High-Purity Single-Walled Nanotubes Manufactured

The Pitch

Since their discovery several decades ago, single-walled nanotubes (SWNTs) have received significant attention from developers in the electronics, energy, materials, and biomedical industries for their unique materials properties. For example, SWNTs can be either conductive (metallic) or semiconducting, they are thermally and environmentally stable, and they can be readily functionalized with a wide array of biological molecules (see Figure 1.)

Despite the outstanding properties of SWNTs, the widespread use of nanotubes in commercial applications has so far been precluded by limitations in SWNT manufacturing. SWNTs can currently be produced in large quantities using growth methods such as arc-discharge synthesis and chemical vapor deposition. These manufacturing technologies, however, can only generate batches of tubes with mixed optical and electronic properties. (Most growth methods produce SWNTs that are 70% semiconducting and 30% metallic.) This is problematic for many potential carbon nanotube (CNT) applications—for example, transistors, transparent conductors, telecommunications devices, and optical sensors—where a high degree of electronic uniformity is required.

NanoIntegris, a supplier of single-walled carbon nanotubes and graphene (one-atom-thin sheet of carbon) nanoplatelets, has effectively solved this polydispersity problem. The company has developed a robust, scalable technology for sorting as-grown SWNTs by their optoelectronic properties. NanoIntegris takes raw nanotubes, which are 70% conductors and 30% semiconductors, and sorts them so that their samples are 99% semiconducting or 99% metallic. By providing researchers with high-quality, electronically pure nanomaterials, the company seeks to enable new useful advances in nanoscience and technology.

Figure 1. Metallic, unsorted, and semiconducting single-walled nanotubes (SWNTs) dispersed in a simple water-based solution.

During the past several years, NanoIntegris has optimized and scaled-up its technology to serve the needs of the nanomaterials community. Since initiating product sales in October 2008, metallic and semiconducting SWNTs have been purchased by over 100 academic and industrial customers worldwide. The company's metallic and semiconducting SWNTs have been used to achieve record-setting SWNT performance in applications such as field-effect transistors and high-frequency electronics.

The Technology

A technique called density gradient ultracentrifugation (DGU) is used to sort the carbon nanotubes by electronic type. DGU works by exploiting the subtle differences that exist among SWNTs with different optoelectronic properties. First, unsorted SWNTs are dispersed in a water-surfactant solution. The solution is then inserted into a density gradient and centrifuged. During centrifugation, the nanotubes migrate to their isopycnic (same density) points in the gradient. Because the optoelectronic properties of CNTs are determined by their physical structure (diameter and chirality), separation by density enables separation by electronic type. After centrifugation, the sorted nanotubes are collected for analysis (see Figure 2.)

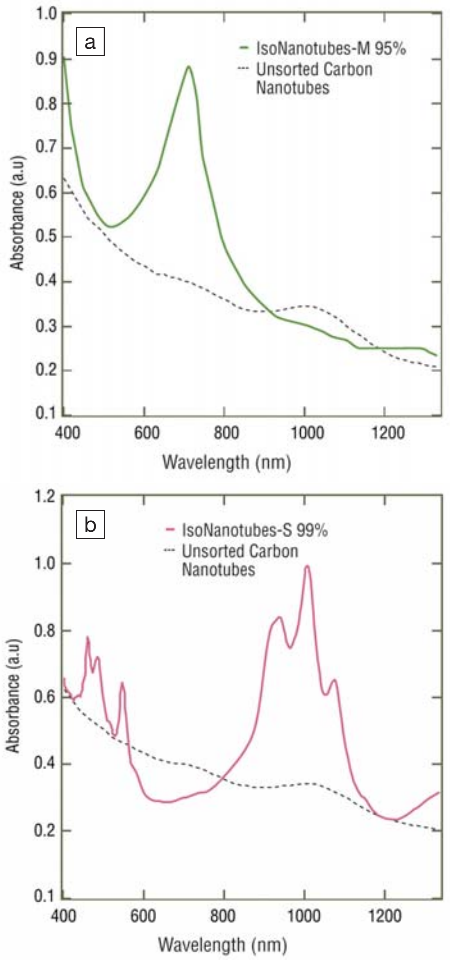

Figure 2. Optical absorbance plots for metallic, semiconducting, and unsorted single-walled nanotubes. Reduction in the metallic/semiconducting transition-energy peaks (e.g., M11, S22, S33) is clearly visible after sorting.

There are several characteristics of the NanoIntegris technology that make it particularly suitable for commercialization. In addition to electronic type, enrichment by DGU has been reported with respect to nanotube diameter, chirality, length, and handedness. DGU has also been used to sort pristine graphene nanoplatelets by flake thickness and layer number. The company's separation technology is compatible with SWNTs of virtually any dimensional range (e.g., small-diameter, large-diameter, long, short) plus SWNTs produced by any synthesis method. In addition, the sorting process removes many of the carbonaceous and metal catalyst impurities that occur naturally in as-grown nanotubes, thereby producing material that is not only electronically uniform but also of high purity.

Opportunities

NanoIntegris is seeking research collaborations with academic and industrial CNT and graphene scientists. Research areas include, but are not limited to, transistors, transparent conductors, saturable absorbers, infrared detectors/emitters, high-frequency electronics, chemical sensors, composites, and drug delivery.

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TECHNOLOGY ADVANCES seeks materials developments on the threshold of commercialization. Send suggestions to Renée G. Ford, Renford Communications, renford@comcast.net.

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Carbon Nanotube Processing Techniques Enable Advances in High-Aspect Ratio Atomic Force Microscope Imaging

The Pitch

Since its invention in 1985, the atomic force microscope (AFM) has allowed scientists to understand materials properties by looking at and characterizing features at the nanoscale. However, the full potential of the AFM as a nanotechnology tool has been limited by the shape, size, and availability of reliable AFM probes that can be used to explore the extreme regions of a sample with high resolution. Carbon nanotubes (CNTs) have been thought to offer a solution, but until now manufacturers have been unable to produce reliable CNT probes for the AFM. The problems encountered with CNT AFM probes include bending, off-vertical imaging angles, and weak attachment to the cantilever that make it difficult to perform repeat image scans. Their high-cost, lack of data reliability, and short lifetime have deterred researchers from using CNT AFM probes.

Carbon Design Innovations (C|D|I) has developed CNT AFM probes to resolve these problems. The probes make it possible for researchers to see and characterize details at high resolution and in the vertical (*Z*) range that they have not been able to examine previously. The probes extend the capabilities of AFM and have the potential to increase the overall market by enabling researchers in life sciences, materials research, and metrology to further their work in applications such as drug discovery and defect analysis. In recent tests using the single CNT AFM probes, high-quality images have been produced for between 70 to more than 500 consecutive scans without any observable degradation at a cost of about $10.00 to as low as $1.50 per scan (see Figure 1). At the low-cost end, the useful life of currently available Si probes that have much poorer *Z*-imaging capability averages four scans per probe at a cost of about $6.00 per high-quality scan. At the high-end for another CNT probe or for a focused ion beam milled high aspect ratio probe, the cost per scan could be as high as $60.00 to $100.00. C|D|I can attach its CNTs to any AFM probe and CNT probes have the potential to improve performance for any commercially available AFM. The total AFM probe market is estimated to be more than $100 million.

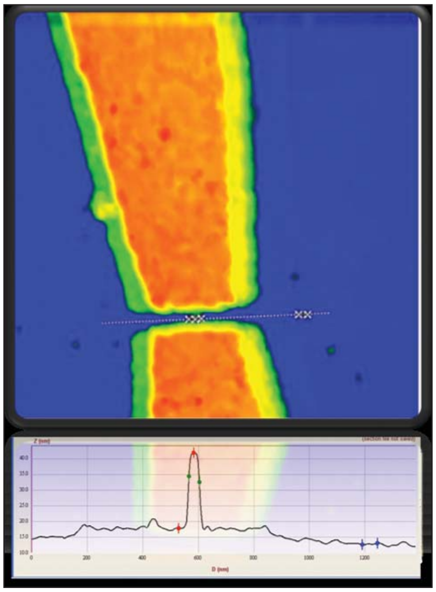

Figure 1. Three-dimensional representation of an atomic force microscope scan of a semiconductor superconducting quantum interference device (SQUID) part featuring a “bridge” at the base of the trench with a histogram of vertical relief below.

The Technology

In a new approach to CNT processing, C|D|I has developed technology that addresses the issues that plagued early attempts to make CNT AFM probes. The company’s patented ion flux molding (IFM) process allows C|D|I to introduce a new class of CNT AFM probes by controlling the shape and form of the nanotube and thus producing probes that are straight, strong, and durable. Using the IFM process, CNTs, which naturally grow in a curly fashion, are straightened and firmly attached to AFM cantilevers at an angle that is normal to the imaging surface (see Figure 2). This process, plus the intrinsic strength of CNT, allows C|D|I to reliably produce high-aspect and high-resolution CNT AFM probes that offer longer imaging lifetime and allow researchers to explore extreme regions of a surface with higher accuracy and more detail than previously possible.

The IFM process is not necessarily limited to producing AFM probes. The company believes that the same nanomaterial control techniques can be applied to CNTs for applications in other areas thereby allowing CNTs to be more practically integrated into other devices and to offer improvements in many other fields such as cellular probes, biosensors, energy conversion and storage, nano-antenna, and similar photonic devices.

Opportunities

Carbon Design Innovations is seeking investment and development partners for its patented CNT processing techniques.

Source: Vance Nau, CEO, Carbon Design Innovations, 1745 Adrian Road, Burlingame, CA 94010, USA; tel. 408-404-0023; e-mail vnau@cdi-nano.com; and www.carbondesigninnovations.com.

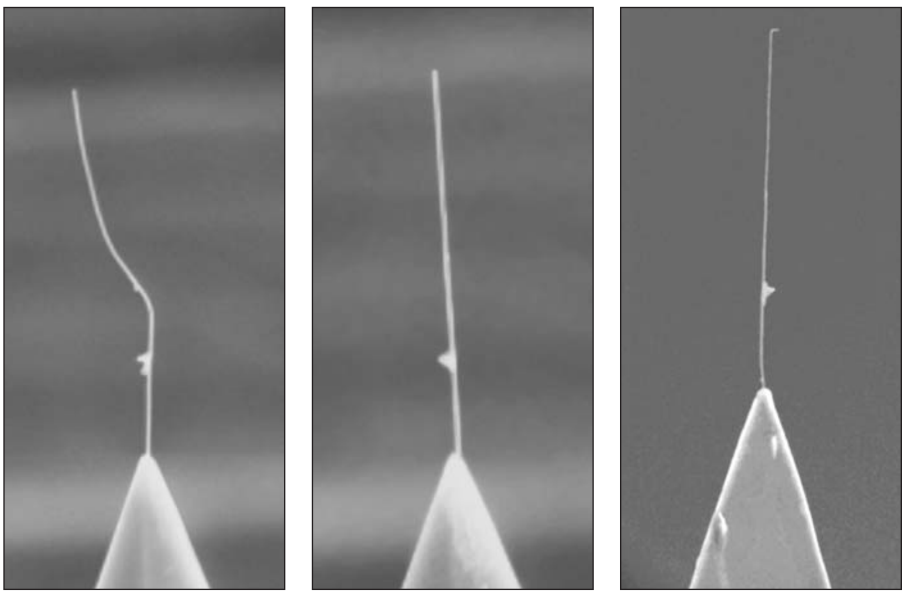

Figure 2. Scanning electron microscope scans of carbon nanotube atomic force microscope (CNT AFM) probes (*left to right*) in natural “curly” state, after IFM (ion flux molding) straightening, and with a 90° angle near the tip demonstrating ability to control shape.

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Glowing Images in Glass Using Nanomaterials

The Pitch

The company SuperImaging uses nanoparticles to make transparent display screens that glow under ultraviolet (UV) light. Their innovative technology makes it possible to create digitally animated displays on clear glass. Previously, the size and viewing angles of small transparent surface displays such as heads-up displays have been limited. To create large projections has involved frosting the glass so it will catch part of a projected image or hanging an opaque TV-type screen in a window. SuperImaging's technology makes displays of any size possible that are viewable from any angle on 100% optically clear surfaces.

SuperImaging's technology is expected to markedly reduce the cost for display equipment. For example, if heads-up displays (HUDs) replace normal auto instrumentation and Global Positioning Systems (GPS), overall equipment costs could be reduced by as much as $150 per car. Estimated prospective savings based on current annual auto volumes could reach as much as $7.4 billion. The combined size of applications markets, which include automotive, home theater, and digital displays, could reach well over $500 million.

Current applications for SuperImaging's technology include an automotive company for driver vision enhancement, a glass manufacturer for architectural glass, and consumer electronics firms. Other potential applications include original equipment manufacturers (OEMs) of military vehicle, aircraft, and automotive instrumentation.

Figure 1. Superimaging's dual color automotive heads-up display (HUD) projector.

Figure 2. SuperImaging's HUD highlighting a road in the fog.

Figure 3. Saint Gobain, Paris showroom display.

The Technology

SuperImaging's research evolved from their basic concept that using reflection to display on clear surfaces was a flawed approach. They sought instead to make an emissive or glowing screen from minute particles that at less than 100 nm would be small enough to be invisible even with substantial loading on the surface. Although commercially available materials could be used to create a temporary display screen that could work for a few hours, for one that would operate for years, the company needed to specially engineer nanoparticles so they would last for many years. By using a combinatorial approach to hasten the research process and check different materials with a wide range of dopants, the materials science was gradually improved such that materials lasted longer and longer. The researchers found they could achieve a higher quantum yield with materials that reacted to UV radiation compared with materials that reacted to infrared radiation. They also investigated techniques for producing self-adhesive films that adhere to any flat surface as well as to many curved glass and plastic surfaces. A subsidiary was also set up to coordinate the production of projectors to work with their film.

Investigation of the HUD market revealed that the materials could be incorporated into the plastic layer inside the windshield. Compared with the existing systems of making a small (10 cm × 10 cm) HUD speedometer or having to use a suction cup to adhere a navigational display device (10 cm × 7.6 cm) to the windshield (see Figure 1), SuperImaging's capabilities offer the opportunity for new applications. These include projecting navigational information and highlighting potential external hazards anywhere on the windshield. Drivers who have difficulty seeing at night or who are driving in low-visibility conditions such as snowstorms or sandstorms could have the borders of the road highlighted for safe driving (see Figure 2). Police, firefighters, and military drivers could display critical GPS HUD information as well as other critical information from central dispatchers about victims, suspects, or the emergency scene.

In the digital display market, the message can glow on the window and be equally visible on both sides. Creating laser displays that move on the window through foreshortening, animation, and having a borderless projection area, not a lit-up rectangle, the images appear to be three-dimensional line art holograms not projected on the glass in two-dimensions, but floating in mid-air (see Figure 3).

For home theaters or corporate meeting room projection applications where a white reflective screen is usually used, SuperImaging's high contrast black emissive screen is <1 mm thick. Image quality is improved because with current systems the "black" parts of the image are a white surface without light projected onto it. Whereas SuperImaging's system provides a crisper image since the image glows from the black surface.

Opportunities

SuperImaging is interested in working with potential licensees for applications such as touchscreens as well as to develop projection devices for use with their technology.

Source: Doug Bragdon, SuperImaging, Inc., 43239 Osgood Rd., Fremont, CA 94539, USA; tel. 831-334-1840; and e-mail: doug@superimaging.com. Demo videos are available at superimaging.com or on YouTube under username superimagingdoug.

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