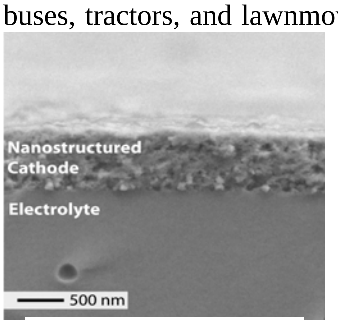
Nanotechnology in Energy, Electronics, and Medicine

Nanotechnology, the understanding and control of matter at the atomic and molecular level, will have a broad impact on nearly all aspects of our lives. This white paper highlights key roles of nanotechnology in three sectors critical to the Commonwealth and nation: ***Energy, Conservation and the Environment; Future Microelectronics in Virginia; and Lifespan Biology and Medicine***. These areas arose from a study undertaken at the request of the Secretary of Technology to the Virginia Research and Technology Advisory Commission (VRTAC). The results of this study are summarized in the report entitled "Collaborative Research and Development Strategies and Directions for the Commonwealth of Virginia" http://www.cit.org/vrtac/vrtacDocs/07-03-05-VRTAC_Univ-Fed_Lab_report.pdf. VRTAC examined areas where, with investment and alignment of its research resources, Virginia could achieve national leadership. Three thematic research areas of mutual priority among Virginia universities, federal laboratories and industry emerged. The maturity of these areas varies greatly, affecting the current level of industry involvement. To capitalize on these research strengths, private and federal funding must be attracted to support collaborative industry / academic translational research and development (R&D) partnerships and business development. For an overview of nanotechnology and related industrial activities in the Commonwealth, please refer to the 2006 report "Nanotechnology in Virginia," presented to the Virginia Joint Commission on Technology and Science (JCOTS) by the JCOTS Nanotechnology Research and Development and Manufacturing Advisory Committees, http://www.cit.org/vrtac/vrtacDocs/07-03-05-VRTAC_Univ-Fed_Lab_report.pdf .

Energy, Conservation, and the Environment

Energy is a critical issue facing the Commonwealth and the nation. Nanotechnology will play a significant role in the development of solutions for both the generation of electricity and the supplementation of petroleum for transportation. In support of alternative energy solutions, Virginia institutions have research programs in biorenewables, fuel cells, hydrogen, photovoltaics, and wind and coastal sources.

Biorenewables may have a profound impact on several sectors of Virginia's economy, including agriculture. Crops, rich in cellulose for processing into biofuels and engineered to grow in local soils, are currently being tested. The use of waste materials, such as poultry waste, is being investigated to transform an environmental problem into a potential energy source. Although unlikely to replace petroleum in the short term, use of biodiesel fuels in public and university buses, tractors, and lawnmowers is happening, and the construction industry has indicated that a local source of biofuels could have a significant impact on their fuel costs. ***Nanoscale catalysts*** (materials that promote a chemical reaction, reducing the activation energy and increasing the reaction rate) play a role in the processing of the feedstock to biofuels and will be key in improving yields and decreasing costs to make these fuels a viable option.



SOFC, McIntosh, UVa

Fuel cells for the generation of electricity are ideal for applications such as home use and distributed power. Solid oxide fuel cells

(SOFC), which use a range of combustible fuels such as gasoline, diesel, or biofuel and proton exchange membranes (PEMs) for use in hydrogen or methanol-based fuel cells, are areas of active research and development in the Commonwealth. Nanomaterials, as ***nanoscale catalysts, nanoporous membranes and as nanostructured electrodes,*** are critical to the function and efficiency of fuel cells. For vehicular use, hydrogen fuel cells will not see widespread use until methods for clean production and safe storage are fully developed. ***Nanoporous*** materials with extremely large internal surface area (storage capacity) offer the potential for safe storage at commercial levels.

In 2006, The Virginia Coastal Energy Research Consortium was formed to develop offshore renewables, primarily focusing on the development of wind energy and biodiesels from algae. It is estimated that up to 20% of Virginia's electricity needs could be satisfied with offshore wind. With respect to the impact of nanotechnology on wind energy, ***nanoscale lubricants*** enable the efficient operation of wind turbines while ***nanocoatings*** prevent corrosion, damage from weather and other impacts, and biofouling of the turbine blades improving efficiency and wear.

Another active area of R&D across the Commonwealth is photovoltaics. Nanotechnology offers many opportunities to improve the efficiency of solar cells to enable them to become a practical addition for distributed power applications. For example, laser texturing of traditional silicon-based systems at the nanoscale improves the absorption of sunlight. Organic materials offer lighter, cheaper, and flexible photovoltaic systems and may eventually be incorporated in windows, painted on buildings, etc. Organic materials such as self-assembled ***monolayers***, organic systems involving ***fullerenes***, ***carbon nanotubes***, ***titanium oxide nanoparticles*** and silicon/germanium ***quantum dots*** are under investigation for application in future photovoltaics.

For a long-term solution to the energy issue, it is necessary to address both the supply of energy through greater efficiencies and renewable sources and reduce the demand for more energy by conserving and by designing more efficient structures, communities, and transportation systems. Nanotechnology will assist sustainable design by offering distributed power options and through advanced materials.

Virginia can draw upon its significant strength in environmental sciences to evaluate the impact of energy options, with consideration of global climate, local wildlife, crop run-off into our waterways, emissions, etc. Nanotechnology will also be a part of the solution as ***nanoparticles***, such as iron oxide manufactured by NanoChemonics, offer unique opportunities for environmental remediation. The use, production, and impact of nanomaterials used in new alternative energy sources will need to be included in this evaluation. Luna Innovations is recognized for its leadership in the development and implementation of a risk management program in its Danville manufacturing plant.

Future Microelectronics in Virginia

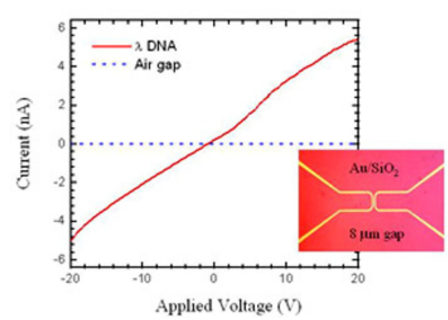
In the mid-1990s, the Commonwealth recognized the future potential and importance of the microelectronics industry to Virginia and established, with the major semiconductor companies, the Virginia Microelectronics Consortium (VMEC) focused on the development and support of a strong engineering workforce. This investment helped build a strong microelectronics education and research program at all six of the state's engineering schools. Now the investment is paying great dividends as microelectronic devices have become the leading export of Virginia, having surpassed tobacco in 2005 and coal in 2006 in total value of exports. Micron Technology, Qimonda, and BAE Systems are the major producers and employers and continue to actively recruit graduating engineering students from state universities, technicians from two year community colleges and manufacturing technicians from local high schools.

Microelectronics continues to be the industry that most aggressively drives the advancement of nanotechnology as electronics need increasingly higher performance and density at lower power consumption. The industry needs to implement new nanotechnology in the form of designs, materials, processes, production methods and characterization techniques every twelve to eighteen months to meet the insatiable demands for modern electronics such as computers, cell phones, PDAs, HDTV, displays and automobiles.

The advancement of the microelectronics industry requires continual enhancements on its base technology, prominent examples are focused on ways to integrate nanotechnology features such as developing carbon nanotube based devices at BAE Systems, or the development of automated production systems at Micron Technology, both in Manassas. Virginia also has active programs in the foremost nanotechnologies directed toward extending the current leading edge silicon based systems. Some of the novel technologies that will transform the microelectronics industry in the future are: spintronic devices, molecular electronics, quantum dot electronics, nanotube based devices (carbon and inorganic) and semiconductor nanowire devices. These important and innovative technologies are being worked on in the industries and universities of our Commonwealth. One or several of them may very well hold the keys to furthering the nanotechnology revolution.

Spin transport electronics (***spintronics***) carry and store information based on an electron's spin instead of its charge. Advantages of combining spin and conventional charge based microelectronics, or using spin alone include non-volatility (information is not lost when your computer is turned off), faster processing speeds, lower power consumption, and smaller devices. Several Commonwealth universities are actively engaged in spintronics research and one of the pioneers of this field has moved to the University of Virginia from his position as a program manager at Defense Advanced Research Projects Agency (DARPA) and is now leading collaborative research programs. Many of these projects are joint programs with and directly funded by industry. Industry partners include Intel, IBM, Hewlett-Packard, Seagate, Micron Technology, and Freescale Semiconductor, a Motorola spinoff.

The unique electrical properties of specific molecules, such as DNA, can be used to build devices referred to as ***molecular electronics***. Success here would lead to computers that work an order of magnitude faster than current ones and would be able to avoid the "heat issue" which is the major road block to the continued evolution of computers in today's silicon based transistor technologies. Several research efforts exist in Virginia, and commercial entities such as Hewlett-Packard and Xerox are interested in this area of electronics.



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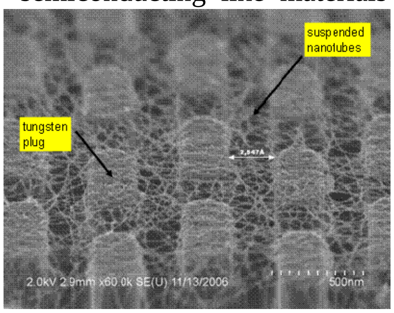
Quantum dot electronics involve the use of epitaxial semiconductor quantum dots to store, manipulate and transfer charge down to the single electron. Virginia has a nationally leading program in this field in spatial control of quantum dot assembly, development of new nanoscale doping methods, and proposed quantum dot based spin switch architectures with spintronics efforts. IBM and FEI are industrial partners in this research. Quantum dots detectors have been fabricated and tested in collaboration with NASA Langley.

There are significant research efforts across the state investigating the properties of ***nanotubes***, (carbon and other materials), ***fullerenes, and other carbonaceous nanomaterials*** for use in electronics. Depending on their structures, carbon nanotubes can be conducting, like a metal, or semiconducting like materials such as silicon. This makes them very interesting for use in microelectronic devices. This is an area of particular interest to Virginia businesses, for example, a joint development effort between BAE Systems with Nantero, Inc. in Manassas focused on carbon nanotube-based devices for aerospace and advanced defense systems. Other significant efforts in the production, properties, and use of carbonaceous nanomaterials, are underway at Luna nanoWorks, Jefferson Laboratory and NASA Langley. Nanowire material development with SiC and GaN are in progress in collaboration with the National Institute for Science and Technology (NIST) and the Army Research Office.

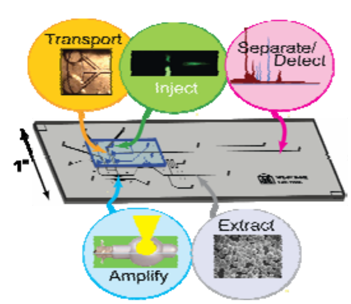


Courtesy of BAE/Nanotero

Nanotechnology development occurs daily in the high volume semiconductor production facilities of Micron and Qimonda. As minimal feature sizes proceed below 50 nanometers and integrated circuits are manufactured with memory storage capacities exceeding eight billion bits (8 gigabits), new and exotic materials such as hafnium are integrated into the ever changing semiconductor production process. Developing nanotechnology manufacturing processes that deposit, pattern and etch materials an atomic layer thick on thousands of wafers each week is a formidable challenge for the engineering personnel working at these companies. Together with the new processes come regular investments in new equipment and techniques for electrically, physically and chemically studying and analyzing the resulting structures. These facts demonstrate that nanotechnology is an essential part of the business for producing modern electronic devices and the advancement of the science is fundamental for the future success of this industry in Virginia.

Lifespan Biology and Medicine

Nanotechnology has a natural overlap with biotechnology, life sciences, and medicine due to the size scales involved. Nanotechnology enables the ability to probe sub-cellular biochemical activity. The development of detection ***nanobiosensors*** and ***nanobioprobes*** capable of penetrating and locating specific sites within a single living cell is made possible through ***nanobiotechnology***. The intersection of nano and biotechnology is already having a profound impact on the study of Biological Processes, Regenerative Medicine, Cancer, and Public Health and Safety. For example, nanotechnology-enabled cancer drugs designed to target malignant cells have been in use for several years. These drugs rely on ***nanocomposites*** that encapsulate pharmacological chemicals and have functionalized surfaces to direct them to the desired site within the body and initiate the drug release. Studies have shown that this method of drug delivery can reduce the amount of the drug needed to treat a disease with a reduction in the associated side effects. The ***nanoparticles*** may also be used to encapsulate genetic material for gene therapy. In some cases, the nanoparticle itself can become the therapeutic



Landers, UVa

agent. In hyperthermia treatments, the temperature of a cell can be increased high enough to trigger cell death by heating a nanoparticle near the cell. The energy coupled to the nanoparticles can be delivered as light (a variation on photodynamic therapy) or in magnetic fields (magnetodynamic therapy), which can eliminate invasive surgical procedures and reduce collateral tissue damage. The presence of certain catalytic **nanoparticles** has been shown in studies at the Virginia College of Osteopathic Medicine to modify the longevity of cells and organisms. A small dose of ceria nanoparticles have provided protection from free radicals generated when cells or an organism has been stressed by physical trauma or exposure to a biochemical agent.

Another area in which nanotechnology is being deployed is for diagnostic and preventative medicine. For example, lab-on-a-chip diagnostics combine microfluidics (for the introduction and transport of sample fluid on the chip), with nanotechnology in the separation and extraction and microelectronics for data analysis and readout to accomplish in minutes on a chip that can be held in your hand what it used to take a laboratory full of equipment days to perform. Semiconductor quantum dots, fluorescence ***nanobeads***, and metallic nanoparticles are used as optical markers to tag cells, monitor biological events, and initiate biochemical reactions. These ***nanoparticles*** are enabling researchers to monitor biological activity real-time in living cells and organisms, which provides significant insight into the mechanisms involved in disease on-set and progression. This knowledge will, in turn, enable the scientists to develop new methods to treat and prevent disease. As the biochemical signatures associated with the onset of various diseases are identified, ***nanoscale*** diagnostic tools may be developed that can monitor a person's health in-vivo and initiate treatment at the earliest possible stage.

In the area of medical imaging, nanoscale materials are playing a significant role to enhance the performance of diagnostic equipment. Examples include superparamagnetic ***fullerenes***, organic ***nanoconstructs***, and semiconducting and metallic ***nanoparticle***s used as contrast agents with magnetic resonance imaging (MRI), ***nanoparticles*** of various densities for use as contrast agents in ultrasound and x-ray imaging, and ***fluorescent nanoparticles*** that can be used with optical imaging. Nanoparticles can enhance the performance of new imaging techniques, such as bioluminescence tomography. Luna nanoWorks is engaged in the commercial development of metallofullerenes for medical imaging as well as in the area of ***nanoimmunology***.

Regenerative medicine and tissue engineering is another area of strength for Virginia, and nanotechnology plays a critical role. The scaffolding systems utilized to enhance the regrowth of tissue employ ***nanoscale fibers***, ***nanocomposites***, or and ***nanoscale*** textures to stimulate cell and tissue growth. For example, NanoMatrix (a VCU spin-out) electrospins natural materials into a matrix of nanoscale fibers creating a structure where cells have an appropriate three dimensional environment for promoting growth. This three dimensional ***nanofibe***r structure can include natural materials which promote clotting for use to stop bleeding and promote growth as a tissue scaffold in surgical, accident, or battlefield applications. Texturing of prostheses can increase the speed and likelihood of the fusion of bone to the artificial joint or other appliance. Nanobiotechnology has also been applied to reduce the inflammatory response of the body to implanted tissue and prostheses, avoiding the delay or inhibition of the fusion process.

Various industrial and university research groups across Virginia are addressing critical elements within nanomedicine. These include research and development on the synthesis of biocompatible nanoscale materials and coatings; novel techniques to encapsulate, target, and release pharmaceutical agents; new imaging modalities, image processing techniques, and systems; design and fabrication of nanoscale sensors for diagnostics as well as for homeland security applications; and nanoscale scaffolding for tissue engineering.

Supporting the transition of the research priorities to economic impact for Virginia.

The VRTAC report mentioned above outlines an approach to collaborative research programs that build capacity and leverage resources and strengths among the academic institutions. Collaborative research development and deployment projects for economic development are also described. Beyond research, support for existing and new companies is required to reap the benefits of nanotechnology research. By nurturing spin outs and small companies that complement existing regional areas of technical expertise, opportunities will evolve to transfer new technologies into the marketplace. Starts-ups often need more than an understanding of the technology. They need management support, assistance finding investment capital and other funding, access to resources and equipment, and networking/promotion for the development and growth of their nanotechnology businesses. To accelerate the transition of research into new products, processes, and services, a range of support is required.

In the area of leadership and business support, services required include a wide breadth of executive-level management advice and support on issues of strategy and market positioning, product development, operations, strategic alliances, financing, and organization development. This could be addressed with attention to the following three areas: 1) a network of senior management, legal resources and technical executives interested in working with start-up nanotech companies; 2) consultants spanning all aspects of commercializing a nanotech technology from basic market research through product and regulatory development to support to marketing and sales support and 3) the establishment of a set of preferred relationships with professional service firms for business law and intellectual property, accounting and business administration, and regulatory services.

Nanotechnology business often need technical resources and access to specialized research, evaluation and fabrication equipment. Close working relationships with the many clinical and research institutions in Virginia would benefit emerging companies and could involve consulting arrangements, joint programs funded through federal programs, and other funding arrangements. The establishment of the Virginia Nano Users Network as discussed at VRTAC and recommended by the 2006 JCOTS Nanotechnology Advisory committees, would be an excellent mechanism to assist small business with this critical requirement.

Finally, investment capital and other start-up funding is critical to the successful transfer of research to commercial success. A local resource with relationships to nanotech and other venture capital firms, private equity groups, and investment banks across the country would have a tremendous impact on the success of new businesses. Furthermore, support to prepare for interactions with the investment community and identification of contract and grant opportunities to support product and market development is also essential.