Nano is not yet a multitrillion dollar market, but applications are bursting previous bounds.

BY ALAN S. BROWN

Some things sound just too good to be true. It is easy to place nanotechnology in that category.

Like many breakthroughs, from superconductivity to the Internet, nanotechnology bulldozed its way into the limelight with a long list of promises. It promised affordable solar cells, green chemistry, quantum computing, and lightweight composite aircraft, to say nothing of cell-size robots to clean plaque from our arteries and cancerous growths from our organs.

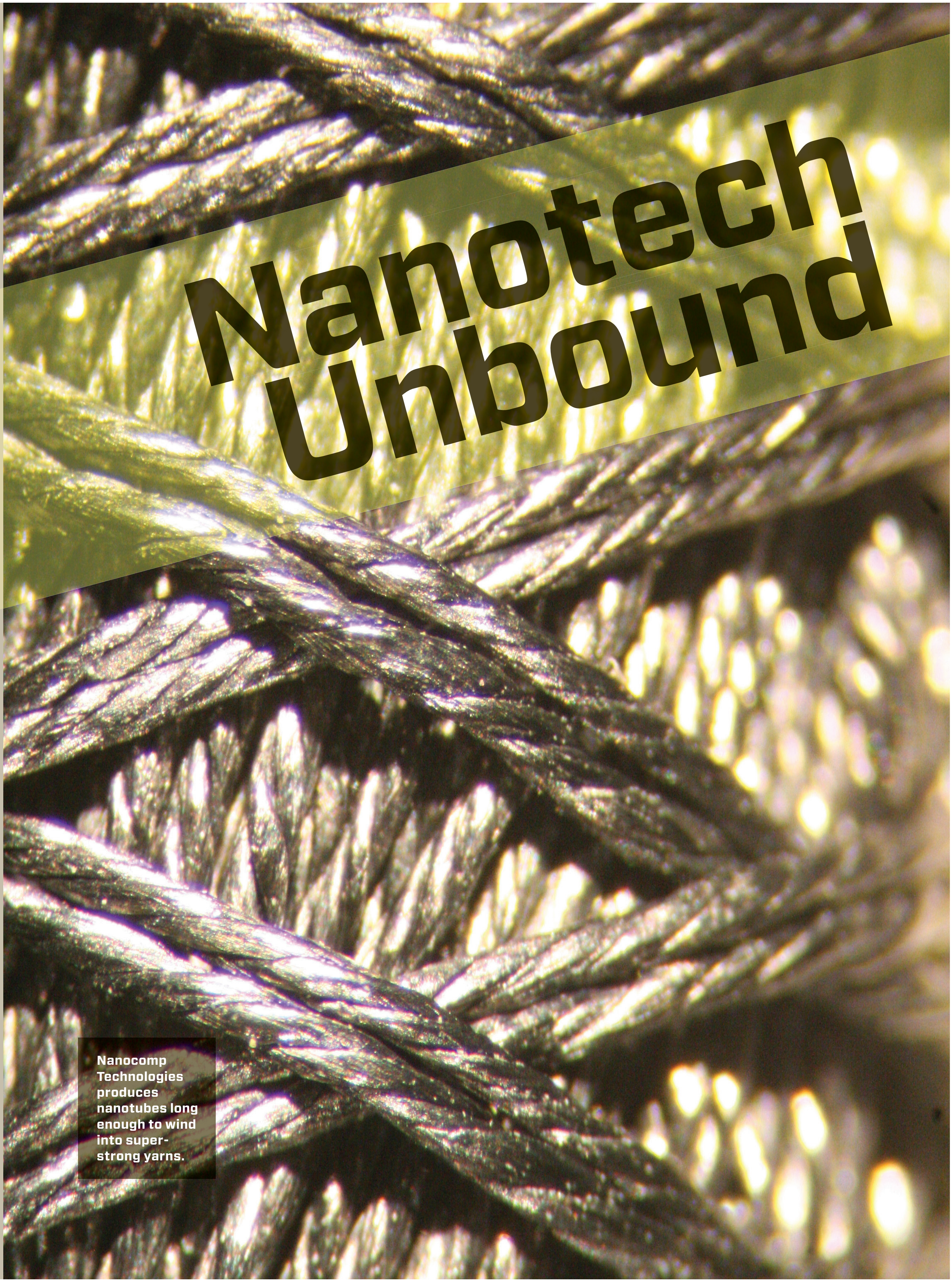
The hype did not stop there. In 2001, the National Science Foundation released a report, *Societal Implications of Nanoscience and Nanotechnology,* which casually mentioned a $1 trillion market sometime in the first half of this decade.

Market researchers, never shy about pumping the virtues of a hot technology, went further. In 2004, Lux Research projected the nanotech value chain would reach $2.6 trillion in 2014, almost as large as information technology or telecommunications. Three years later, Cientifica upped the ante to $2.95 trillion, about half in semiconductors. A 2010 report by Global Industry Analysts, San Jose, Calif., predicted a slightly more modest $2.4 trillion

Alan S. Brown is an associate editor of Mechanical Engineering.

NANOCOMP TECHNOLOGIES

Nanotech Unbound



Nanocomp Technologies produces nanotubes long enough to wind into super-strong yarns.

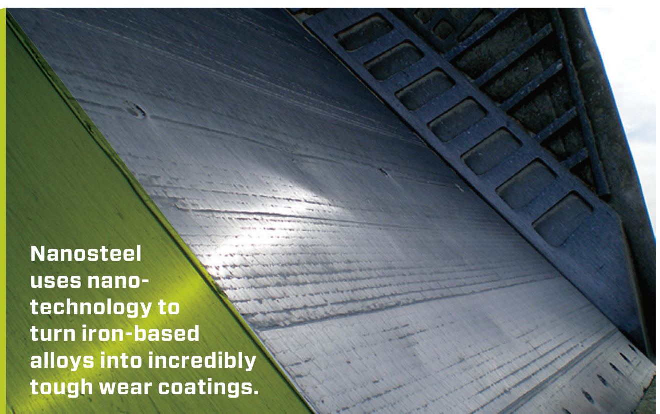
market within five years.

Such eye-popping numbers inspired startups. Entrepreneurs argued that if they captured just a small fraction of the total market, they could become huge. After all, a 0.1 percent share of a $2 trillion market equals $2 billion in sales. Wall Street jumped on the bandwagon.

Yet those numbers had a flaw, and it was not just unbridled optimism. According Michael Berger, the founder of the popular nanotech website, Nanowerk.com, the definition of "nano-enabled" was suspect.

In 2007, he found that a recent market study based its projections on the value of final products rather than their nanotech components. So if a $100 drug used 0.1 gram of nanomaterial costing $1, the study tallied the full $100 in its totals. Similarly, the $100 worth of nanomaterials in a scratch-resistant auto topcoat was rung up as a $40,000 Mercedes-Benz.

Even on Wall Street, that kind of accounting is a stretch. So when milestones on the road to trillion dollar markets



Nanosteel uses nanotechnology to turn iron-based alloys into incredibly tough wear coatings.

NANOSTEEL

failed to materialize, investors backed off. The nanotechnology bubble burst. Even businesses with promising technologies and solid markets could not line up financing. Then came the Great Recession.

Yet today, the nanotech scene is surprisingly upbeat. "While Wall Street lost interest, researchers at companies like IBM, DuPont, ExxonMobil, and Hewlett-Packard are still working away," said Steve Waite, a former Wall Street nanotech analyst who co-founded Research 2.0, an investment research service in Boston, Mass. He can point to scores of nano startups with promising technologies.

"Over the last decade, everybody was asking, 'Where is it?' We're just at the stage now where it's going to start seeping into everything. It is going to be part of the general technology landscape. The reason? It has taken a while to harness nanotechnology and learn to create products," Waite said.

One would expect Waite to be optimistic. His firm, after all, makes money by touting nanotech investments. Yet he can point to venture capitalist Harris & Harris, which specializes in nanotech investments. Last year, it sold one nano-enabled cancer drug maker, BioVex, to Amgen for $425 million in cash and up to $575 million in additional payments. It also launched two IPOs: NeoPhotonics, a maker of photonic integrated circuits, for $82.5 million; and Solazyme, which has modified algae to make oil and biomaterials in fermenters, for $227 million.

He can also point to market studies that paint a more realistic picture. Earlier this year, Global Industry Analysts Inc., which provides in-depth nanotech analysis, projected a $30 billion nanotech market by 2015, led by nanoscale thin films used in electronics, solar cells, light-emitting diodes, photonics, and wireless communications. Last year, the company projected a $4.4 billion nanobiology industry in 2014, chiefly for drugs to treat cancer, diabetes, heart disease, neurological issues, orthopedic ailments, and other problems. It also expects global demand for nanocomposites to reach 1.3 billion pounds by 2015.

The Project on Emerging Nanotechologies, a joint project of the Wilson Center, a Washington think tank, and the Pew Charitable Trusts, runs a database where manufacturers can list nanotechnology-enabled consumer products. Its offerings range from non-stick cookware to self-cleaning window treatments. It lists more than 1,300 products, up from 212 when it started in 2006.

In fact, nanotechnology may wind up looking a lot like the Internet. The dot.com bubble that burst in 2000 spawned thousands of companies. Many attracted funding with little more than a business plan and a promise, and collapsed virtually overnight when the air went out of the bubble.

Yet the Internet did not go away. Some companies, such as Google, Amazon, and eBay, lived up to early promises. Others resized their ambitions and became profitable purveyors of everything from hotel rooms and computers to shoes and pet supplies. Nearly every established company developed a web presence.

Moreover, the Internet continues to innovate. Google, Facebook, and YouTube have created entirely new ways of interacting. Smartphones have made those connections mobile, in ways that would have been impossible to imagine only 10 years ago.

Could nanotechnology trace a similar arc?

The New Nano

Vincent Caprio, executive director of the NanoBusiness Commercialization Association, is one of nanotechnology's most ardent champions. Yet he avoids calling it an industry.

Instead, like the Internet, he describes it as "a foundational technology platform." It is embedded in many industries, like aerospace, electronics, transportation, and energy. I can't think of a major industry that it will not affect," Caprio said.

He argues that businesses are using nanotechnology the same way they use information technology to achieve competitive advantages across a broad range of business processes, from selling products and automating transactions to optimizing production and managing logistics.

Nanotechnology has begun to cut an equally wide swath in products. These range from downhole drilling and solar energy to photonic circuits and drug delivery. Hewlett-Packard and Hynix Semiconductor plan to manufacture the first computer memory to take advantage of nanoscale phenomena.

"These companies all have different technologies that are built around the science of nanotechnology," Caprio said. "They all have different products, and they are all absorbed into different industries."

Nanotechnology's successes are underreported because successful startups rarely mention their nano roots, Caprio added, sounding defensive. He points to Metabolon in Durham, N.C., as an example.

Metabolon makes diagnostics to analyze cellular traces of metabolic processes. The analysis can determine how drugs and disease affect a specific patient, so physicians can optimize treatment for each individual. When Metabolon started out, it proclaimed its unique nanotechnology. Today, the word has vanished from its website.

Why? If Metabolon goes public, Caprio said, it will have to compete in a crowded financial marketplace. That means creating a simple story—it's a medical diagnostics company with breakthrough technology—that it can sell to potential investors. Adding "nano" only makes the story more complex.

Alexium uses nanostructured coatings to make fabric flame-resistant.

ALEXIUM

Besides, nanotechnology is not so easy to define. According to the definition used for the National Science Foundation R&D program, it involves working at the atomic, molecular, and supramolecular levels. That takes in scales of 1 to 100 nanometers. Often, such small structures have fundamentally different properties from larger structures of the same material.

By restructuring matter at the nanoscale, researchers can take advantage of these unique effects, according to Mihail Roco, NSF's senior advisor for nanotechnology. The outcome could range from using the high surface activity of nanoscale titanium dioxide to break down dirt on windows catalytically to developing extremely small memory devices based on atomic spin.

According to Roco, researchers created the interdisciplinary foundation for nanoscience during 2001 to 2010. They learned to make indirect measurements, uncover empirical correlations, understand individual scale-related phenomena, and create nanocomponents by empirical design.

This produced a flowering in the field. Roco estimates that between 2000 and the end of 2010, the field's primary workforce grew more than sixfold to 400,000 people. Scientific papers quadrupled to 65,000. Patent applications rose an order of magnitude to nearly 13,000. So did R&D funding, to $14 billion. Venture capital investments rose sevenfold to $1.4 billion.

BRIDGELUX

Roco believes the next step in development will involve designing integrated nanosystems scientifically, rather than by trial and error. Such systems could leverage new discoveries in fields such as spintronics, plasmonics, metamaterials, nanoelectronics, and nanobiomedicine.

Transitions

The future may sound grand, but producing usable forms of the most basic commercial products, such as nanoscale particles, has proven a long, hard slog. Take, for example, the experience of nanotube producer Southwest Nanotechnologies of Norman, Okla.

Carbon nanotubes have been the poster child for the promise of nanotechnology since they burst upon the scene in the early 1990s. They have remarkable properties. They are from one to several orders of magnitude stronger and stiffer than steel or even Kevlar reinforcing fiber.

Nanotubes can range from semiconducting to superconducting. They are ten times more thermally conductive than copper, and have 1,000 times greater electrical current density. They absorb microwaves, making them invisible to radar, and emit and detect light. Researchers hope to use them to make electronic, photonic, and electro-optical devices.

Yet progress in nanotubes has not come easily. They are difficult to produce. A two-story-high reactor typically produces hundreds of grams—not tons or even kilograms—per day. They are often difficult to purify. While prices have dropped sharply from thousands of dollars, they still cost tens of dollars per gram today.

Southwest Nanotechnologies demonstrates how difficult incremental progress has been. The company was spun out of the University of Oklahoma 10 years ago to make single-wall nanotubes. These are cylinders whose walls consist of highly structured, one-atom-thick carbon arrays. They have far better physical and electrooptical properties than more common multiwall nanotubes, but they are also more difficult to manufacture.

Southwest started with a cobalt-molybdenum catalyst that grows single wall nanotubes from carbon dioxide. Over the years, it has boosted reaction speeds and lifted purity levels to more than 90 percent. Equally important, it has shown it can scale up to large reactors to drive down costs.

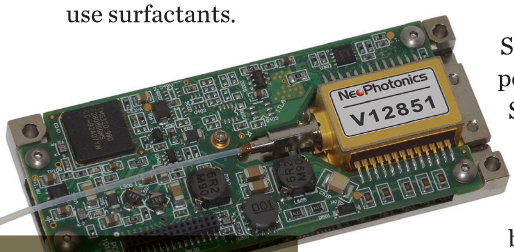
"In 2005, we were making 1 gram per day. Since we moved into our new facility in the fall of 2008, we've become one of the largest single-wall carbon nanotube manufacturers, making 800 to 1,000 grams per day," CEO David Arthur said.

Once Southwest scaled up production, Arthur discovered another pressing reality: "Customers want solutions and convenience. They want something that is easy and safe to use," he said.

Safety has become a major hurdle for all nanomaterials. Because they are so small, nanoparticles could easily go airborne and slip through protective clothing, skin, and tissue membranes, or interact with animals and plants in the environment. Southwest needed to show its products met evolving environmental, health, and safety standards.

The obvious solution is to disperse nanotubes in water or a solvent so they cannot get into the air. Also, large manufacturers prefer to buy liquids because they are easy to disperse into the mixers and reactors they use to make their products.

Unfortunately, nanotubes have a strong attraction for one another and not the water or solvent. They form large clumps, which makes them difficult if not impossible to use. Several companies that sell nanotubes for composite reinforcements have resolved this problem by chemically modifying nanotube surfaces to make them soluble. Others use surfactants.



Neophotonics has mastered light switching using nanoscale mirrors.

NEOPHOTONICS

Such solutions pose problems that Southwest tries to solve. Its V2V Ink was developed to print nanotube-based circuits, including wires and electronic and photonic devices, using the same equipment used to print flexible electronic circuits on plastic substrates. In these applications, a little nanotube goes a long way. In fact, it takes 15 milligrams of nanotubes to coat a square meter of surface. The coating is so thin, it is transparent, Rick Jansen, Southwest's vice president of sales, said.

Unfortunately, typical strategies used to disperse nanotubes, such as modifying their surface or using surfactants, also alter their electrical properties and introduce impurities. While Jansen won't discuss the combination of techniques Southwest uses to disperse nanotubes, he does note that using high-viscosity molecules constrains the nanotubes and keeps them apart.

Possible applications include solar cells, batteries, lighting, and the electronic backplanes used in touch screen displays. In fact, Southwest CEO David Arthur argues that printing touch screen backplanes would cost 80 percent less than producing them by conventional semiconductor deposition methods. Companies are already buying V2V Ink, and Jansen said that at least one company plans to incorporate it in its next product.

Nanocomp Technologies of Concord, N.H., found a different way to package nanotubes. It produces continuous strands of multiwall nanotubes with lengths in the millimeters, orders of magnitude longer than usual. The greater length improves their physical and electrical properties. It also makes it possible to spin them into strong, lightweight, electrically and thermally conductive yarns, tapes, and sheets.

The U.S. Department of Defense recently contracted Nanocomp to expand output. It hopes to test Nanocomp's yarns and weaves in multifunctional composites, such as conductive aircraft wings that can withstand directed energy weapons and stiff satellite structures that act as heat sinks.

Nanomaterials have achieved a degree of commercial success in coatings. Some coatings, like the ones used to protect vehicles from scratching and pitting, contain dispersed ultra-hard nanoparticles.

Others rely on formation of nanoscale grains. Ordinarily, any coating (or bulk metal or ceramic) will consist of pure grains separated by channels of less pure material. These interstices are usually more brittle and prone to corrosion than the surrounding grains. As those grains shrink to the nanoscale, though, the interstices become less significant and the materials grow stronger, tougher, and more corrosion resistant.

Creating nanoscale grains throughout an ingot or other bulk material is difficult. Forming them in thin coatings is far easier. Many of these coatings consist of conventional metals and ceramics, and are relatively economical to produce.

The results can be profound, explained Andy Sherman, chief technology officer of Abakan. His Miami, Fla., firm produces nanostructured metal and ceramic coatings. "When it comes to wear and corrosion protection, you can add nanotech into metals and make products that last a lifetime," he said.

That might be true for some applications, but not for the components Abakan manufactures for its key markets, offshore oil and gas wells, and tar sands refineries. These environments are highly corrosive. In the past, companies relied on expensive exotic alloys or laser cladding, coupled with conservative designs, to prevent failure.

Abakan uses a high-speed infrared fusing process licensed from Oak Ridge National Laboratory to produce nanocoatings. In tests with Brazilian oil company Petrobras, Abakan's nanocoatings showed one-sixth as much corrosion as competing conventional coatings. The company coats pipe up to 40 times faster than conventional laser cladding, and its products cost significantly less than pipes of exotic alloys.

Other nanocoatings companies have taken similar paths to commercialization. NanoSteel of Maitland, Fla., for example, uses a process developed by Idaho National Engineering and Environmental Laboratory to thermal spray hard, iron-based coatings and weld overlays. Australia's Alexium uses a cold microwave process developed by the U.S. Air Force Research Laboratory to protect textiles against flame, oil, water, acid, and chemical and biological agents.

The Future

Nanomaterials have already begun to penetrate the market. In addition to oil and gas components, nanostructured coatings find application in industrial wear parts. Several sporting goods companies use nanotubes as composite reinforcements. Inorganic nanoparticles have been used to prevent scratches in automotive coatings, block UV radiation in suntan lotion, kill bacteria on surfaces and socks, and catalyze reactions that break down grime on self-cleaning windows. These are essentially evolutionary advances. They simply make the coatings, lotions, and windows better.

Nanotech is also living up to at least some of its early hype, creating entirely new products. Take, for example, drugs.

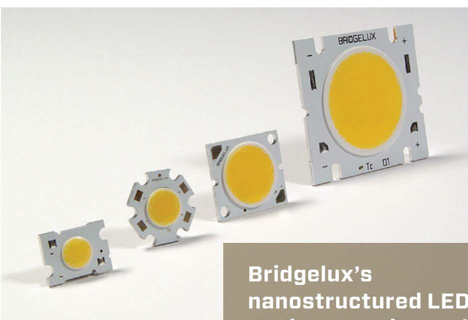
In 2005, the FDA approved the first nanodrug, Abraxane by Abraxis BioScience, for metastatic breast cancer. Abraxane is based on Taxol (paclitaxel), a well known breast cancer drug. Because it is so difficult to dissolve, Taxol requires solvents that have toxic side-effects.

Abraxis took a different route. It encapsulated Taxol in a 130 nanometer shell of the protein albumin. Not only is albumin water-soluble, but breast cancer activates a metabolic pathway that absorbs albumin. The coating essentially tricks the tumor into swallowing the medicine.

Since then, according to Roco at NSF, more than 50 cancer-targeting drugs based on nanotechnology have reached the market. Meanwhile, other companies are investigating even more sophisticated medical strategies.

NanoViricides of New Haven, Conn., shows what may be coming next. It uses nanotechnology to bait a trap for viruses ranging from seasonal flu to herpes and HIV. It does this by creating molecules that mimic the receptors that viruses attach to on cell surfaces. The nanoviricide then wraps around the virus, so it can no longer bond to cells, and eventually rips it apart. The company is closing in on human testing for its first new drug, which targets influenza.

Similar advances abound in the semiconductor world. Intel, ADM, IBM, and other large computer processor and memory manufacturers are already producing products with 32 nanometer features. This is evolutionary, producing faster and more powerful PCs.



Bridgelux's nanostructured LEDs are inexpensive and bright white.

BRIDGELUX

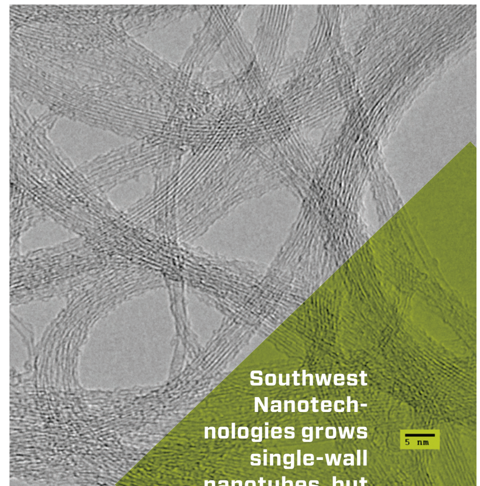
The revolution will be driven by entirely new types of devices that would be impossible without nanoscale engineering. One is the memristor, short for "memory resistor." It is a fundamentally new type of electrical circuitry that stores data through changes in electrical resistance. According to Hewlett-Packard senior fellow Stan Williams, running a voltage through a memristor moves a few atoms a fraction of a nanometer—and changes electrical resistance by three orders of magnitude. This is difficult to determine in large devices, but obvious at the nanoscale.

"This is a fundamental property of matter," Williams said. "It just doesn't become useful until we've shrunk the device down to the nanoscale."

Memristors have many desirable attributes. They are simpler than transistors, and retain memory even without an electrical current. They work better as they grow smaller, and can be stacked in dense layers because they do not require constant electricity (which generates heat) to operate. Equally important, manufacturers can make them from conventional materials and integrate them with existing semiconductor technology.

Last September, HP announced plans to team with South Korea's Hynix Semiconductor to manufacture memristor memory. Williams expects Hynix to launch the first commercial memristors at the end of 2013. He also projects that they will ultimately cost significantly less than conventional transistor-based memory.

There are more nanotech innovations coming. Neophotonics, for example, is selling integrated photonic circuits on silicon chips. They route and transmit data at the speed of light, much faster than conventional wired electronics. In the past, optical circuitry floundered because mirrors and gratings used to manipulate light had to be at least as large as the wavelength of the light. Neophotonics' optical chips are among the first that use nanoscale devices that are smaller than these wavelengths to split and route light on a chip.



Southwest Nanotechnologies grows single-wall nanotubes, but needed a better way to deliver them to customers.

SOUTHWEST NANOTECHNOLOGIES

Bridgelux is manufacturing inexpensive LEDs that produce white light that rivals conventional incandescent light bulbs and last for years.

Stion and Alta Devices, two solar cell manufacturers that lined up major funding in 2011, are using nanostructured thin films to boost photovoltaic performance and slash costs. This past March, Stion began shipping panels from its new Hattiesburg, Miss., plant, which has capacity for 100 megawatts of panels. Alta, which demonstrated a 23.5 percent efficient solar panel at the National Renewable Energy Laboratory, operates a 2 megawatt pilot line. Its flexible solar cells have drawn attention from the military, company president Christopher Norris said.

Meanwhile, Siluria Technologies has raised $33 million to commercialize a nanocatalyst that converts methane from natural gas into fuels and chemicals ordinarily made from oil, and does so at lower cost with fewer emissions.

These applications—many already commercialized, some on the way—create new types of products and methodologies that did not exist before. Just as Roco predicted, researchers are applying their understanding of nanotechnology to create systems that are likely to have greater impacts.

Moreover, many manufacturers appear to have embraced nanoscience. Two years ago, the National Center for Manufacturing Sciences surveyed 270 manufacturers about their nanotech commercialization plans. One quarter had already commercialized products that used nanotechnology. Nearly four out of ten expected to have nano-based products by 2010, and seven out of ten by 2013.

This is exactly the type of growth Roco envisioned. Waite agreed. "We're at the beginning stages of exponential growth of nano-enabled product innovation," he said. "It's becoming the mainstream. The Fortune 500 and global companies—they're going to have to use it. That's where innovation is going to occur, at the molecular level."

Waite ticked off some commercial possibilities, then paused after he mentioned more affordable solar cells. Then added: "We believe they're going to become commonplace in 30 or 40 years. My children are going to grow up and ask, 'What's a gas station?' " ■