone. We use this technology to make three standard probe types: the carbon core high-resolution (CCHR) probe, carbon core high-aspect ratio (CCHAR) probe, and carbon core biosciences (CCB) probe.

All three probe types have an MWCNT at the center of a composite structure consisting of two or more materials with the largest difference between the three probe types being their overall length. The composite structure starts with an MWCNT and follows with sequential addition of one or more from the choices of Si, SiO₂, Si₃N₄, metals, and various polymers, including biocompatible materials, depending on the tool being developed.

**FIGURE 1** A CNT atomic-force microscope probe fabricated by CDI Inc. shows precisely defined angle and length. The CDI CNT probe has been straightened, aligned, and stabilized with proprietary coatings and fabricated for microelectronics metrology applications.

**FIGURE 2** (a)–(d) A CNT exhibiting multiple 45° bends applied sequentially using a patented CNT molding process.
The technique used to shape the CNT is so versatile that the CNT can be precisely bent to any angle, and multiple bends can be used to create a 3-D form out of the CNT, as shown in Figure 2. CNTs in more complex shapes can be used for everything, from scanning probes to CNT nanoantennas.

Progress toward many crucial nanotechnology research goals has been slowed for lack of proper probe technology. CNTs have a high-aspect ratio, and they have been proposed for various SPM applications because SPM topography data types are derived from a convolution of the shape of the probe employed and the shape of the sample of interest. A well-defined probe shape engineered for specific sample types simplifies the deconvolution of the topography data and maximizes the data extracted. One of the applications envisioned is critical dimension metrology in integrated-circuit manufacturing. SPM provides a nondestructive technique to map the shape of a trench or via in silicon chips. Obtaining vertical sidewalls is often a goal of the process engineer, and using SPM to measure such structures has been a goal of the SPM community.

However, this is a difficult task for pyramidal-shaped silicon SPM probes, and high-aspect ratio silicon-spike probes are brittle and can break during imaging. In a CNT, carbon atoms self-assemble as a high-aspect ratio structure, and CNTs are physically very robust. However, it took new nanoengineering techniques to make a CNT probe with a precisely defined CNT angle, as in Figure 1, and with a tapered stabilization coating around the CNT that allows these CNT core probes to set a new benchmark for stable long lifetime high-aspect ratio imaging for metrology applications.

**FIGURE 3** (a) A silicon probe, (b) single-crystal diamond probe, and (c) CNT probe imaged the same microelectronic circuit defect. Because of its high-aspect ratio and cylindrically shaped tip, the CNT probe is able to track vertical steps and minimizes tip-sample convolution and tip-broadening artifacts.
Imaging lithographically defined microelectronic structures using standard probe types can obscure crucial data required for failure analysis and quality control due to tip broadening and tip shape artifacts induced by the probe–sample interaction. For example, a microelectronic device that had undergone a catastrophic failure was analyzed for defects, and CDI CNT probes were able to more accurately track the sample surface compared with standard probe types. As shown in Figure 3, a platinum-coated silicon probe (ANSCM-PT), single-crystal diamond probe (SCD15/AIBS), and CNT probe (CHAR) were compared.

The CNT probe is able to track 1.2-µm vertical steps with a measured vertical angle of 87.64°, whereas the silicon probe measured a maximum vertical feature angle of 73.05°, and the SCD probe measured a maximum vertical feature angle of 75.22°. The CDI CNT probe stabilization coating allows their CNT probes to acquire stable, artifact-free images at longer lengths than has been employed with other CNT probes.

Adoption of SPM analyses of biological high-aspect ratio sample types has similarly been slowed because of lack of proper high-aspect ratio probe technology. SPM is only recently gaining acceptance in whole-cell imaging applications. Cells have dimensions of interest ranging from microns down to nanometers. With new probe tools commercially available, whole cells can be imaged in buffer solution, and the cell can remain viable during analysis of dynamic cellular morphological changes over time. Recent results from researchers at the University of California, Davis, using CDI CCB probes show that these probes accurately resolve the whole cell, including details on the top and down the sides of the cell, as shown in Figure 4 [5]. The CDI CCB probe is the longest high-aspect ratio CDI probe type and the longest CNT probe currently offered on the market. The CDI CCB probe can have lengths up to 5 µm.

Imaging artifacts caused by the convolution of the standard tip shapes and cell surface can obscure desired morphological analysis. The silicon probe, in this comparison, generates strong artifacts, but CDI’s high-aspect ratio CCB probe is able to accurately track the cell surface resolving data with minimized imaging artifacts in lateral dimensions so that morphological differences in the cell surface can more easily be identified. Such studies are becoming increasingly more important in the life sciences with improved understanding of the relationship between cell morphology and the status of a cell, both in terms of the health of the cell and its differentiation state. For example, monitoring cellular differentiation is vital for stem-cell research, and by using high-aspect ratio scanning probes, the state of a viable cell can be monitored over time to elucidate dynamic cellular relationships and increase applicability of SPM analysis in the biosciences.

**CONCLUSION**

The history of probe-tool development has gone from a one-size-fits-all silicon pyramid shape to differentiation of the silicon pyramid forms, and recently carbon and other materials are being brought together and combined with existing silicon technologies to make precisely engineered probe tools for specific imaging and other SPM tasks. The next step for this industry entails applying newly developed probe technologies to build the next generation of scanning probe tool types. Probe developments will be combined with increases in scanning speed and accuracy, and more advanced designs will begin to address many of the other anticipated SPM technologies to deposit, remove, pick and place, or modify materials at the nanoscale. Such tools will enable fabrication of increasingly sophisticated devices on the nanoscale using both top–down and bottom–up approaches. Nanotechnology is evolving beyond the first flash of discovery, and recently nanoscale tools and the necessary supporting machinery are beginning to be available that will fuel growth for this industry.

**ABOUT THE AUTHOR**

Ramsey M. Stevens (rstevens@cdi-nano.com) received his B.S. degree in physics from the University of California at Santa Barbara. He is the founder and president of Carbon Design Innovations Inc. and a leader in the development and use of CNTs. He has authored more than 40 technical papers, has three patents pending, and has worked in nanotechnology development for more than 15 years at leading nanotechnology institutions.

**REFERENCES**


![Figure 4 The 3-D atomic-force microscope topographic images of the identical rat basophilic lymphocyte cell with an arrow showing the same region in each image. Images are 15 × 15 µm scans. (a) Topographic image using a commercial silicon probe reveals that it is unable to image the side of the cell, obscuring the region highlighted by the arrow. (b) Topographic image using a CDI CCB probe resolves the same cell surface accurately.](image)