Small Scale, Big Impact

Imagine a swarm of insect-inspired robots flying through the sky, using tiny sensors that can continuously monitor pollution levels or the use of chemical weapons. This futuristic vision may actually become reality, thanks to the innovative research spearheaded by Igor Bargatin, Class of 1965 Term Assistant Professor in Mechanical Engineering and Applied Mechanics (MEAM). By developing the thinnest freestanding ceramic plates that can be picked up by hand, he has come one step closer to enabling wings that are both lightweight and robust. These wings could be used in flying robots for a variety of environmental and military applications.

“Despite being made up of a brittle ceramic material, the plates are remarkably tough and can recover their original shape after sharp bending,” explains Bargatin. “When used to make wings for flying robots, the lightweight plates could potentially enable long flight times without the need for an onboard power source. This stands in stark contrast to existing types of insect-inspired robots, which are not practical for long-term use because they consume so much power.”

To construct the freestanding plates, Bargatin and his team combined a process called “atomic layer deposition” with advanced microfabrication techniques. The two-centimeter-wide plates are formed by depositing ultrathin alumina films on a honeycomb-patterned silicon wafer, and then removing the silicon to leave behind only the ceramic material (see back cover). “The secret to our success is the honeycomb pattern, which allows the plates to stay rigid enough to maintain their shape under gravity,” says Bargatin.

Currently, the thinnest manmade wing material commonly available is Mylar film. Similar to cling wrap, this material wrinkles easily, sags under its own weight, and generally cannot maintain its shape unless it is stretched on a heavy frame. But the freestanding plates hold promise for overcoming these limitations, potentially enabling the widespread implementation of lightweight insect-inspired flying robots for various sensor applications. Moreover, these plates could lead to the development of novel ultra-strong materials that benefit from nanoscale strength enhancement, which could be used in jet engines or thermionic energy converters.

IGOR BARGATIN
Class of 1965 Term Assistant Professor
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"Igor's work complements existing research at Penn because he combines nanoscale concepts with larger-scale issues, like structural stability and energy conversion," notes Robert Carpick, John Henry Towne Professor and chair of MEAM. "The exceptional facilities here in the Singh Center for Nanotechnology provide him with the tools he needs for this extremely fine-scale fabrication and characterization. It is a unique strength of Penn that makes his innovative work possible."

HARNESSING WASTE HEAT

Bargatin did not always envision becoming a mechanical engineer. As a teenager, he won first place in the All-Russia Physics Olympiad before pursuing a bachelor's degree in theoretical physics at Moscow State University. "My undergraduate research focused on quantum-optics systems, which have inspired a lot of Nobel Prizes, but have a long way to go before they make a big impact on our daily lives," he says. "That's when I started to sense that I wanted to do something more practical."

> BARGATIN HAS DEVELOPED THE THINNEST FREESTANDING CERAMIC PLATES THAT CAN BE PICKED UP BY HAND.

During his doctoral studies at Caltech, Bargatin embarked on the challenging transition from theoretical to experimental physics when he decided to work on nanomechanical devices for sensors. His career path took another turn as a postdoctoral scholar in the Department of Electrical Engineering at Stanford, where he started trying to revive the field's interest in research on thermionic energy converters.

In its heyday, this technology was used to directly convert heat to electricity for powering space missions. Here's how it works: electrons evaporate from a hot electrode (i.e., the cathode) into a vacuum gap and are collected by a cooler electrode (i.e., the anode) to create an electric current. "Most of U.S. thermionics research was tied to the space-nuclear program, which ended in 1973," notes Bargatin. "Thermionics research never fully recovered from this blow."

After joining the Penn faculty three years ago, Bargatin and his collaborators received a large grant from the U.S. Department of Energy to breathe new life into this research area by developing highly efficient thermionic energy converters. Recent advances in materials science and microfabrication techniques have translated into radically higher performance and lower manufacturing costs, making thermionic energy conversion an attractive option for both residential and industrial applications.

For example, the devices could be used to generate electricity in homes by harnessing waste heat produced by household water heaters or industrial processes. While the conventional method of producing usable heat and power separately has a typical combined efficiency of 45 percent, combined-heat-and-power systems can operate at levels as high as 80 percent. Moreover, thermionic energy converters could be combined with solar panels to make houses more independent from the power grid.

To roughly double the efficiency of these systems, Bargatin and his collaborators have proposed two key innovations: fabricating higher-quality anode materials, and reducing the size of the gap separating the electrodes to optimize the flow of current. Whether the new devices are used in houses or power plants, they hold promise for reducing greenhouse gas emissions and lowering consumer energy costs.

ENERGIZING ENGINEERS

To inspire the best work from his graduate students, Bargatin fosters a positive, collaborative environment. He encourages students to work independently while remaining accessible and open to new ideas. "Dr. Bargatin has a way of challenging you to learn more, dig a little deeper and try to find the answer yourself," remarks John Cortes, a MEAM doctoral student in the Bargatin lab. "He is always available to answer questions if you get stuck, but at the end of the day, I feel like I

Bargatin demonstrates a Stirling engine with Chen Lin (right) and John Cortes (center), third- and second-year doctoral students, respectively. A Stirling engine can convert the energy from hot water (seen in the cup below the engine) into mechanical work, driving the crankshaft of the engine.

have accomplished a lot with his guidance, which is ideal in engineering."

While teaching lessons for his newly developed course, MEAM 503: Direct Energy Conversion: From Macro to Nano, Bargatin relies extensively on analogies to make the material accessible to students who are completely new to the topic. This tactic has paid off, making the popular course among the most highly rated in the department. Similarly, as the instructor for MEAM 203: Introduction to Thermodynamics, Bargatin has worked hard to explain the abstract and challenging material to a large number of students who enter with varying levels of preparation.

"To help the students learn, Igor overhauled the course, creating a full set of new problems with real-world examples and consequences, and developed new in-class demonstrations to help illustrate the concepts at play," remarks Carpick. "This is leading to positive learning outcomes for the students, thanks to his substantial efforts."

Whether it's in the classroom or the lab, Bargatin is optimistic that his innovative and imaginative approach to engineering will pay off. "I hope that my lessons will get students as excited about research as I am," he says. "Maybe one day they too will be inspired to dream of something new, and figure out whether it has legs to stand on, or wings to fly, for that matter. And hopefully that invention can change the world, at least a little bit."

By Janelle Weaver