Historically, scientists and engineers have searched for answers with their eyes, ears, and hands. As they have invented better scientific instruments, they have extended their senses and peered further into the vastness of the universe, the inner workings of living cells, and the composition of matter. Today’s extremely powerful instruments allow scientists and engineers to work on the scale of nanometers—billions of a meter.

Dr. Kwok-Siong Teh, an associate professor of mechanical engineering at San Francisco State University since 2006, has been working with his enthusiastic undergraduates to develop the Advanced Materials Research Laboratory, a lab devoted to micro and nanoscale materials research. An important focus of their work is developing rapid, scalable, low-cost fabrication processes for synthesizing nanomaterials that can be used as a charge transport layer in solar cells as well as in other applications. Someday, the nanomaterials, nanocomposites, and nanocrystalline thin films they are generating in the mustard yellow Science Building at the center of campus may help strengthen America’s renewable energy industry.

Nanomaterials are 80,000 times smaller than a human hair. These days, nanotechnology researchers are able to assemble individual elements such as carbon atoms to synthesize nanoscale materials, including carbon nanotubes, graphene, and buckyballs (C60). They use these “components,” in turn, to build nanostructures and systems known as nanoelectromechanical systems (NEMS)—6,000 of which would fit on the head of a pin. Scientists assemble nanomaterials such as nanotubes because of stiffness, elastic modulus, or other outstanding properties. Carbon nanotubes, for instance, have an elastic modulus five times that of steel at 1 tera pascal. Carbon nanotubes can also transport electrons ballistically and conduct electricity with negligible resistance. Such a property makes them uniquely suited for use in nanoelectronics.

With nanomaterials like these, engineers can improve the performance and efficiency of solar cells, batteries, semiconductors, and other advanced electronics. Manufacturers are also using today’s nanomaterials in flat-panel displays for computers and televisions, in scanning probe microscopes, and in various types of sensing devices for research and manufacturing. These microminiature sensors are embedded in a variety of everyday applications such as the iPhone, automotive air bags, and medical instruments that record patients’ blood pressure and other vital signs. They are useful for detecting motion, acceleration, temperature, pressure, inertial forces, chemical species, magnetic fields, and radiation levels. These devices, like these are ubiquitous as they are cheaper to produce and made with environmentally friendly materials compared to their older counterparts with similar functions.

Teh was trained originally as a mechanical engineer and microelectromechanical systems (MEMS) researcher and has extensive experience in silicon processing. His current research aims to develop scalable, rapid deposition techniques for non-silicon nanomaterials and to understand how heat treatment and dopant implantation affect their properties. These nanomaterials include nanocrystalline thin films, nanostructures of different geometries and orientation, and nanocomposites made up of binary oxides (zinc oxide, tin oxide), conductive polymer (polypyrrole), and low-dimensional carbons (carbon nanotubes, graphene). The nanomaterials Teh studies could have potential applications in energy generation and storage, tissue engineering, biochemical sensors, and self-cleaning coatings.

Teh is currently mentoring four undergraduate researchers in his laboratory and calls them “my most important assets in the lab.” Over the years, Teh has served as the research advisor for more than 15 SFSU engineering undergraduate students who have contributed their expertise and effort in various ways to build the Advanced Materials Research Laboratory. Several of the students have gone on to pursue graduate degrees at major research universities such as Purdue University, University of California at Davis, University of Washington at Seattle, and University of Maryland.

The Nanotechnology Revolution:

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former undergraduate students, Joachim Pedersen, Heather Esposito, and Mark Brunson, have participated in Teh’s research effort to find cheaper and better ways to manufacture transparent, conducting binary oxide nanocrystalline thin films for use in a special type of solar cell known as a dye-sensitized solar cell (DSSC)—a topic with particular importance and interest to consumers. Silicon-based solar cells are essentially PN diodes that generate electricity with a high cost that is a result of the unique processing means that if you shine a light bulb having one-fourth as much light. This relatively low efficiency necessitates very large arrays in order to collect usable quantities of energy. Though thin-film solar panels are less efficient at converting sunlight to electrical energy, they are much less expensive to produce, potentially reducing the cost for the same amount of power generation.

In third-generation solar cells, Teh’s research group uses an active layer made up of synthetic ruthenium-based dye and synthesizes an electron-collecting layer made up of zinc oxide or titanium dioxide nanostructures. At a fundamental level, the synthetic dyes are similar to the pigments in blackberries or blueberries. Natural dyes are inexpensive and readily accessible, Teh explains, although they tend to suffer from oxidation-induced degradation. Because synthetic dyes are so expensive, Teh’s students have been experimenting with natural dyes extracted from blackberries to practice their fabrication skills. These pigments have evolved, says student Mark Brunson (currently a materials science graduate student at the University of Washington, Seattle), “to get as much visible light [as possible] from the sun and to get as much chemical energy [as possible] out of them.” To construct a prototype DSSC, while at SF State, Brunson would begin by creating a titanium dioxide paste which he then sintered in an oven to allow the formation of a nanostructured titanium dioxide layer. He then applied this titanium dioxide paste by screen-printing it onto the anode, which is a piece of glass, plastic, or mica that has been coated with a transparent conducting oxide. The anode is subsequently dipped in a dye solution in order to coat the titanium dioxide layer. Meanwhile, the cathode is typically a piece of glass coated with a thin platinum film. He pressed the anode and cathode together, injected an electrolyte (a redox couple) between them to form the redox layer, and then sealed the cell. The titanium dioxide or zinc oxide layer helps collect and conduct electrons ejected from the dye molecules in the active layer. The beauty of this kind of solar cell, comments Pedersen, is that the assembly steps can be performed under ambient conditions and without the need for high-tech equipment.

Teh and his students’ main research goals for this line of research are to synthesize and optimize the transparency and electrical conductivity of zinc oxide, thereby improving the conversion efficiency of their inexpensively made solar cells. To do this, they are increasing the number of captured photo-excited electrons.

Dr. Kwok-Siong Teh
School of Engineering

Left: Undergraduate researchers in Dr. Teh’s lab. (Left to right) Mark Brunson, Rabiah Harrison, Heather Esposito, and Joachim Pedersen.

Photo by Dr. Teh

Right: Thermal plasma chemical vapor deposition system for depositing ZnO nanocrystalline thin films.

Photo by Dr. Teh

Top: 100nm-thick ZnO nanocrystalline thin film as deposited on a p-type Silicon (100) wafer.

Photo by Joachim Pedersen

Photo by Dr. Teh
California-based manufacturer of high-tech vision screens, and just about any appliance cells on the windows of buildings or on utility will allow people to use low-cost solar platforms such as plastic, and such flexibility could potentially be built on a flexible substrate. But, when the cost and other factors are taken into consideration, the 12-percent efficiency rate is too low for practical applications. The public may initially find this producing only a 12-percent conversion efficiency. "Theoretically," he says, "the efficiency of thin-film deposition rather than crystal-slicing, however, they require inorganic and toxic materials such as amorphous silicon or cadmium telluride. Such tedious, precise, and toxic manufacturing processes are what make currently available generation solar cells so expensive. The panels needed to power a typical three-bedroom home in a sunny inland area of California can cost $25,000 to $40,000.

Despite the fact that renewable energy currently occupies only 8% of our national energy portfolio, Teh thinks that by 2025, that percentage should be closer to 15%. By then, we should be able to rely more heavily on solar, wind, and other renewable technologies to supply energy for industry, transportation, and households. His students also express the hope that nations will employ new forms of energy before the next energy crisis, rather than after it. "Petroleum-based materials are finite," says Heather Esposito. "Eventually these materials will become more difficult to extract and the costs of solar cell production will crisscross the costs of coal and petroleum."

Generating new energy sources is just one part of the renewable energy equation, Teh points out. The second and often-neglected part is conservation. "Conservation is less sexy from a technical standpoint and people don't talk about it a lot," he says. But "doing really simple things can result in savings that are quite substantial immediately." Line drying clothes under the sun is a good example. "In California, we have a lot of sunshine. So why not?"

Other simple techniques include turning off your computer when you're not using it," he says, "and turning off the TV if you are not watching it." It's also a good idea to alter energy habits when you are young, he adds, because older people can become entrenched and ask "Why should I be giving up my personal freedom for this?"

Conversing brings up such individual issues, Teh continues, as well as legal and municipal ones, whereas energy generation is straightforward. Americans are "going all out" to research new materials "to get a little bit more energy from sunlight or wind or biomass," when at the same time, "We seldom realize we are just throwing energy out the door because we are not using it efficiently." We may not need to generate a lot more energy now, he concludes. "We just need to consume energy more wisely in a less wasteful manner. And it's something that each of us can begin to do immediately!"