Fabricating the Future---Argonne's Atomic Layer Deposition Technology

With the U.S. population exceeding 300 million, a flood of SUVs crowding an increasingly concrete earth and a buildup of waste growing by the second, inefficient technology can no longer sustain us. There is a budding demand for processes that are fast, inexpensive and accessible—and fast food drive-through lanes just won't suffice. In a joint effort between the Materials Science and Energy Systems divisions at Argonne National Laboratory, scientists are working to perfect Atomic Layer Deposition, or ALD, and apply its potential to solar cells, catalysis, solid state lighting, separation membranes and superconductivity. These all translate into efficient processes that can produce alternate forms of energy efficiently and economically.

ALD is a thin-film growth technique that offers the capability to coat complex, three-dimensional objects with precise, conformal layers. The scientists expose the objects' surface to a sequence of reactive gas pulses to apply a film coating one atomic layer at a time. The chemical reactions between the gases and the surface naturally terminate after the completion of exactly one monolayer. ALD can deposit a variety of materials, including oxides, nitrides, sulfides and metals.

What makes ALD more effective and flexible than traditional methods for producing thin film coatings, such as evaporation, is its ability to coat every nook and cranny of a complex object. The best way to think about the difference between traditional deposition techniques and ALD is in terms of a deep trench. Evaporation is a "line-of-sight" method that will coat only what the vapor can see straight on, namely the surfaces on the very top and bottom of the trench. But ALD coats the entire trench uniformly, including the surfaces on the walls.
Scientists use this procedure to fabricate structure nanostructured catalytic membranes, or NCMs. These structures enable catalytic reactions to occur—most notably, reactions that convert inexpensive feedstocks into valuable products and reactions that can synthesize hydrocarbon fuels.

To create ultra-uniform NCMs using the ALD process, Argonne scientists start with anodized aluminum oxide (AAO) membranes, which are formed by the electrochemical etching of aluminum metal. Each square centimeter of the AAO membrane is permeated with billions of tiny pores with diameters of approximately 40 nanometers that are arranged in a honeycomb-like array. The scientists then use ALD technology to shrink down the pores to a predetermined size and apply catalytic layers to the interior surfaces.

The first step in the process is to coat the AAO membranes with aluminum oxide to tune the pore size within plus or minus 0.1nm to control the reactant's contact time with the catalyst, as well as provide filtration capability.

The exact nature of the support layer and the active catalyst layer depend on what chemical reaction the NCM is designed to catalyze. ALD technology allows a nearly limitless palette of layers to be synthesized, and consequently these NCMs can positively impact a broad range of technologies to address to the nation's energy needs. ALD catalysts have an advantage over conventional catalysts because they avoid a mishap called agglomeration, which is the uneven distribution of catalytic particles on a surface that can occur with the traditional technique. Instead, researchers can create perfect, evenly dispersed layers of coating every time using ALD.

Michael Pellin and Jeffrey Elam are two of Argonne's primary researchers involved with ALD technology and its applications, especially NCMs. According to Elam, a research chemist in the energy systems division, fabrication of the membranes has been accomplished in the laboratory, and a patent has been filed for the NCMs. "We are focusing our attention now on measuring the properties of the catalysts and synthesizing other catalytically relevant materials inside the NCMs," Elam said.

Elam and Pellin have been working to take what they have done with NCMs and carry out chemical reactions that actually result in materials that will help the nation sustain itself in a more cost-effective and efficient manner.

One of the attractive features of ALD technology is its scalability. "With ALD, we can make membranes one at a time or 20 at a time with no more effort," said Pellin, deputy division director responsible for the materials chemistry programs in the Materials Science division. Currently, ALD is used commercially to make computer chips, but the ability to apply the technology to many other branches of research is where ALD's potential greatness lies.

One of the Argonne researchers' goals has been to improve the effectiveness of the catalyst in Fischer-Tropsch synthesis. The Fischer-Tropsch process takes syngas, a mixture of carbon monoxide and hydrogen, and converts that into synthetic hydrocarbon fuels. Syngas can come from a variety of materials, including natural gas, coal or biomass. The process has been used and commercialized in Malaysia and South Africa to make a variety of synthetic petroleum products, food-grade wax and low-sulfur diesel fuels.

The enhanced performance of Fischer-Tropsch catalysts afforded by Argonne's NCMs could potentially allow the production of clean, sulfur-free fuels to become commercialized and economically viable in the U.S. sometime in the next decade or two. By synthesizing transportation fuels in an economic and sustainable fashion, the researchers can reduce the nation's consumption of fossil fuels.
This research could contribute to a successful transition for the U.S. from energy abuse to greater environmental preservation. Combined with other technologies such as carbon capture and storage, synthetic transportation fuels could make an emissions-free energy future possible.

In another application, researchers are developing selective oxidation catalysts. One example of selective oxidation is the conversion of propane to propylene, which can then be used to make polypropylene plastic products. The ALD technology will allow selective oxidization processes to occur at dramatically lower temperatures, leading to tremendous energy savings and cost reduction.

Recently, researchers have begun to apply ALD technology to solid-state lighting, which refers to the use of light-emitting diodes, or LEDs. Unlike incandescent light bulbs, LEDs consume very little electric power and do not burn out or overheat. They are illuminated by the movement of electrons in a semiconductor material, and are considered to be the most efficient light source in existence. LEDs can be found in many electronic devices, from digital displays to traffic lights.

The ALD research also plays a supportive role in partnerships with other research institutions. In collaboration with Lawrence Livermore National Laboratory, Argonne researchers are helping to develop laser ignition targets for nuclear fusion. Further, along with researchers at the Fermi National Accelerator Laboratory, they are applying ALD technology to improve the performance of superconducting radio frequency cavities for particle accelerators.

In cooperation with Northwestern University, researchers are fabricating highly efficient solar cells for converting sunlight into electric power. They are focusing on types of solar cells known as dye-sensitized solar cells (DSSCs). These improved DSSCs use ALD technology in a similar way as the NCMs—namely, precise and conformal layers are deposited on the inner surfaces of nanoporous membranes.

In the case of these DSSCs, the layers consist of transparent conducting oxide materials such as indium oxide and tin oxide, as well as semiconducting coatings such as zinc oxide and titanium dioxide. The researchers aim to eventually commercialize these novel and efficient solar cells. Because no pure, costly silicon is involved in the fabrication process—as it generally is with conventional solar cells—the researchers will effectively be able to produce electricity at a much lower cost.