

UC SANTA BARBARA

THE *Current*

November 5, 2024

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Little-understood physics in gallium-nitride LEDs garners UCSB's Jim Speck a prestigious Vannevar Bush award

UC Santa Barbara materials professor [Jim Speck](#) is one of only 11 people — from an initial group of 170 applicants, 27 of whom were invited to submit full proposals — to receive a prestigious 2024 Vannevar Bush Faculty Fellowship (VBFF). The award allots recipients up to \$3 million in funding, over five years, to “explore the frontiers of knowledge and advance transformative, fundamental research at their respective universities.”

Speck's proposal, “Beyond the Band Minima: High Energy Electron Dispersion, Physics, and Technology,” is an outgrowth of work he has been pursuing for some 15 years in collaboration with UCSB materials science colleagues and with industry members of the UCSB Solid State Lighting and Energy Electronics Center (SSLEEC).

Around 2010, Speck began long-term research with fellow UCSB materials professors Claude Weisbuch, an experimentalist, and Chris van de Walle, a computational theoretician, to explore a phenomenon that limits the performance of gallium-nitride (GaN) light-emitting diodes (LEDs), a material and a device in which UCSB is a world leader. (GaN is the semiconductor material that UCSB materials professor Shuji Nakamura used to develop the blue LED, which led to a world revolution in lighting

and to his Nobel Prize in Physics in 2014.)

“We were trying to understand not why (comparatively highly efficient) gallium nitride LEDs are efficient, but rather, what physical processes there are that can make them inefficient,” Speck said.

That loss of efficiency, known as current “droop,” occurs in LEDs as voltage is increased beyond a certain threshold. Normally, an LED emits light as electrons and holes combine in a quantum well, and light is emitted. Sometimes, however, instead of an electron recombining with a hole to make a photon, Speck explained, two electrons recombine with a hole to make a “hot” electron, in a process aptly called non-radiative, because it emits only heat, not light, and is therefore an element of efficiency loss.

Speck and Weisbuch began designing experiments to measure hot electrons arising from that non-radiative recombination process, 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 said. “If we look at the science of the semiconductor and the way light-emitting diodes work, there are no processes that should generate what we call hot carriers.” Releasing those hot electrons allowed them to then measure the particles and their energy in vacuum in a spectrometer, in an experiment referred to as electro-emission spectroscopy (EES).

In 2013, Speck and Weisbuch published a paper describing research in their labs that had yielded the world’s first direct measurement of hot electrons. Thanks to work that they, with Van de Walle, have done together since then, Speck said, “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 the Vannevar Bush fellowship. “We were the first and still are the only group in the world to make these measurements related to Auger recombination. And it wasn’t that we had the smoking gun. We actually had the bullet from the process. The Auger hot electrons that we measure are the ones that physically were involved in the non-radiative recombination process.”

One of the big surprises in electron emission spectroscopy was that the energy of the electrons that comes out doesn’t correspond to what theory says it should be. “We had a big discrepancy between our experimental results and theory,” he

added.

That discrepancy, in turn, was a big motivation for his VBFF proposal. In the program, Speck will develop techniques to directly measure the electronic structure of semiconductors — namely, the normally empty states, known as the conduction band. Existing techniques such as angle-resolved photoemission spectroscopy (ARPES) measure occupied states, or valence bands in semiconductors. The first major goal of the VBFF research is to develop the techniques and instrumentation, the latter of which may involve modifying extremely sophisticated existing instruments, to measure conduction-band structure.

“Direct measurement of the conduction-band structure would profoundly impact many problems in semiconductors,” Speck explained. “For example, in high-voltage devices used for radio-frequency electronics and power electronics — such as those used to change voltage or to change AC to DC or vice versa — electrons can be accelerated to high energies; that is the area of high-electric-field transport. Understanding the physical processes in high-field transport depends on having knowledge about the conduction structure at energies far in excess of those usually considered for conventional semiconductor devices.

“You can think of the band structure as being like a map of the energy of the semiconductor,” he continued. “To really understand what's happening, you need the map and currently, part of the map is not on such firm ground, experimentally. Other parts are on firmer ground. This project is really about closing that knowledge gap by conducting experiments to see what processes are occurring, what is really happening. So, there's real discovery taking place as we look for physical processes we haven't identified previously.”

Other goals of the VBFF research are to measure hot-carrier distributions in high field transport, and to continue investigating non-radiative processes in semiconductors. “There is huge interest in this work in the solid-state community,” Speck noted, “and more so in the condensed-matter physics community in measuring the conduction-band structure, whether in semiconductors, metals, or exotic materials, such as the topological insulators being pursued for use in quantum applications.”

Speck is UCSB's newest Vannevar Bush Fellow, but not its first. Van de Walle received a VBFF in 2022, while materials professors Tresa Pollock, Susanne Stemmer

and Christopher Palmstrom earned VBFFs in 2017, 2016 and 2015, respectively).

The Vannevar Bush Faculty Fellowship is the Department of Defense's most prestigious single-investigator award and supports basic research with the potential for transformative impact. Reflecting the DoD's commitment to "blue sky," unfettered research and the exchange of scientific knowledge between fellows and the government to benefit the country, the awards program supports new, out-of-the box ideas where researcher creativity intersects with the unknown.

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