



Surrey NanoSystems' Gamma 1000n, with multiple carbon nanotube/nanomaterials synthesis modules, provides a view to production-scale capability.

A growing need

Nanotube synthesis tools await electronics applications

BY TOM CHEYNEY

The number-one player in the precision nanotube/nanowire research and production equipment market is not one player at all, but a cast of thousands. "Our biggest competition is not a company; it's the people who are building it themselves," explains Brian Lim, CEO of Atomate.

"The biggest competition that we've seen so far is in-house builds," says Gary Dyal, First Nano's business development director. "There are probably thousands

of those types of systems found around the globe, with hundreds of them still being built every year."

Yung Joon Jung, professor at Northeastern University's NSF Center for High-rate Nanomanufacturing, is one of those do-it-yourself types. "I use a home-built system since my research requires a lot of modification of nanotube CVD processes for my own purposes. Also, I am doing research defining the fundamental growth of CNT and developing new CVD processes for nanotube growth."

Despite his own experience, Jung does believe there will need to be a dedicated precision CNT growth/synthesis tool sector. "For the nanotube-based electronic applications, we need to develop this. We have to design the tool toward chirality [electronic structure of CNT], structure [single-wall, multi-wall, and double-wall nanotubes], and length control. Still, more fundamental studies are required in this area, especially on the growth mechanisms of CNT. But once it is defined, industries need to develop tools to exactly produce CNT on very carefully designed substrates."

Brent Segal, co-founder and COO of Nantero, believes CNT growth tools may not be a necessity, or at least would depend on what people are trying to create. "For certain applications such as field emission displays [FEDs], these tools could be quite useful. In our experience, random arrays of CNTs work especially well and can be used in combination with photolithography for nearly any process desirous of electrical conductivity. I would need to know an application where grown CNTs on a substrate are preferable. That said, several groups have shown that random networks [vertical] work just as well as aligned."

Small but growing market

Although many foresee a volume-production sector emerging in the future, the lower margin research-tool market remains the bread and butter of the CNT equipment companies, with numerous academic and national lab customers and a growing number of industrial clients. In terms of actual market size, although annual growth rates are sky-high, the numbers won't add up to a multibillion-dollar segment for years.

SEMI statistics released in May 2007 show the entire nanotechnology tools/equipment sector hitting \$3.6 billion in 2010, but metrology and lithography account for \$2.26 billion of the total, leaving less than \$1.4 billion for the remaining categories, such as "atomic manipulation," deposition, furnace, and other possible CNT production tool slots. On the nanoelectronics materials side, SEMI forecasts

a market growing to \$1.135 billion by 2010, with the fullerenes/nanotubes subgroup earning just over \$100 million.

In the beginning, NanoScience

The roots of the CNT precision-synthesis systems sector go back to 1999, when a company called NanoScience hung out its shingle in Santa Barbara, Calif. NanoScience had a nice little business making and selling atomic-force microscope probe tips. The company's innovative technology and relative success caught the attention of Veeco Instruments, which bought NanoScience in 2003. But the large metrology and equipment supplier had little use for the EasyTube components and equipment NanoScience had developed.

"There were no real commercial tools for growing nanotubes, so we saw a real market opportunity," recalls Atomate's Lim. Two spin-off companies—Atomate and First Nano (with most of the EasyTube team)—went their separate ways. Both companies' businesses have grown, albeit by different means: First Nano, through acquisition—it was bought by CVD Equipment in May 2005; and Atomate, through expansion—the company, which has more than 150 customers worldwide,

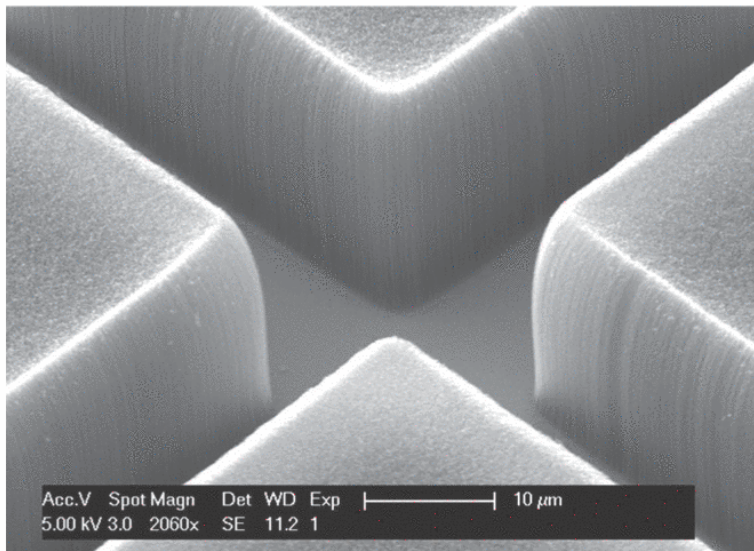
moved from its original location to a much-larger site in Simi Valley, Calif., in October 2006.

Lim believes his and his NanoScience colleagues' experience trying to fabricate CNTs at the end of probe tips provided valuable lessons.

"What we learned from growing nanotubes at the ends of AFM probes is that when you try and come up with a process that works for a few and you try and work [the process] over a 4-inch wafer, your uniformity goes down quite a bit. But that's when you work on other, different variables so that you can actually tune that uniformity back up.

"But creating that first chip, where you can get over 50% uniformity, I think that's a critical step. Then you can understand the chemistry and physics to figure out what's happening, identify the problems, and then come up with designs that get around them. The biggest challenge is repeatability. You have to be able to build that device over and over again."

Lim says Atomate has a system capable of "running 4-inch wafers on a production scale" and sees 8-inch capability within the next three years. "We have a production process with which we are able to grow this uniformity over a half-wafer, and now



Atomate's plasma enhanced CVD process runs at nearly 500°C to enable, as shown here, vertical growth of highly aligned single-wall carbon nanotubes on glass.

the project is going forward to full-wafer uniformity. You have to be able to use nanotubes over 80% of the surface to even call it uniform. I think we've achieved that: Now we're introducing the whole wafer to this process, and we expect to get 80%.

"We're not as interested in mass production of multiwall CNTs and such," claims Lim. "We're interested in equipment that leads to electronic devices using nanotubes or nanowires of different materials, and that requires a tremendous amount of process knowledge. We're basically driven by process, and we believe that our competence is the process itself."

The other progeny of NanoScience has seen its installed base edge ever-closer to the 100-system mark, according to First Nano's Dyal. "The EasyTube 2000 and 3000 were designed for synthesizing carbon nanotubes and silicon nanowires at the research level. We have identical equipment in our in-house laboratory that we operate on a daily basis, and we develop base recipes that are transferable to the systems we sell.

"So if we have a customer that comes in and they have a specific requirement, we can grow a sample for them, they can test it and make sure it meets their requirement. If it meets the requirement, then they'll order the system, and we can build it identically to the one we did research on, ship it to their location, and transfer that recipe, and then they have a base recipe to start their research programs on."

First Nano will soon offer a new system capable of higher-volume manufacturing. The next-generation EasyTube tools—the 12000—will be coming out later this year, says Dyal. "It's a larger production platform. We'll be able to do 6-, 8-, 12-inch, and even-larger substrate sizes for CNTs or silicon nanowires."

Competition

The new kid on the block is Surrey NanoSystems, which started as a U.K. joint venture in 2005 between thin-film tool manufacturer CEVP and the University of Surrey's Advanced Technology Institute, when the research unit developed a process for fabricating CNTs at room temperature. With funding from the IP Group, the two

joined forces in December 2006 to form a new corporation—Surrey NanoSystems. The company made its commercial debut at NSTI Nanotech 2007 with the launch of its NanoGrowth 1000n platform.

One of Surrey's strategic goals is to provide tools for growing CNTs that will replace copper as the interconnect of choice in advanced CMOS manufacturing. "CEVP was approached to build a specialized small-geometry sputtering tool," explains Gerry Thurgood, company executive chairman and CEO. "They developed the current [Gamma] tool, where you can physically put down a nickel coating, which can then be patterned.

"One challenge is, 'how can you actually control the carbon interconnect, the quality of it, the structure of it, the adhesion of it?' By incorporating several technologies into one tool, what we can do is grow reliable and high-quality carbon interconnects, generally between 5nm and 20nm thick, and we can control the density.

"We can place the carbon down at low temperatures, between 200°C and 300°C, which is well within the CMOS bracket. The system we've got today incorporates in situ etching, the sputtering tool for putting down the catalyst, and we've also got the growth tool, all integrated into one system.

"The challenge going ahead is that it's an R&D tool," notes Thurgood. "We've been selling the basic tool as it is, but when you talk to the bigger end users, the bigger manufacturers, the question is, 'is it an R&D tool or is it production-worthy?'"

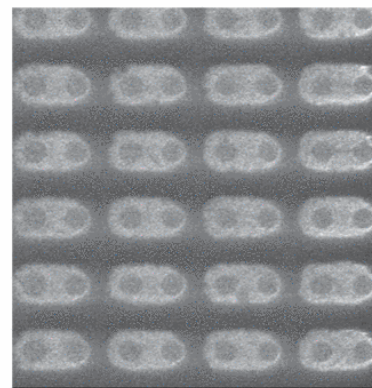
"We're talking to some of the large equipment manufacturers to see how we can scale it. We feel that in 2010 or 2012, it could become a practical application. We understand all of the physics and chemistry of the nanotubes, so the next thing is how we would make it production-worthy. What we're doing now is talking to some potential OEM partners, who could manufacture the equipment for us, about how we can scale it and accelerate it into a 300mm model."

CNT bears and bulls

Despite the optimism of the CNT precision-synthesis tool companies as well

as the research community and some in the industrial world, the bears may be as numerous as the bulls. "The scaling of microelectronic devices could lead to a desire to use carbon nanotubes or semi-conducting nanowires in about 10 years," summarizes Cambridge University's John Robertson in his paper, "Growth of nanotubes for electronics," in the January-February 2007 issue of *Materials Today*. Noting the difficult requirements for the precise synthesis of nanotubes, including "controlling growth location and achieving high-enough nucleation densities," he says "these barriers to implementation may lead to more-pessimistic time scales."

But Nantero claims that, along with fab partner ON Semiconductor, it has successfully integrated CNTs using stan-



Nantero has integrated carbon nanotube arrays into CMOS processes—one of the first nanoelectronics applications for CNTs.

dard semiconductor processing into its NRAM devices. Brewer Science recently announced the availability of a line of microelectronics-grade nanotubes. On the equipment side, Atomate, First Nano, and Surrey NanoSystems find themselves in a nascent OEM market and are optimistic about the adoption of an increasing number of nanoelectronics applications for nanotubes and nanowires—and their roles in developing them.

Whether it's five or ten years away, "once nanotubes prove themselves suitable materials for the semiconductor industry [as interconnects or transistors]," says Northeastern's Jung, "wafer-scale nanotube synthesis tools will be needed." ■