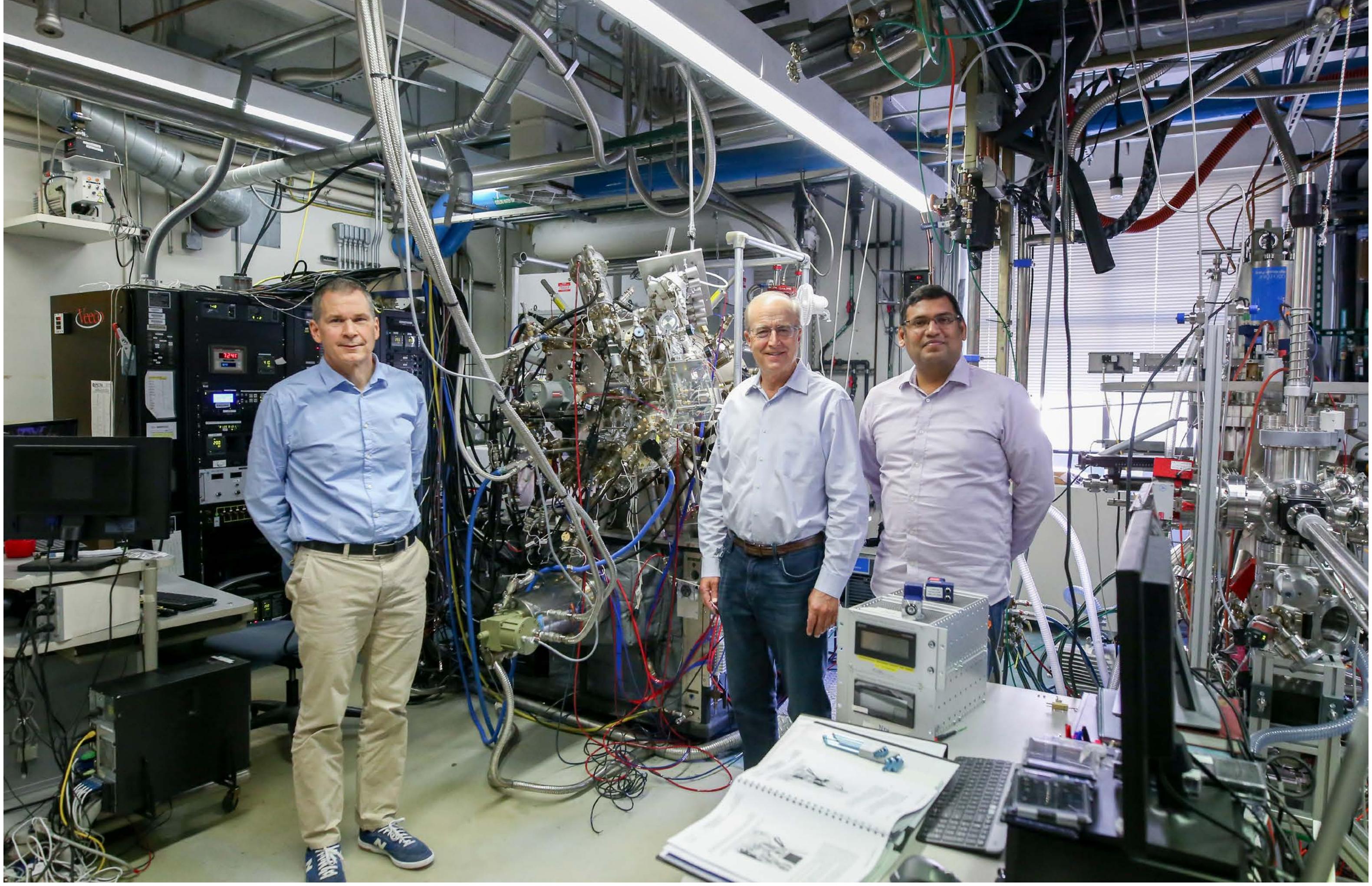


UC Santa Barbara professors (left to right) Jim Speck, John Bowers, and Sriram Krishnamoorthy are collaborating to develop compact high-velocity switches.

TWO MAJOR GRANTS FOR THE JIM SPECK LAB

THE MATERIALS PROFESSOR WON BOTH A VANNEVAR BUSH AWARD AND AN ARPA-E GRANT

UC Santa Barbara materials professor **Jim Speck** received two major grants in 2024. The first was a Vannevar Bush Faculty Fellowship (VBFF), which will allow him to further investigate loss mechanisms in gallium nitride (GaN) light-emiting diodes (LEDs). GaN, of course, is the semiconductor material that **Shuji Nakamura,** before becoming Speck's colleague in the UCSB Materials Department, used to invent the blue LED, which enabled the white LED and a world revolution in lighting and would earn Nakamura the Nobel Prize in 2014. The other award Speck received is an ARPA-E grant to develop a new generation of optically controlled high-voltage power switches.

Vannevar Bush: Hot-Electron Physics

Speck received the highly prestigious Vannevar Bush Faculty Fellowship — only eleven were awarded in 2024 — from the U.S. Department of Defense to pursue high-risk, high-reward research, the kind, the DoD said in a release last summer, that has "transformed entire disciplines, birthed novel fields, and challenged established theories and perspectives." The five-year, $3-million award will enable Speck to build on research he has pursued for nearly fifteen years related to the little-understood physics behind a loss mechanism in GaN LEDs known as *current droop*.

Normally in an LED, electrons and holes combine in a quantum well, rise to a higher energy level, and then emit light as the extra energy is released. Sometimes, however, rather than an electron recombining with a hole to make a photon, *two* electrons recombine with a hole to make a "hot" electron, in a process aptly called *non-radiative*, because it does not emit light, only heat, and is therefore an element of efficiency loss. Speck will work closely with UCSB colleagues, such as materials professors **Chris Van de Walle,** an expert in modeling loss mechanisms in GaN semiconductors and

LEDs, and **Claude Weisbuch,** with whom Speck designed and ran experiments that enabled them to become the first to measure hot electrons arising from non-radiative recombination, called *Auger* recombination.

"We worked hard to design experiments that would enable us to extract the very-high-energy Auger electrons out of the semiconductor," Speck explains, adding that their desire for a better understanding of the Auger process was driven by a curious fact: "If we look at the science of the semiconductor and the way light-emitting diodes work, there are no processes that should generate *hot carriers*."

Releasing those hot electrons allowed them to measure the particles and their energy in vacuum in a spectrometer, and in 2013, Speck and Weisbuch published an important paper describing their research to achieve the world's first direct measurement of hot electrons. Thanks to work that Speck, Weisbuch, and Van de Walle have done together since then, Speck says, "All aspects of the technique have gone forward by leaps and bounds. It is still a very active area of our research, and is the foundation for our pursuits made possible by the Vannevar Bush Fellowship."

Much remains to be understood, however, about the complex physics behind Auger recombination and the resulting current droop. Speck's VBFF will allow him and his UCSB colleagues to spend the next five years diving deep into that knowledge frontier.

Compact High-Voltage Switching

Imagine that a utility needed to shut down some part of the electrical grid it manages in order to prevent an imminent cyber attack or avoid having power lines come down in a wind storm, possibly setting off fires. (The DoD says that power disruptions cost the U.S. more than $150 billion per year.)

That is the realm of power switching, and in August, Speck received a three-year, $3.1-million grant from the DoD's ARPA-E Program to develop more efficient power switches. Speck and his collaborating co-PIs, UCSB professor of electrical and computer engineering and Institute for Energy Efficiency director, **John Bowers,** materials associate professor **Sriram Krishnamoorthy,** and a colleague at Ohio State University, Jin Wang, intend to develop switches on a gallium oxide (Ga_2O_3) material platform that integrate optics to make them faster, simpler, smaller, and more powerful than their predecessors.

Currently, high-voltage direct-current (HVDC) power systems are used primarily to send power a relatively short distance, say, from an offshore wind farm to the mainland, because that is the fastest way to move the electricity. It is then switched to alternating current (AC) once it reaches a device on the other end, as is the case with the HVDC cable that crosses San Francisco Bay.

HVDC is too expensive, however, for long-range transmission and involves many elements that have to be combined to do the job. For instance, Krishnamoorthy explains,"If you're talking about moving, say, a megavolt or hundreds of kilovolts, and an individual power module is 6.5 or 8.5 kilovolts, then you need to stack hundreds of power converters in series and control them synchronously to switch very high powers at the grid scale.

"That requires sophisticated switches," he adds. "In one aspect of this program, which has three parts, we're exploring whether we can develop an individual power switch or, eventually, a module that can handle higher voltages, replacing the "stacks of modules and dramatically simplifying the system in many areas of power electronics."

The hardware in current switching systems is built with silicon technology, but the researchers would like to replace it with one requiring a smaller number of switches built on a platform of Ga_2O_3. Speck has been a longtime leader in gallium oxide research, having received a seed grant from the UCSB Materials Research Lab in the 2000s to work on it as a transparent conducting oxide. (The metals often used in semiconductors absorb light; transparency allows more light to be pulled from a heterostructure that incorporates the Ga_2O_3.) He was one of the first to grow gallium oxide crystals, and he ran the first U.S. Department of Defense Multidisciplinary University Research Initiative (MURI) program on the material. Van de Walle has also done extensive modeling of gallium oxide semiconductors.

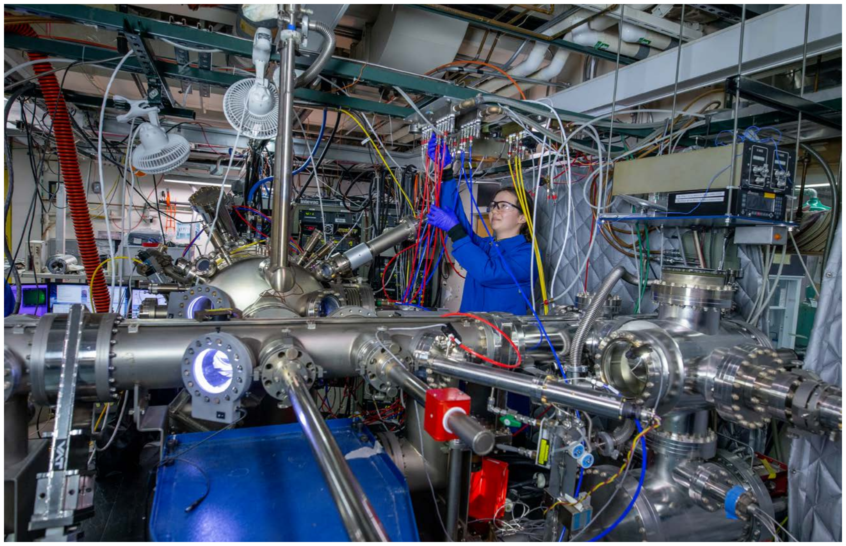
"A long sequence of activities has led to the kind of generational experience and the program we have now at UCSB," says Krishnamoorthy. "You need that kind of history of excellence to convince funding agencies to give you money."

The second aspect of the project is to make the new switch faster, and while questions remain as to the desirability of that approach *at the grid scale,* Krishnamoorthy explains that it has obvious benefits for consumer electronics. "At that scale, if you can make switches that can switch faster by increasing the power density, then your capacitors and inductors can be smaller while still managing the current," he says.

The third part involves figuring out how to control the new devices. Typically, stack modules and anything in the power system or power electronic circuit are controlled with electrical signals. But they have an inherent problem, knowns as *parasitics,* a type of loss mechanism that any wire has and that leads to issues of electromagnetic interference (EMI), which equates to inefficiency and creates feedback loops that can negatively affect the switch.

Seeking to address that shortcoming of wired systems, Bowers, with his expertise in photonics, is aiming to control the new high-voltage switches optically rather than electronically. "Typically, a transistor is controlled with a gate; we're planning to use John's opticals to control Jin Wang's circuit," explains Krishnamoorthy. "They will be like light-controlled high-voltage fast switches, and they'll be based on a high-speed gallium arsenide heterojunction photo transistor from John's lab."

"This project is very exciting, especially since we will be scaling multiple levels of abstractions," Krishnamoorthy says. "We are doing cutting-edge material science, because we'll be using both metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) work to grow the gallium oxide crystals for the power devices. [Using those two systems allows the team to determine which method produces crystals that are best for the application.] I will build the high-voltage power switches, and John will build the fast-response optically controlled transistors, which will be part of the gate drive circuit, built by Jin Wang and incorporating Bowers's optics. We've built the first round of devices, and so far, everything seems to be working."



Rosalyn Koscica, a fifth-year PhD student in John Bowers's group, works in the Molecular Beam Epitaxy lab, attending to a setup required to grow gallium nitride.