Title
Marine Bio-Nanotechnology: High-Performance Materials from Sponge Silicatein

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Project Information
Year: ’06-‘07
Project No. R/MP-95.
Project Title: Marine Bio-Nanotechnology: High-Performance Materials from Sponge Silicatein
Project Subject Area: Marine Biotechnology and New Marine Products

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Fiscal Information
Sea Grant $: 102,725 Year 1
103,127 Year 2
103,547 Year 3

Project Start Date: 3/1/04-
Project End Date: 2/28/07

Matching Funds $: 145,807 Year 1
76,203 Year 2
40,989 Year 3

Please answer the questions in a style appropriate for laymen

Major goals and objectives of the project

We recently discovered the molecular mechanism by which a common California marine sponge synthesizes the fiberglass-like structures that form the internal skeleton of this simple marine animal. Our goals are: (1) to harness the proteins and molecular mechanisms that control this synthesis to make valuable semiconductors inexpensively under environmentally friendly conditions; and (2) to use this new approach to develop, low-cost, high-efficiency solar energy converters and other practical electronic applications. Training of students in the unique interdisciplinary approach of this project, combining new developments in biotechnology, advanced instrumentation, and materials engineering to produce advanced high-performance materials, also is a major objective of our project.

Summary of progress and accomplishments toward meeting goals and objectives

We made the surprising discovery that a special protein – that we found hidden inside the fiberglass-like structures that form the skeleton of an abundant sponge from California coastal waters – acts as a catalyst to direct the synthesis of the glass-like skeleton at low temperature and under very mild conditions. These conditions are very different from those typically required for the industrial manufacture of glass and related materials, which typically require high temperatures (high energy costs) and caustic chemicals. By cloning and sequencing the DNA from the sponge that codes for this unique protein, and using the genetic code and computer-modeling techniques, we learned the detailed structure of this unusual protein and discovered how it works as a catalyst to direct the synthesis of glass-like materials at low temperatures and in the absence of caustic chemicals. We then discovered that we could extend the use of this protein as a catalyst to direct the synthesis of titanium oxide and several other valuable metal oxide semiconductors at low temperature. This too was a radical departure from the conventional methods of synthesis of these materials, that typically requires high temperatures, harsh solvents and dangerous chemicals. What was even more surprising was our finding that this protein, that we named "silicatein, directs the synthesis of unique crystalline forms of several of these semiconductors that previously could be made only at very high temperatures (nearly a thousand degrees) – even though the protein is operating at room temperature! In several of these cases, the crystalline forms of the semiconductors made by the protein display very useful properties as solar energy converters, changing the energy of sunlight directly into electricity.

We used gene cloning and special high-magnification electron microscopes and X-ray analyses to reveal the fine-structure details of the protein that are responsible for its special catalytic and structure-directing activities. These findings helped us to harness the protein (and components of the protein that we are anchoring on silicon chips and other electronically useful platforms) to make the valuable high-performance semiconductors and solar energy converters. This then led to our development of a generic, low-cost and low-temperature method for the synthesis of nanostructured thin-films of more than 30 different valuable semiconductors, many with novel structures and electronic properties that had not been attainable through conventional high-temperature (and high cost) manufacturing methods. In the past year, we have succeeded in extending this work to the bio-inspired, low-temperature synthesis of bimetallic semiconductor nanoparticles, with potential applications to improvements in low-cost solar energy, battery safety, infrared and pressure sensors, and opto-electronic communications.

Further applications of our work extend to the area of medicine. New means for encapsulating and safely delivering cells and therapeutic agents, and the development of new restorative agents for repair of bone and other tissue damage, also are being developed from the novel method of synthesis we discovered.

Dow Corning Inc., the world's largest manufacturer of silicon-based materials, provided financial assistance as matching support for these efforts. Scientists at Bell Laboratories (Lucent Technologies) provided direct assistance through collaboration. Additional corporations, including GE, IBM, Raytheon, Hewlett-Packard, and DuPont have expressed interest as well.

PROJECT MODIFICATIONS: (none)

BENEFITS, COMMERCIALIZATION, AND APPLICATION OF PROJECT RESULTS:

Our discoveries provide the first biocatalytic route to low-cost synthesis and nanostructural control of silica, silicones, solar energy converters and semiconductors at low temperature and under environmentally benign conditions. Socioeconomic benefits are anticipated in the solar energy, electronics and communications industries, and the chemical and materials manufacturing industries undergoing transformation from traditional "smokestack" methods to new "green" manufacturing aimed at reducing use of polluting chemicals and energy. Benefits for further miniaturization in microelectronics (for faster and smaller computers and communications devices) are anticipated. Testimony to the commercial value of this research is seen in the fact that Dow Corning and Genencor (Palo Alto, CA), industrial supporters of our previous Sea Grant project, recently announced a $38-million strategic alliance to commercialize products from the "Silicon Biotechnology" developed in our previous Sea Grant project.

Dow Corning provided financial matching support, and Bell Laboratories (Lucent Technologies) provided assistance through collaboration. GE, IBM, Raytheon, Hewlett-Packard and DuPont are interested; we are working with scientists from these companies to explore avenues for commercialization. One of the first areas of practical application under investigation with these companies is in the manufacture of low-cost, high-efficiency photovoltaic materials for the conversion of sunlight directly to electricity.

PUBLICATIONS:

Kisailus, D., J.H. Choi, J. C. Weaver, W. Yang and D.E. Morse. Enzymatic synthesis and nanostructural control of gallium oxide at low temperature. 2005. Advanced Materials 17: 314-318.

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Thurner, P.J., B. Erikson, Z. Schriock, J. Langan, J. Scott, M. Zhao, J. C. Weaver, G. E. Fantner, P. Turner, J. H. Kindt, G. Schitter, D. E. Morse and P. K. Hansma. 2006. High-speed photography of human trabecular bone during compression J. Mater. Res. 21; 1093-1100.

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Subramanayam, G., R. Lakshminarayanan, J. C. Weaver, D.E. Morse, R M. Kini, and S. Valiyaveettil. 2007. In vitro study of magnesium-calcite biomineralization in the skeletal materials of the seastar, *Pisaster giganteus*. Chemistry (in press)

MEDIA COVERAGE:

YES

MEDIA NOTES

1. Our work was the focus of a major feature in the *MIT Technology Review* ("Silicon and the Sun," October, 2006).

2. The Editor of the prestigious international science journal, *Nature,* published an enthusiastic summary of our recent work. The citation and an excerpt from that report follow:

Nature 433: 210 (2005)

Materials chemistry: Shaping silica softly

> "Nature is renowned for its 'soft processing' of materials. In contrast, traditional materials-processing technologies have involved high-vacuum, high-temperature conditions, organic solvents and caustic reagents. Taking a leaf from nature's book, [Morse and his colleagues] have identified a small molecule capable of precipitating silica from soluble silicon-containing precursor compounds. A similar process occurs in the marine sponge, *Tethya aurantia*, which uses an enzyme called silicatein to form its silica spicules. [They] found a small molecule, cysteamine, which contains two key chemical groups like those in the active site of silicatein. Using this catalyst, they could encapsulate fluorescent proteins, and even living bacteria engineered to express such proteins, in a silica matrix. These encapsulated biomaterials could be useful for sensing and catalytic applications. Conventional (sol–gel) methods for making silica structures from solution use harsh reagents that can damage cells and proteins. But the biomimetic catalyst requires only the mildest of conditions."

3. Interviews with Dr. Morse on this work were broadcast on NPR Radio (national), KCLU Radio (local) and KCET TV (local) in July, 2005.

4. Highlights of our work were published in: *Scientific American (*July, 2005), *GEO* magazine (Germany, July, 2005), *Der Speigel* (Germany, July, 2005); *Science Direct* ("Top 25 Hottest Articles", October, 2005); *Materials Research Bulletin* (November, 2005); *Current Opinions in Chemical Biology* (2005); *Nanotechnology Review (2005, 2006); Nanomaterials News* (November, 2005); *Nanotech Web* (April, 2006); *Compound Semiconductors* (October, 2006); *Die Welt* (Germany, November, 2006); *Semiconductor News* (November, 2006)

COOPERATING ORGANIZATIONS:

Bell Labs (Lucent) is cooperating in further investigations of structures, compositions,and the optical properties of glass-like structures of other marine sponges. **DuPont** (world's leading manufacturer of titanium dioxide), is providing expertise in this area. **IBM, Raytheon, GE** & **Hewlett-Packard** are providing expertise, industrial guidance and interest in solar energy conversion. **Dow Corning** (world-leader in manufacture of silicon-based materials) provided significant financial assistance used as matching support.

INTERNATIONAL IMPLICATIONS:

(1) **Dept. Biotechnol., Tokyo U. Agricult. & Technol., Japan:** 1grad student and 1 postdoc from this group worked on current project in our lab; collaborations continuing. (2) **Dept. Chem., Natl. U. Singapore:** 2 profs did sabbatical research on current project in our lab; collaborations continuing. (3) **Inst. for Inorg. Chem., U. Frankfurt, Germany:** Collaboration with the Inst. Director in progress. (4) **Center for Bioelectronics, Toyo Univ., Japan:** reciprocal research visits for collaboration; PI appointed Visiting Prof.

AWARDS:

Prof. Morse (PI) has been honored by selection as: "Research Leader of the *Scientific American* 50" - Honored by *Scientific American* among the Top 50 Technology Leaders for 2006, in recognition of innovative research leading to biologically inspired routes to novel semiconductor thin-films, December, 2006; The Kelly Lecturer, Dept. of Chemistry, Cambridge University, Cambridge, UK, 2005; The 3M Lecturer, Depts. of Chemistry and Materials, University of British Columbia, Vancouver, Canada, 2005; Outstanding Research Award, International Abalone Symposium, Chile, 2006; and Appointed Visiting Professor of Bio-Nano Electronics, Centre of Excellence in Bio-Nano Electronics, Toyo University, Japan (2005-present)

KEYWORDS:

Marine biotechnology; nanotechnology; sponge; silica; silicatein; genetic; DNA; protein; titanium; solar energy; photovoltaic; semiconductor; electronics;

PATENTS:

"Biologically Inspired Synthesis of Thin Films and Materials;" D.E. Morse, B. Schwenzer, K. Roth, R. Brutchey, J. Gomm;" Provisional Patent # UC05-170-2 granted November, 2005; full patent pending.

NOTES: (none)

FOR ALL STUDENTS SUPPORTED BY THIS GRANT, PLEASE LIST:

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