GROWING SEMICONDUCTORS, Reducing Cost

Research engineer Caitlin Chapin shows a collection of drift step recovery diodes (DSRDs) produced using the team's time- and cost-saving fabrication technique.

DRIFT STEP recovery diodes (DSRDs) are specialized circuit components that transform steady, direct-current voltages into nanosecond-long pulses of electricity. This “pulsed power” amplifies voltage tenfold compared to continuous high-voltage delivery. High-powered electronics systems as well as radiation-generating instruments such as accelerators, high-power lasers, and x-ray sources require the significantly higher power yields that pulsed power can offer. Manufacturing these devices requires thousands of DSRDs to amplify a direct current voltage and confine it to near-instantaneous bursts.

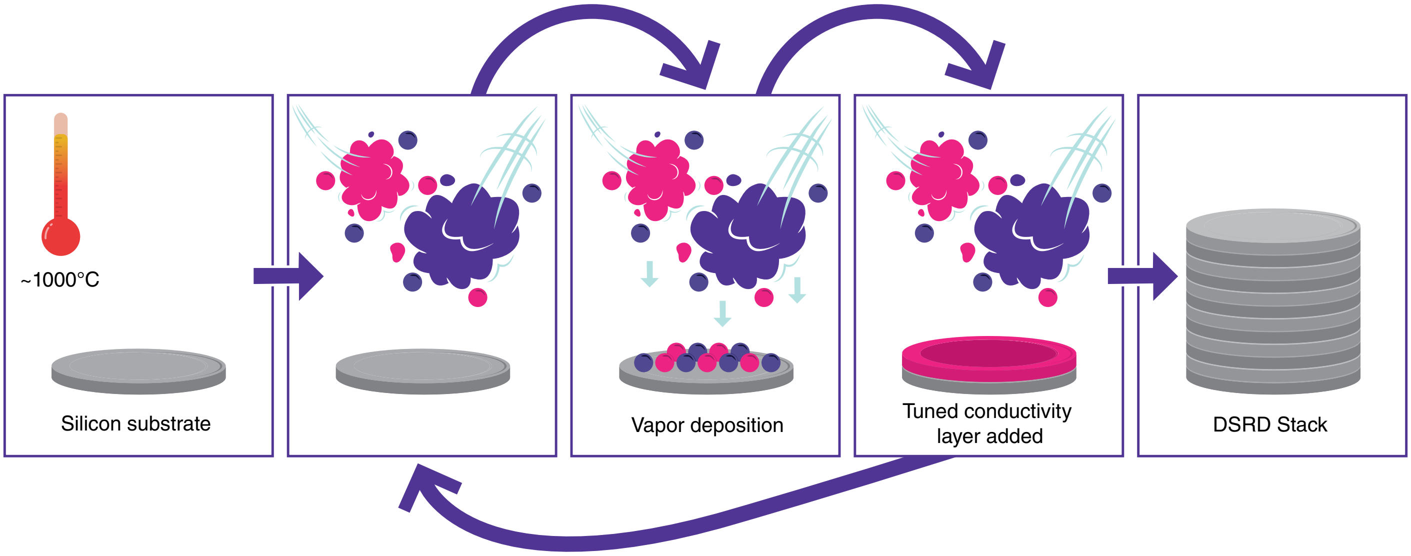
Despite the critical need for DSRDs, their expensive and time-intensive fabrication process has prohibited widespread use. Other less expensive circuit components might be used as substitutes, but none come close to the performance capabilities of DSRDs. New solutions are necessary to ensure the capabilities of such tools are not compromised with reduced costs. “Given the national need for DSRDs, we must be able to produce them affordably,” says Lars Voss, associate program leader for Electronic Warfare and group leader for High-Power Electronics Research in Livermore’s Materials Engineering Division (MED). “DSRDs have other applications beyond directed-energy systems—for example, within internal combustion engines—but makers of such systems could never justify the increased cost. Almost no one sells DSRDs, virtually eliminating the domestic supply.”

In 2018, Voss’s team began work with multiple Department of Defense partners to develop an economical method of DSRD fabrication. A semiconductor fabrication process refined by Livermore scientists to produce DSRDs was selected as a finalist for the 2023 R&D 100 awards. The process yields DSRDs that meet or exceed the functionality of legacy manufactured components, all while reducing production cost by an order of magnitude or more.

Fundamental Design Changes

Semiconductors are conventionally created through a deep diffusion process that introduces dopants—elemental impurities—into the crystal lattice of a silicon wafer. Dopants transform the wafer into a device that effectively conducts electricity. Dopant type dictates the conductive properties of each semiconductor region: N-type dopants, such as phosphorus, produce regions of negative charge carriers, and P-type dopants, such as boron, produce regions of positive charge carriers. DSRDs also contain a lightly doped intrinsic region. This high-temperature region—where electricity conduction in the semiconductor is dominated by excited electrons between the valence and conduction bands—is sandwiched between the N and P semiconductors.

Controlling the distribution of dopants and thickness of each semiconductor layer is vital to ensuring optimal performance of the final device. However, the diffusion process used for many years to produce first-generation DSRDs is cumbersome, time-consuming, and expensive, making it challenging to align manufacturing timelines with demand. “Dopant diffusion is a standard semiconductor manufacturing process, but in the case of DSRDs, the process is neither well controlled nor scaled to large production volumes,” says Sara Harrison, an engineer in MED and member of the epitaxial DSRD team. The prolonged diffusion process required for dopants to burrow sufficiently deep into the silicon can take more than a week, throughout



DSRDs are built layer by layer (epitaxy) via atmospheric-pressure chemical vapor deposition (APCVD), which incorporates gaseous dopants (shown in pink and purple) into silicon layers growing on top of the substrate. These dopants, such as boron, phosphorus, and arsenic alternately integrate into growing silicon layers to dictate the electrical conductivity properties of each layer.

which the operating temperature of specialized equipment must be maintained at or exceed 1,200°C.

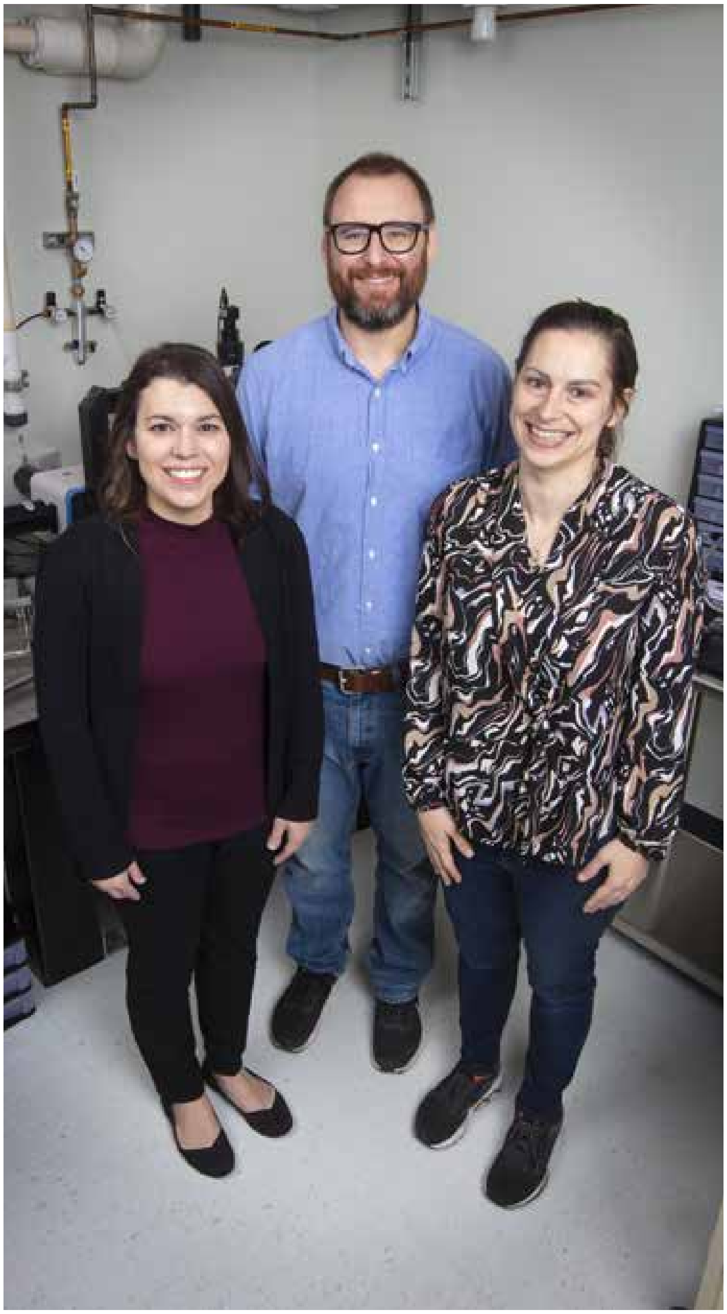
To move beyond legacy DSRDs made using dopant diffusion and the levels of control required for efficient DSRD production, scientists needed to explore alternative fabrication options. In 2019, Voss's team identified a common fabrication technique in the semiconductor manufacturing industry that, when modified, showed promise in outperforming the legacy diffusion process: atmospheric pressure chemical vapor deposition (APCVD). Rather than slowly infusing a silicon wafer with dopants, the device could be built layer after layer by alternately depositing gas-phase ingredients onto a highly doped substrate of crystalline silicon—a process called epitaxy.

"Epitaxy is an elegant additive process that allows us to alter semiconductors' conductivity profile by controlling temperature and gas composition during deposition," says Harrison. To perform APCVD and promote epitaxial growth, gaseous precursors containing elements such as boron, phosphorus, and arsenic decompose and incorporate into silicon layers growing on top of the substrate. The selected dopants and their concentrations dictate the tailored conductive properties of the growing crystal layers. Compared to diffusion, epitaxy permits finer manufacturer control at each step. Dopant profiles can be strategically ramped during growth to achieve desired conductivity attributes and thickness for each deposited layer.

Magnitudes of Improvement

What once required a week of constant heating to produce first-generation DSRDs via dopant diffusion was slashed to a mere 2.5 hours by switching to epitaxial growth. In addition, the team's APCVD setup for epitaxial growth could support silicon wafers approximately 20 centimeters in diameter, whereas the furnaces used for the legacy diffusion process only supported 7.5-centimeter wafers. "Epitaxy is used to grow one device layer, and afterwards, multiple layers are bonded together to create a DSRD stack," says Caitlin Chapin, who has led the epitaxial DSRD research at Livermore since 2022. By increasing the wafer diameter and supporting larger batch sizes, the new method significantly decreases DSRD production cost per unit, a necessity given the large quantity required for the radiation-generating instruments used in the medical, manufacturing, and security sectors.

Further work to reduce cost and augment device performance on the second-generation devices involved fine-tuning growth parameters and experimenting with different bonding and packaging techniques. "Livermore brings expertise in solid-state switch semiconductors, but we do not work in a vacuum.



Livermore's epitaxial DSRD technology was named a finalist in the 2023 R&D 100 awards. The development team: (from left) Sara Harrison, Lars Voss, and Caitlin Chapin.

Developing epitaxial DSRDs is an iterative process that requires close collaboration with our research partners," says Harrison. Livermore collaborated with the United States Army Space and Missile Defense Command, BAE Systems, and the Lawrence Semiconductor Research Laboratory to co-develop the technology to suit national defense needs.

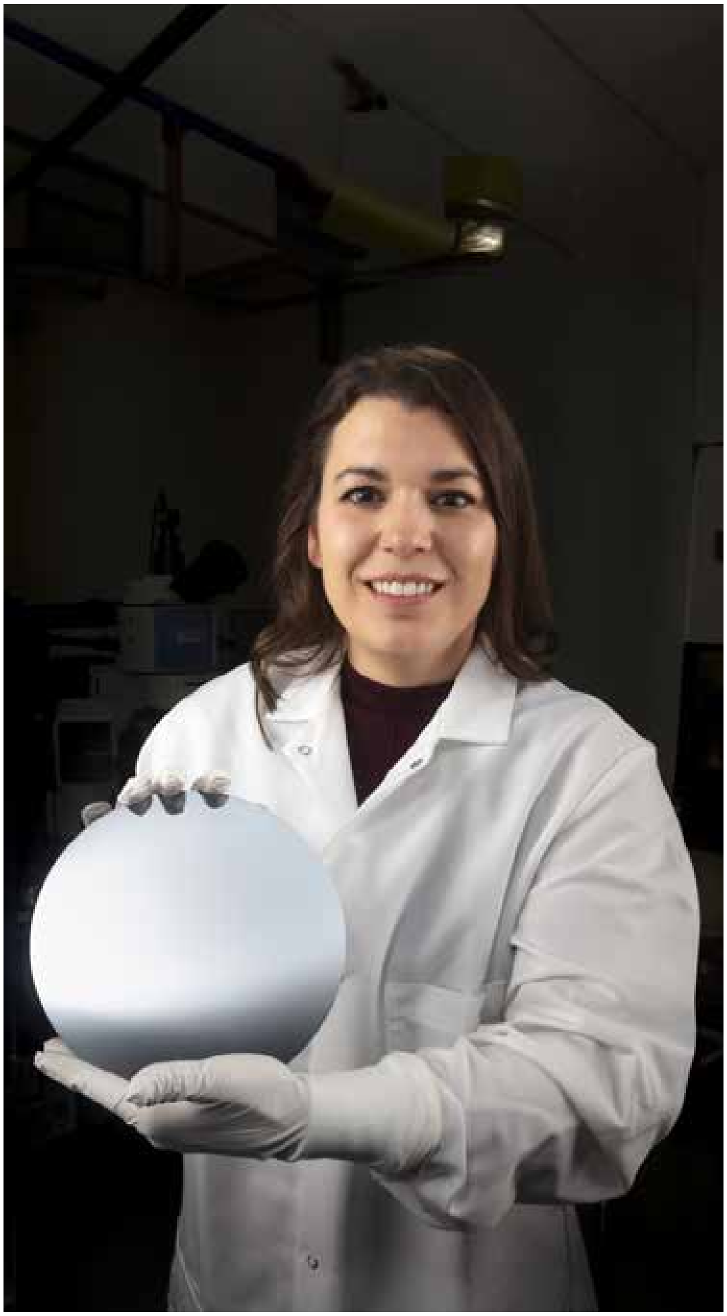
With process design for second-generation DSRDs nearing finalization, the team has been proactive in identifying opportunities for even greater performance and manufacturability in the form of third-generation devices. Voss says, "We continue to improve the dopant profile and optimize thermal management to enable operation at higher power. Crucially, third-generation DSRDs will also usher in another magnitude reduction in manufacturing cost, eliminate bonding and dicing processes in manufacturing, and give DSRDs our best chance so far at commercialization."

Making DSRDs available to commercial markets is key to broadening the component's use beyond defense-related applications. For instance, DSRDs have applications in internal combustion engines, replacing spark plugs for increased fuel efficiency, and reduced greenhouse gas emissions.

Chapin explains the team's goals for additional refinements. "Second-generation DSRDs represent a significant leap forward from the legacy dopant diffusion process, but they still require multiple wafers. We aim to grow a full DSRD on a single wafer in a single run."

Other improvements are in sight. Although the streamlined epitaxy technique has reduced the time requirement significantly—hours versus days—temperatures required to perform vapor deposition still exceed 1,000°C. In a high-temperature environment, unwanted dopant diffusion can occur in the deposited structure and interfere with the growth process. Chapin says that mitigating effects from heat is a priority in their third-generation designs. Further improving the procedure and component performance opens up possibilities for industry partnerships and product commercialization. For now, with significant progress already made to streamline DSRD manufacturing and decrease costs, the research team is confident that further innovations will broaden device availability for existing national defense applications and other industries.

—Elliot Jaffe



Engineer Sara Harrison holds the epitaxial substrate used to grow DSRDs layer by layer through APCVD.

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