Harnessing Biology to Produce Inorganic Materials

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A Silicon Valley startup is taking on the world of inorganic materials production, but with an unorthodox starting point—biology. At Siluria Technologies, researchers started with one basic pursuit: take inspiration from biology and apply genetic engineering and protein biochemistry to the creation of inorganic materials in a ''bottom-up'' fashion, similar to the way nature works, but with materials that were never present in the primordial soup.

The approach appears to be working. Working on foundational science first developed by Dr. Angela Belcher, Professor of Materials Science and Engineering and Biological Engineering at MIT, Siluria took shape in 2008 to mimic and commercialize inorganic material production methods using nature as a mentor. Belcher's highly successful academic career has been dedicated to applying nature's approaches to material synthesis to problems that nature does not service; in this case, to production of inorganic materials via catalysis. But don't think enzymes, microbes, or cell culture. Think of metals and metal oxides as the drivers.

Professor Belcher's science grew from her interest in biomineralization, a process by which biology creates hard tissues, things like abalone shells, mother of pearl, bones, cartilage, teeth, nails, and diatomaceous earth. ''If you look at the periodic table, nature uses a very small list of compounds as building materials—maybe a half dozen like calcium, silica, oxygen, phosphate, sulfur, and a few others,'' explains Siluria's President, Alex Tkachenko, Ph.D. ''Yet with this very small list of building blocks, nature manages to create fascinating structures with very interesting performance properties.'' The reason this is possible is that nature has the ability to impose a structure on the material as it grows. ''That structure dictates properties that are far superior to what you would expect from the very mundane and pedestrian nature of the starting materials.''

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Phage Display

At Siluria, biology starts things off through the use of phage display, a technique of molecular biology. Phage display is a very simple and robust technique for changing the sequence of a protein displayed on the surface of a phage. ''Our core technology is to grow inorganic materials—crystals of metals and metal oxides on the surface of a biological template—in our case, phage display,'' says Tkachenko. In a bottom-up approach, Siluria's researchers use M13 phage, a virus, to display particular proteins that cause metals and metal oxides to cluster and ''grow'' on its surface. These nanowire metal-coated materials are the catalysts that Siluria uses to drive chemical reactions of interest.

''Phage display seemed like a very robust and versatile technique for bringing nature-inspired approaches into the world of inorganic chemistry and material science,'' says Tkachenko. ''The advantage of this approach is that we have control over the protein properties, specifically structure, not available with conventional synthetic techniques.'' By using phage-synthesis, which allows researchers to alter the sequence of the gene or the sequence of desired proteins, Siluria's researchers are able to alter the morphology, structure, and therefore the properties of the inorganic materials grown.

''The nature of the phage-based technology makes the catalyst design intrinsically combinatorial,'' explains Dr. Evelyn Hu, Harvard University Professor of Applied Physics and Electrical Engineering. That means that the researchers at Siluria have an opportunity to rapidly proceed through different compositions of phage that can serve as a template for a diversity of catalysts even with the same building block components. ''And with the rapid screening they have they can rapidly assess how effective the resulting catalysts are.'' That means the feedback loop for discovering powerful new catalysts is very fast. ''They can go through and assess thousands of possible choices as catalysts for any particular chemical reaction they focus on,'' adds Hu, former postdoctoral advisor to Angela Belcher and a collaborator with her on this and other technologies.

''This is a high-risk but highly innovative approach offering the potential for taking advantage of genetic engineering methods to vary, control, and logically modify in an infinite way the protein sequences and map that to creating diversity on the solid-state inorganic scale,'' adds Howard Turner, Ph.D., Vice President of Advanced Technologies at Precursor Energetics and a former scientist at Exxon Chemical.

By changing the morphology of crystals in catalysts, one can change most dramatically the catalyst's performance, taking it from not terribly selective to highly selective. Says Tkachenko, ''What we enable is, through a novel biologically inspired approach to synthesis of inorganic materials, we have been able to come up with catalysts that are superior to anything that has been accomplished in this space with conventional synthetic methods.''

Catalyst Synthesis

After identifying the protein of interest through phage display, the catalysis synthesis process begins. Charged functional groups on the protein's surface interface with a solution of precursors that will eventually crystallize into a catalyst that will drive creation of an inorganic compound of interest. The intent is to create so much catalyst over a large, dense surface area that the energy needed to make the catalyst achieve its goal is greatly reduced. The only role that biology has is that the catalyst required to enable this transformation with desired selectivity will have been grown on a biological scaffold.

"Because our synthetic method for growing catalysts is bottom up—we do not simply precipitate in solution but we have the biological template that imposes a structure on the crystal as it grows—we are operating in a very different structural space from anything possible before," explains Dr. Erik Scher, Vice President, R&D at Siluria. "The template is what serves to nucleate the crystal when it starts growing."

Producing the crystal catalyst also appears to be energy-efficient. "We grow our crystals in water at room temp," says Scher. "There are no inorganic solvents or high temperatures." He cites that catalyst scale-up is "eminently doable" and is compatible with the infrastructure of the chemical industry.

Ethylene Production

Siluria's first application of its phage/catalysis approach is in the production of ethylene, the world's largest commodity chemical. The company uses a process called oxidative coupling of methane (OCM) to produce ethylene. The chemistry of OCM has been known for about 30 years, with no shortage of effort or scientific rigor to develop it selectively and efficiently for commercialization. "Nobody has been able to use OCM selectively for ethylene because they have not been able to get a catalyst that would convert the majority of methane to ethylene," says Scher who explains that Siluria's catalysts can do this easily.

Hot natural gas, and air are the inputs into a gas phase reactor. At temperatures several hundred degrees below what was previously achieved with conventional catalysts, Siluria's phage-designed catalyst transforms them into ethylene. The biological scaffold will have been burned off, leaving behind an inorganic material—in this case, ethylene oxide.

Should this technology work at scale for ethylene production, it could replace a 70 year, energy-intensive process called steam cracking. Cracking consists of breaking long carbon chains, specifically naphtha, which is oil-derived, with very hot steam at temperatures near 900°C to produce short carbon chains in the process. "This is an endothermic process, requiring a lot of energy," explains Scher. You have to keep putting heat into the reaction, usually in the form of burning natural gas, in order to maintain the reaction at 900°C or higher."

Methane contains very strong carbon/hydrogen bonds. "Siluria is pursuing an approach to activating methane at low temperatures to produce ethylene, a problem heavily invested in over the better part of refining chemistry, which is traditionally not able to be accomplished without radicals generated at high temperature," says Turner. "Because this is an area in traditional chemistry where a lot of smart people have worked for a long time, if one is going to get beyond the state of the art as it is today in alkane activation, it is going to take a fresh approach like the one Siluria is pursuing."

Siluria, founded in 2008, is the second commercial venture to get its start from Belcher's work in this area. Cambrios Technologies Corp. was founded in 2002 on the work of Belcher and Hu to produce electronic materials. Belcher remains a member of Siluria's board of directors and a scientific advisor.

"The path to improved economics in the chemical industry lies in innovation in catalysis," says Tkachenko. Adds Turner, "If Siluria's technology truly does provide for carbon/hydrogen activation at very low temperatures on solid inorganic catalysts, it would represent a significant breakthrough and open a wide variety of potential catalytic transformations."

Going forward, Siluria hopes to discover catalysts for other high-value target reactions, including those for acetic and acrylic acids, phenols, and to increase yields from existing processes such as those used for maleic anhydride and phthalic anhydride.

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