

# Development of world's first vertical gallium oxide transistor through ion implantation doping

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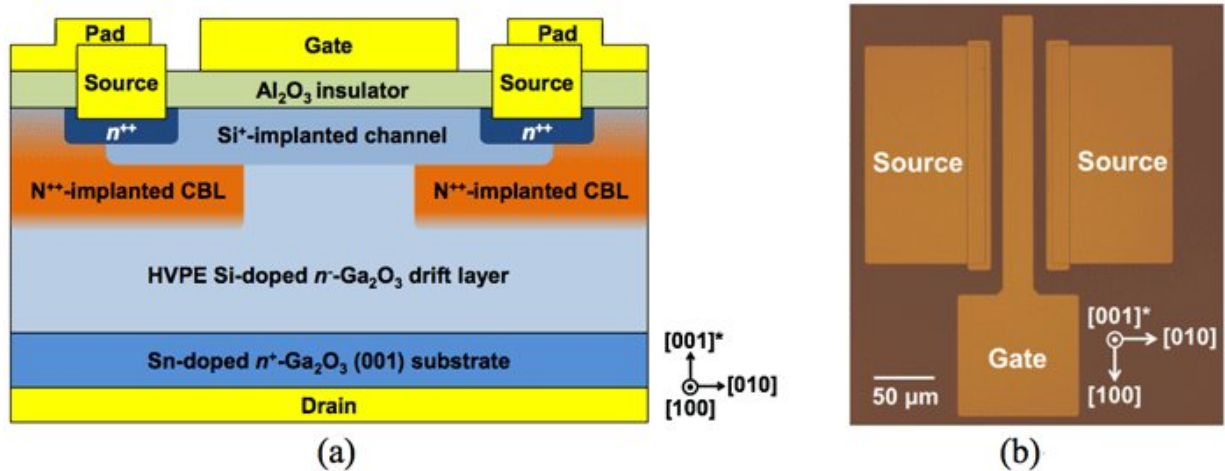


Fig. 1 (a) Cross-sectional schematic and (b) plan-view optical micrograph of the vertical Ga<sub>2</sub>O<sub>3</sub> MOSFET. Credit: National Institute of Information and Communications Technology (NICT)

Researchers at the National Institute of Information and Communications Technology (NICT) and Tokyo University of Agriculture and Technology (TUAT) demonstrate a vertical Ga<sub>2</sub>O<sub>3</sub> metal-oxide-semiconductor field-effect transistor (MOSFET) that adopts an all-ion-implanted process for both n-type and p-type doping, paving the way for new generations of low-cost and highly manufacturable Ga<sub>2</sub>O<sub>3</sub> power

electronic devices.

Power electronics is concerned with the regulation and conversion of electric power in such applications as motor drives, electric vehicles, data centers, and the grid. Power [electronic devices](#), namely rectifiers (diodes) and switches (transistors), form the core components of power electronic circuits. Today, power devices made of silicon (Si) are the mainstream but they are approaching fundamental performance limitations, rendering the commercial power systems bulky and inefficient. A new generation of power devices based on the wide-bandgap semiconductor [gallium oxide](#) ( $\text{Ga}_2\text{O}_3$ ) is expected to revolutionize the [power electronics](#) industry.  $\text{Ga}_2\text{O}_3$  promises dramatic reductions in the size, weight, cost, and energy consumption of power systems by increasing both the power density and power conversion efficiency at the device level.

The groundbreaking demonstration of the first single-crystal  $\text{Ga}_2\text{O}_3$  transistor by NICT in 2011 galvanized intensive international research activities into the science and engineering of this new oxide semiconductor. For the past several years, the development of  $\text{Ga}_2\text{O}_3$  transistors has focused on a lateral geometry. However, lateral devices are not amenable to the high currents and high voltages required for many applications owing to large device areas and reliability issues arising from self-heating and surface instabilities. In contrast, the vertical geometry allows for higher current drives without having to enlarge the chip size, simplified thermal management, and far superior field termination. The properties of a vertical transistor switch are engineered by introducing two types of impurities (dopants) into the semiconductor—n-type doping, which provides mobile charge carriers (electrons) to carry electrical current when the switch is in the on-state; and p-type doping, which enables voltage blocking when the switch is in the off-state. A group at NICT led by Masataka Higashiwaki has pioneered the use of Si as an n-type dopant in  $\text{Ga}_2\text{O}_3$  devices, but the

community has long struggled to identify a suitable p-type dopant. Earlier this year, the same group published on the feasibility of nitrogen (N) as a p-type dopant. Their latest accomplishment involves integrating Si and N doping to engineer a Ga<sub>2</sub>O<sub>3</sub> transistor for the first time, through a high energy dopant introduction process known as ion implantation.

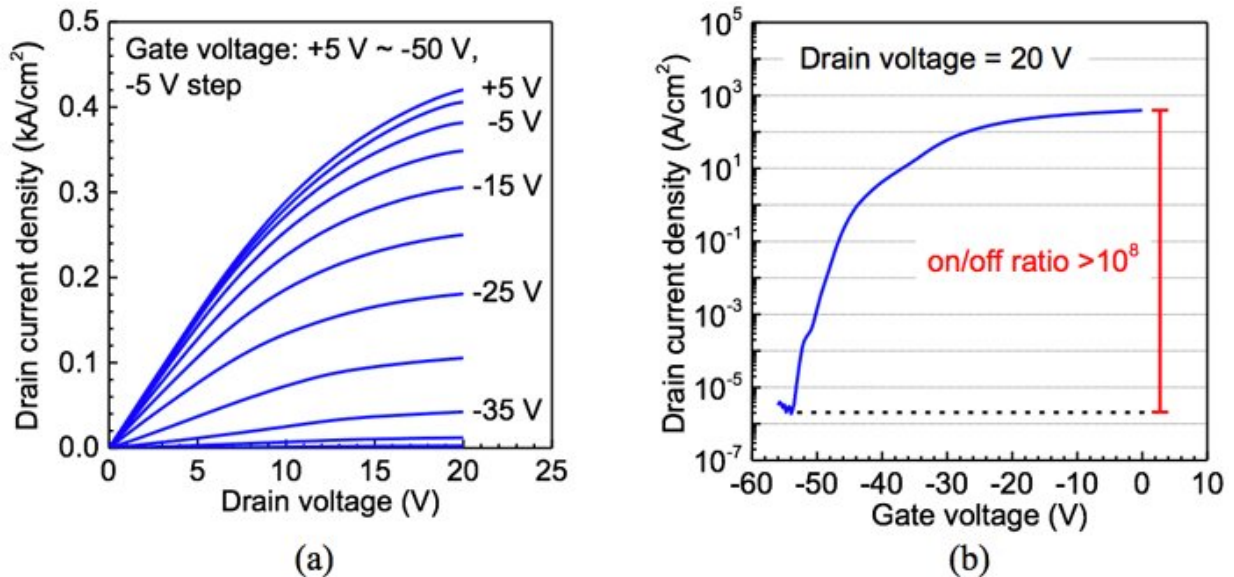


Fig. 2 (a) DC output and (b) transfer characteristics of the vertical Ga<sub>2</sub>O<sub>3</sub> MOSFET. Credit: National Institute of Information and Communications Technology (NICT)

"Our success is a breakthrough development that promises a transformational impact on Ga<sub>2</sub>O<sub>3</sub> power device technology," said Higashiwaki, Director of the Green ICT Device Advanced Development Center at NICT. "Ion implantation is a versatile fabrication technique widely adopted in the mass production of commercial semiconductor devices such as Si and silicon carbide (SiC) MOSFETs. The demonstration of an all-ion-implanted vertical Ga<sub>2</sub>O<sub>3</sub> transistor greatly

enhances the prospects for Ga<sub>2</sub>O<sub>3</sub>-based power electronics."

This study, published December 3 in the *IEEE Electron Device Letters* as an early access online paper and scheduled to appear in the January 2019 issue of the journal, builds on an earlier one in which a different acceptor dopant was used. "We initially investigated magnesium for p-type doping, but this dopant failed to deliver its expected performance since it diffuses significantly at high process temperatures," said Man Hoi Wong, a researcher of the Green ICT Device Advanced Development Center and the lead author of the paper. "Nitrogen, on the other hand, is much more thermally stable, thereby creating unique opportunities for designing and engineering a variety of high-voltage Ga<sub>2</sub>O<sub>3</sub> devices."

The Ga<sub>2</sub>O<sub>3</sub> base material used for fabricating the vertical MOSFET was produced by a crystal growth technique called halide vapor phase epitaxy (HVPE). Pioneered by Profs. Yoshinao Kumagai and Hisashi Murakami at TUAT, HVPE is capable of growing single-crystal Ga<sub>2</sub>O<sub>3</sub> films at high speeds and with low impurity levels. Three [ion implantation](#) steps were performed to form the n-type contacts, n-type channel, and p-type current blocking layers (CBLs) in the MOSFET. The device showed decent electrical properties including an on-current density of 0.42 kA/cm<sup>2</sup>, a specific on-resistance of 31.5 mΩ·cm<sup>2</sup>, and a high drain current on/off ratio larger than eight orders of magnitude. Further improvements in its performance can be readily achieved with improved gate dielectric quality and optimized doping schemes.

According to Higashiwaki and Wong, "Vertical power devices are the strongest contenders to combine currents over 100 A with voltages over 1 kV—the requirements for many medium- and high-power industrial and automotive electric [power](#) systems." The technological impact of Ga<sub>2</sub>O<sub>3</sub> will be substantially bolstered by the availability of melt-grown native substrates—one of the key enablers of the silicon industry that

dominates the global semiconductor market with an annual revenue of several hundred billion U.S. dollars. "The commercialization of vertical SiC and gallium nitride (GaN) [power devices](#) has, to a certain extent, been hindered by the high cost of substrates. For Ga<sub>2</sub>O<sub>3</sub>, the high quality and large size of native substrates offer this rapidly emerging technology a unique and significant cost advantage over the incumbent wide-bandgap SiC and GaN technologies," the researchers explained.

**More information:** Man Hoi Wong et al, Current Aperture Vertical  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> MOSFETs Fabricated by N- and Si-Ion Implantation Doping, *IEEE Electron Device Letters* (2018). [DOI: 10.1109/LED.2018.2884542](https://doi.org/10.1109/LED.2018.2884542)

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