Sandia reports GaN diode with record 6.4kV breakdown

The target is 20kV, to protect the electric grid from electromagnetic pulses.

Sandia National Laboratories has fabricated and tested a gallium nitride (GaN)-based electronic device that can shunt excess electricity within a few billionths of a second while operating at a record 6400V — a step towards protecting the electric grid from an electromagnetic pulse (Yates et al, 'Demonstration of >6.0-kV Breakdown Voltage in Large Area Vertical GaN p-n Diodes With Step-Etched Junction Termination Extensions', IEEE Transactions on Electron Devices; DOI: 10.1109/TED.2022.3154665). The team's ultimate goal is to provide protection from voltage surges, which could lead to months-long power interruptions, with a device that operates at up to 20,000V.

Close-up of Sandia's array of GaN diodes — a step on the path to protecting the electrical grid from EMPs. (Photo by Rebecca Gustaf).

An electromagnetic pulse (EMP) can be caused by natural phenomena (such as solar flares) or human activity (such as a nuclear detonation in the atmosphere). An EMP causes huge voltages in a few billionths of a second, potentially affecting and damaging electronic devices over a large area.

EMPs are unlikely, but if one were to occur and damage the huge transformers that form the backbone of the USA's electric grid, it could take months to replace them and re-establish power to the affected portion of the nation, says Bob Kaplar, manager of a semiconductor device research group at Sandia.

"The reason why these devices are relevant to protecting the grid from an EMP is not just that they can get to high voltage — other devices can get to high voltage — but that they can respond in a couple billionths of a second. "While the device is protecting the grid from an EMP, it's at a very high voltage and thousands of amps are going through it, which is a huge amount of power. A material can only handle so much power for a certain amount of time, but we think the material in our diode has some advantages over other materials."

Regulator valve for the grid

The new diode can shunt a record 6400V of electricity within a few billionths of a second but the team, including Sandia electrical engineer Luke Yates (the paper's first author), is working towards fabricating a diode able to operate at about 20,000V, since most grid distribution electronics operate at around 13,000V.

The voltage surges caused by EMPs are a hundred times faster than those caused by lightning, so experts don't know if the devices designed to protect the grid against lightning strikes would be effective against an EMP, says Jack Flicker, a Sandia electric grid resiliency expert on the team.

"The electric grid has a number of different protections," Flicker adds. "They range in timeframe from very fast to very slow, and they're overlaid on the electric grid to ensure that an event cannot cause a catastrophic outage of the electric grid. The fastest protection that we typically have on the grid reacts against pulses at one millionth of a second, to protect against lightning. For EMPs, we're talking ten billionths of a second, a hundred times faster." The new Sandia device can react that quickly.

Growing perfect layers

"A major challenge of achieving these very high-voltage diodes is the need to have very thick gallium nitride layers. The drift regions of these devices have thicknesses of about 50μm," Crawford says. "The growth process we use can have growth rates of only one or two microns per hour," he adds. "A second major challenge is maintaining very low densities of crystalline defects, specifically impurities or missing atoms in the semiconductor material, throughout the growth time in order to generate devices that work at these very high voltages."

For the team to reach their ultimate goal of a device that operates at 20,000V, they will need to grow the layer even thicker with even fewer defects, Crawford notes. There are several other technical challenges to constructing a device that can operate at such high voltages and currents, she added, including designs to manage the very high internal electric fields within the devices.

Testing ultrafast diodes

After Crawford's team fabricated the devices, Flicker and his team tested how the devices responded to fast voltage spikes, similar to what would occur during an EMP. His challenge has been modifying a tool to measure the very fast response time of the devices.

"Developing the tools that can accurately measure the very fast responses is very difficult," Flicker says. "If we're talking one or two billionths of a second, they need to be able to measure even faster than that, which is a challenge."

Flicker and his team used very specialized equipment to apply a high-voltage pulse, and measure the electric pulse that is reflected back from the diode to tell when the device turns on, very accurately and in less than a billionth of a second.

Useful for smart transformers, solar panel converters and more

Devices like Sandia's GaN diode can be used for other purposes, beyond protecting the grid from EMPs, Kaplar says. These include smart transformers for the grid, electronic devices to convert electricity from roof-top solar panels into power that can be used by household appliances, and even electric car charging infrastructure.

Commonly, solar panel converters and electric car charging infrastructure can handle 1200V or 1700V. But operating at higher voltage allows for higher efficiencies and lower electricity losses.

Another portion of the project is to develop diodes for these types of devices that operate at high but not record-breaking voltage, but are easier to manufacture, Kaplar says. The Naval Research Laboratory is leading this part of the project.

Some smart transformers and electronic devices can now operate at up to 3300V, Flicker says, but efficiencies would be even greater if they could operate at 10,000V or 15,000V with one semiconductor device.

"We have this primary goal of protection of the electrical grid, but these devices have other uses beyond that," Flicker notes. "It's interesting to have our application area but know that these devices can be used in power electronics, power converters, everything that's at very high voltages."

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