Gallium oxide prospects for high-voltage and high-power electronics

Mike Cooke **reports on research plotting and exploring potential routes to commercial application.**

One always feels a flutter of excitement when one discovers that a material that one was barely aware of is being seriously considered for incorporation into the electronic constellation of useful semiconductors. Gallium oxide is one of the more recent contenders.

Gallium oxide has many properties that might be deployed in high-power electronic and radio-frequency amplifier applications: these include a wide bandgap of 4.5–4.9eV, implying a high critical electric field of up to 8MV/cm, and a reasonable electron mobility of the order 200cm^2/V-s. Ga_2O_3 breakdown voltages up to 3kV have been reported. Such devices could also be designed to operate under harsh and high-temperature conditions.

A further attraction of Ga_2O_3 is the commercial availability of native substrates of the material at relatively low cost. This is based on the ability to use growth from molten gallium oxide to produce crystal material in the stable beta polytype. It is crystal growth from silicon melt that enables low cost, high-quality substrates for mainstream electronics.

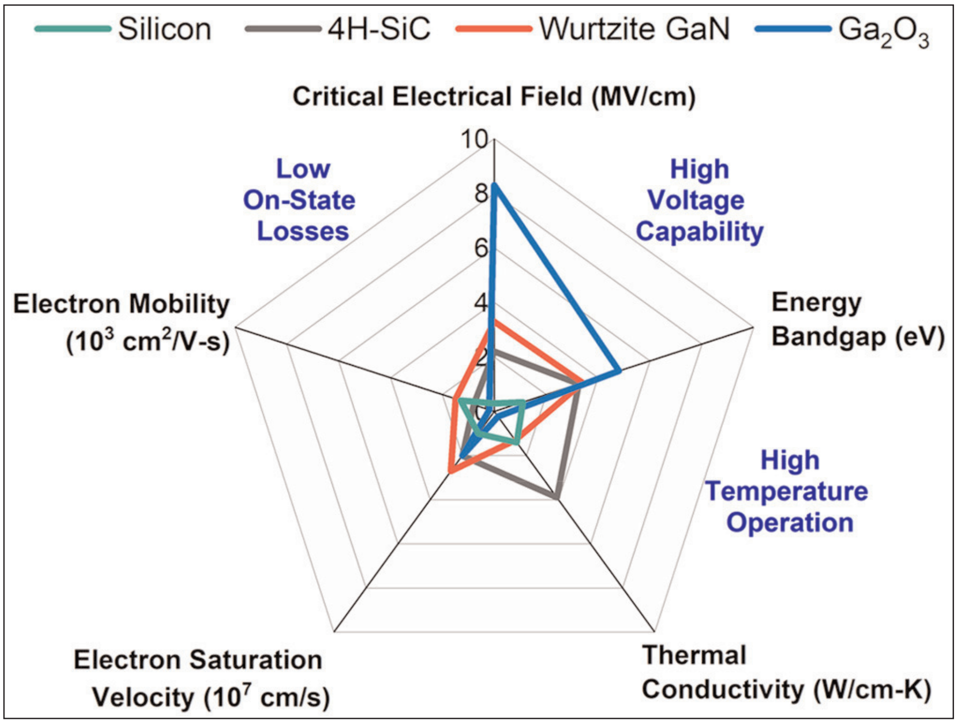

Figure 1. Pentagon diagram showing critical material properties important to power semiconductor devices. Larger pentagons are preferred. Data from G. Liu et al, Appl. Phys. Rev., vol2, p021307, 2015; G. R. Chandra Mouli et al, IEEE Trans. Power Electron., vol50, p97–103, 2018; B. J. Baliga, Semicond. Sci. Technol., vol28, p074011 2013.

University of Florida and the Naval Research Laboratory in the USA and Korea University have made a comprehensive review of the present and potential future status of gallium oxide (Ga_2O_3) electronics development [S. J. Pearton et al, J. Appl. Phys., vol124, p220901, 2018]. The paper covers 19 pages, with about 4 pages of references.

Despite Ga_2O_3's potential benefits (see Figure 1), the authors of the review see a number of hurdles to overcome. In the end, it is likely that Ga_2O_3 electronic devices will provide complementary capabilities to existing silicon (Si), silicon carbide (SiC) and gallium nitride (GaN) technologies with bandgaps 1.1eV, ~3.3eV and ~3.4eV, respectively. The review team sees Ga_2O_3 as possibly contributing in the low-frequency high-voltage arena such as AC-to-DC conversion.

The team highlights "power conditioning systems, including pulsed power for avionics and electric ships, solid-state drivers for heavy electric motors, and advanced power management and control electronics" as potential applications (Figure 2).

Hurdles range from realizing usable, reliable components up to their insertion into sustainable market infrastructures. A big immediate drawback of Ga_2O_3, particularly in high-power-density applications, is a low thermal conductivity (10–30W/m-K versus SiC's 330W/m-K, GaN's 130W/m-K, and silicon's 130W/m-K). Thermal management strategies might include transfer of device layers to another, more heat-conducting substrate, substrate thinning, heat sinks, top-side heat extraction, or active cooling with fans or liquid flow.

While Ga_2O_3 can be doped for n-type (electron) mobility in a controllable manner, another obstacle is the lack of a complementary p-type doping mechanism. This is likely a fundamental problem, according to theoretical analyses.

The reviewers report: "Self-trapping of holes in bulk Ga_2O_3, which decreases effective p-type conductivity owing to the resultant low mobility, is expected from the first-principles calculation of the Ga_2O_3 band structure. Theory indicates that all the acceptor dopants result in deep acceptor levels, which were not able to produce p-type conductivity." Only at high temperature has there been any report of p-type conductivity, likely related to native Ga-vacancy defects.

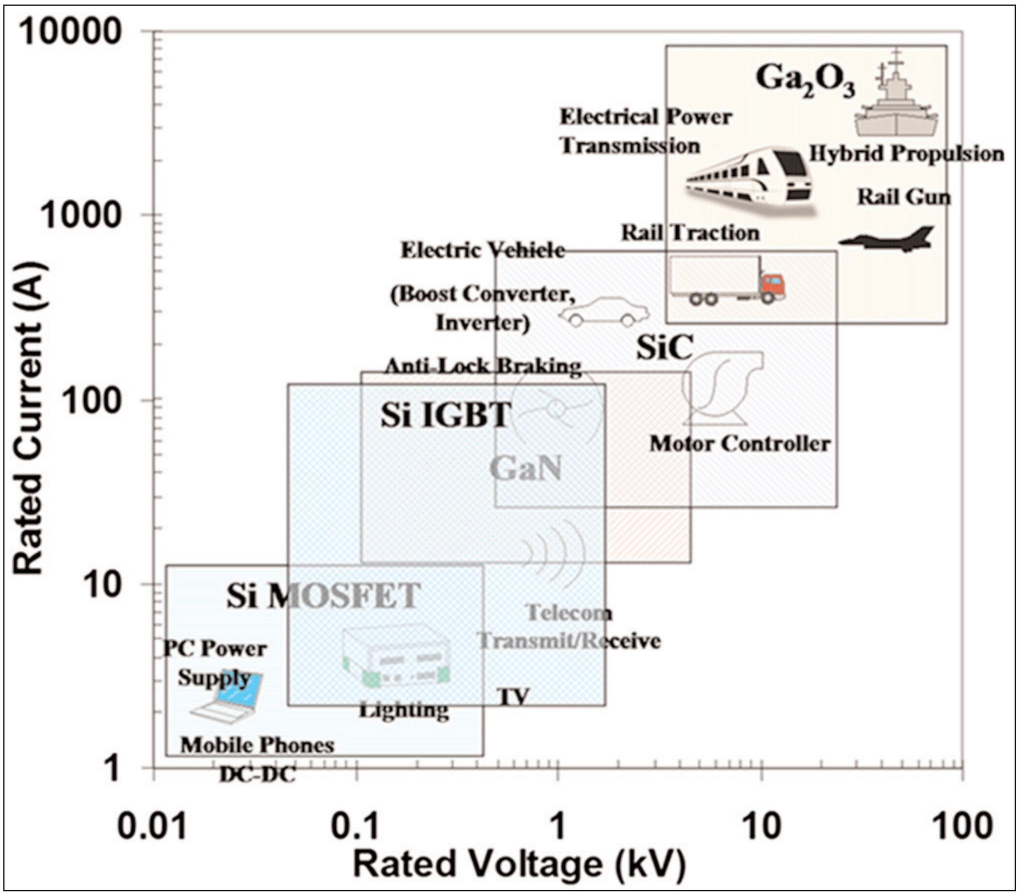

Figure 2. Applications for Si, SiC, GaN and Ga_2O_3 power electronics in terms of current and voltage requirements.

The reviewers suggest that combining n-Ga_2O_3 with other semiconductor materials with p-type conductivity might be possible. Copper iodide, copper oxide and nickel oxide may be in contention for this role.

The team reports that the present market capacity is around $15–22bn for discrete power devices. Making an analogy with the development of over 35 years from conception to commercialization of SiC devices, they ask who will bear the costs for Ga_2O_3's progress to the same state?

The reviewers comment: "A key requirement is continued interest from military electronics development agencies. The history of the power electronics device field has shown that new technologies appear roughly every 10–12 years, with a cycle of performance evolution and optimization. The older technologies, however, survive long into the marketplace, for various reasons. Ga_2O_3 may supplement SiC and GaN but is not expected to replace them."

The review adds: "Without an established revenue stream to support R&D over such a long time span, the clear driver has to be high-payoff military applications so that the necessary funding is there for long enough to truly develop this into a mature, manufacturable technology. It has never been the case with compound semiconductor power electronics that commercial applications have initially driven and sustained the development."

Of course, these are views coming partly from the US Naval Research Laboratory. Further, the University of Florida team receives funding from the US Defense Threat Reduction Agency. However, it is undeniable that most of the early and continuing support of SiC and GaN power electronics development in the USA can be traced back to military research funding.

In Japan, where there has been some reluctance since World War II to be seen to engage directly in weapons markets, development of power technologies has been more focused on things like rail transport, electric motor vehicles, DC–AC conversion for renewable energy, power transmission (including high-voltage DC), control for electric motors in domestic appliances, and power supplies for consumer electronics. Who knows? If recent calls for a 'Green New Deal' in the USA begin to be taken seriously, maybe these drivers may gain more traction there too.

The review sees the need for improvement in Ga_2O_3 development in seven areas: epitaxial growth, Ohmic contacts, thermally stable Schottky contacts, enhancement-mode (i.e. normally-off) transistor operation, reduction of dynamic on-resistance, process integration, and thermal management through passive and active cooling.

The reviewers suggest that a breakthrough for Ga_2O_3 over the status quo is needed "in order to give it at

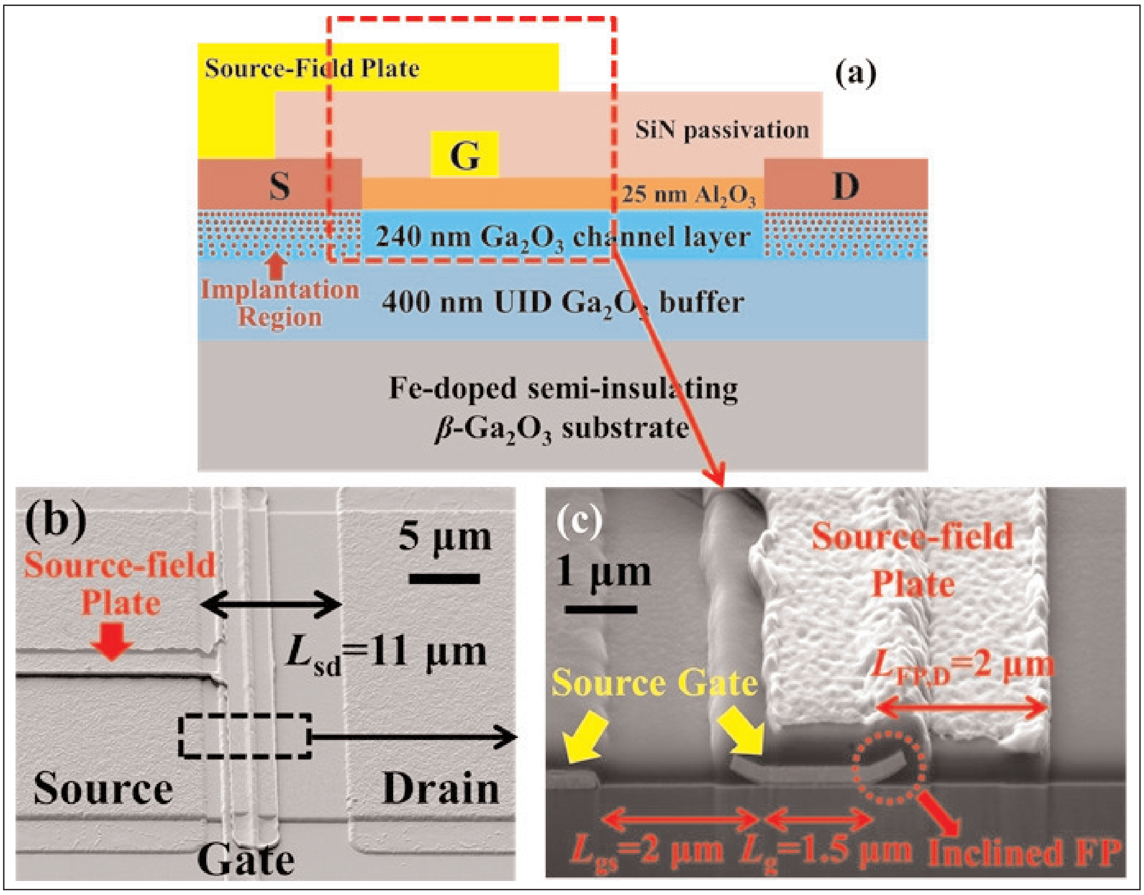

Figure 3. (a) Schematic cross section of source-field-plated β-Ga_2O_3 MOSFET; and scanning electron microscope images of (b) surface and (c) cross section of device.

least one application which will motivate R&D in the years to come."

Metal-oxide-semiconductor field-effect transistors

Some recent research may demonstrate the present stage of Ga_2O_3 development. Hebei Semiconductor Research Institute and the Institute of Microelectronics in China have claimed record power figure of merit performance for β-Ga_2O_3 metal-oxide-semiconductor field-effect transistors (MOSFETs) [Yuanjie Lv et al, IEEE Electron Device Letters, vol40, p83, 2019].

The 50.4MW/cm^2 figure of merit ($V_{br}^2/R_{on,sp}$) achieved represents a high breakdown voltage combined with a low specific on-resistance. High performance of one or the other factor usually entails a reduced characteristic on the other side of the trade-off.

The high figure of merit was achieved by using a source-connected field plate to reduce peak electric fields, increasing breakdown performance. Ion implants in the source and drain regions of the devices reduced contact resistance to 1.0Ω-mm.

In theory with a critical electric breakdown field of order 8MV/cm it should be possible to reach a power figure of merit in the range 34,000MW/cm^2, so there is clearly much scope for development and optimization work. Before the Hebei/Institute of Microelectronics work the highest reported power figure of merit was 10MW/cm^2.

The substrate for metal-organic chemical vapor deposition (MOCVD) was iron-doped semi-insulating (010) β-Ga_2O_3. The precursors were trimethyl-gallium and oxygen delivered at 8Torr pressure. The substrate temperature was 750ºC. Silicon doping for the 240nm n-type channel layer (Figure 3) was provided by silane (SiH_4) flow. Van der Pauw measurements gave an electron density of 1.95x10^{13}/cm^2 with 90cm^2/V-s mobility, and a sheet resistance ~3.6kΩ/square.

Inductively coupled plasma etch was used to create a 350nm-high mesa for device fabrication. Source and drain regions were created with multiple implantations of silicon ions to a depth of ~210nm. Simulations predicted that the surface silicon concentration would be around 10^{20}/cm^3. After annealing the doping implants, Ohmic source/drain (S/D) contacts were formed with deposition of titanium and gold. The gate (G) stack consisted of 25nm of 250ºC atomic layer deposition (ALD) aluminium oxide (Al_2O_3) and nickel/gold metal electrode. The aluminium oxide was annealed before electrode deposition.

Surface passivation was provided by 400nm plasma-enhanced chemical vapor deposition (PECVD) silicon nitride (SiN). After reactive-ion etch to expose the source and drain metal, the nickel/gold source-connected field plate that extended 2μm toward the drain was formed.

The 1.5μm-long gate was 40μm wide. The gate–source distance was 2μm. Devices with gate–drain spacings of 7.5μm and 14.5μm were fabricated. The respective source–drain distances were 11μm and 18μm.

With the gate at 5V, the saturation drain current was 267mA/mm for the 11μm source-drain device and 222mA/mm for the 18μm version. Under the same gate potential, the low-drain-bias on-resistance was 41.6Ω-mm in the 11μm source–drain transistor.

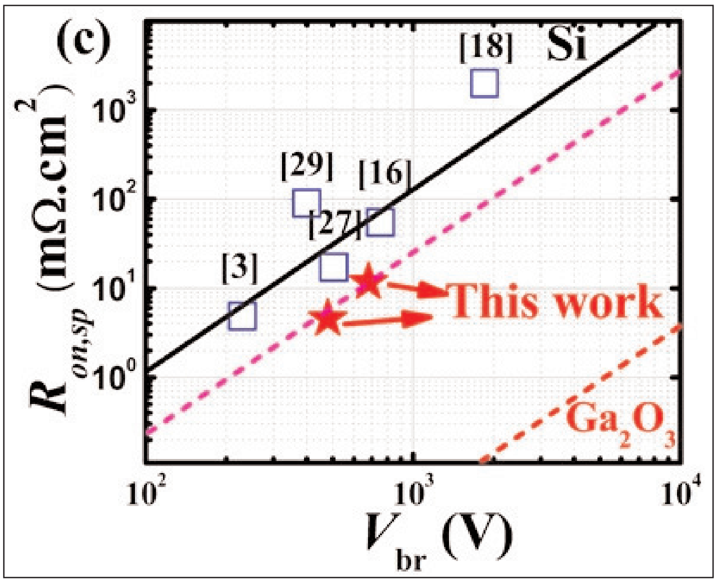

Figure 4. Three-terminal off-state breakdown characteristics of β-Ga_2O_3 MOSFET with and without source-field plate for (a) 11µm and (b) 18µm source–drain distance devices. (c) Plot of $R_{on,sp}$ versus V_{br} for Hebei/Institute of Microelectronics devices ("this work") and other reported lateral Ga_2O_3 MOSFETs.

With 20V drain bias, the maximum transconductance for the 11µm MOSFET was 10.5mS/mm. The 0.1mA/mm threshold gate voltage was at 50.5V. Gate leakage was around 7.1x10^{-7}A/mm. The researchers see this value as being "comparatively large", adding that the culprit may be Al_2O_3/Ga_2O_3 interface traps. They suggest that these traps could be reduced with a better optimized surface-state treatment. Further evidence of interface traps was given by ~0.8V hysteresis in the response under forward and reverse sweeps of gate voltage. The on/off current ratio was of the order 10^6.

Destructive breakdown performance in air was carried out with the gate at –55V (see Figure 4). Without source field plates, the breakdown voltages were 310V and 260V for the 18µm and 11µm MOSFETs, respectively. These values were greater than the 218V value expected from a one-sided abrupt-junction model. The researchers suggest the better-than-theory result as being due to non-uniformity of channel doping and depletion from interface states. Adding source field plates increased the breakdown to 480V in the 11µm device and 680V in the 18µm MOSFET.

Multiplying the on-resistance by the source–drain distance to give $R_{on,sp}$, the researchers found values of 4.58mΩ-cm^2 and 11.7mΩ-cm^2 for the 11µm and 18µm devices, respectively. "Our fabricated devices in this work show much lower $R_{on,sp}$ compared with other β-Ga_2O_3 MOSFETs and also with the theoretical performance of Si-based power devices," the team comments.

Although the saturation drain current is still lower than in reported nanomembrane Ga_2O_3 devices, the researchers claim that their source-field-plated MOSFET shows a record maximum drain current and power

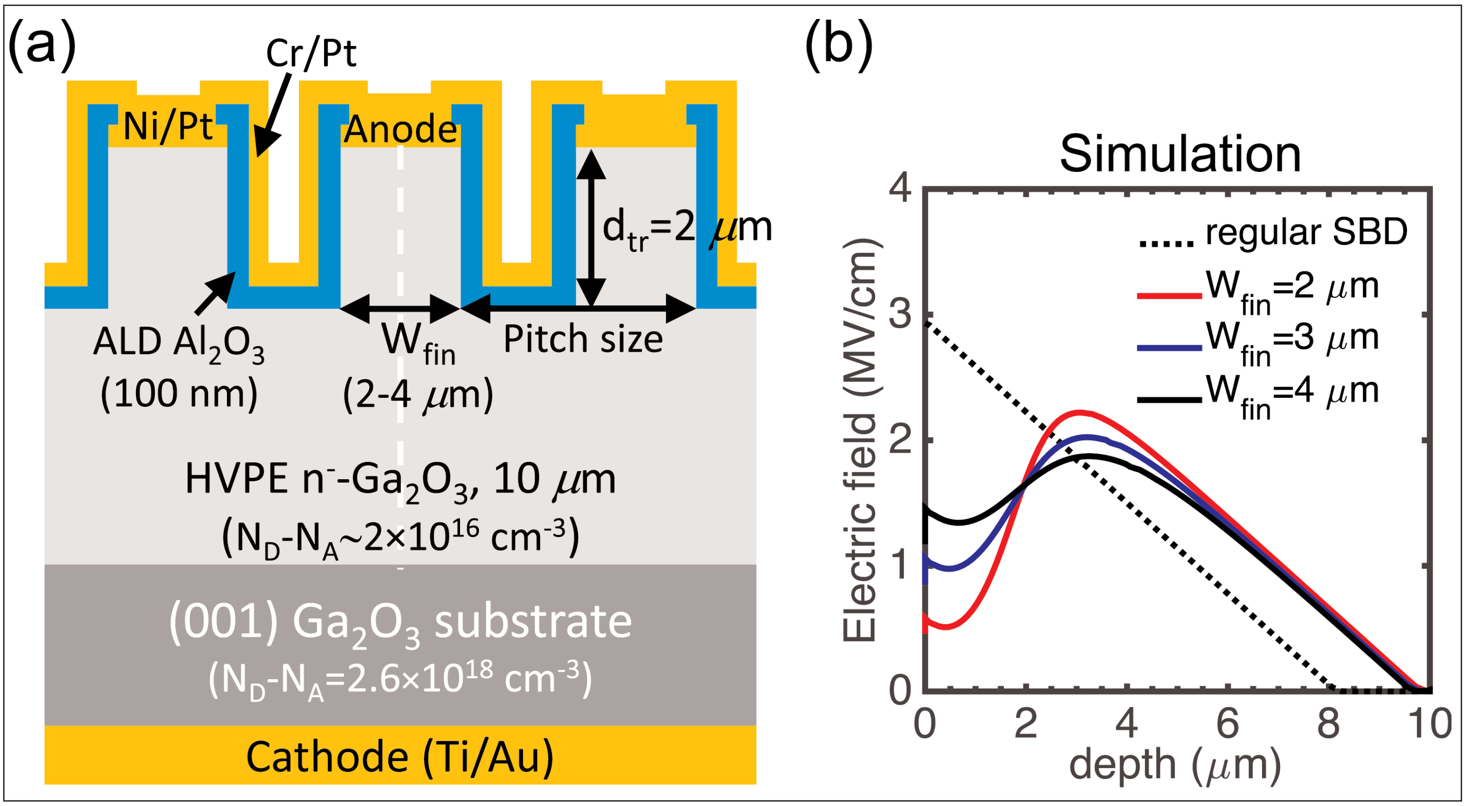

Figure 5. (a) Schematic cross section of β-Ga_2O_3 trench Schottky barrier diodes. (b) Simulated electric field profile at reverse bias of 1200V along dashed vertical cut line at center of fin in (a).

figure of merit among devices fabricated on homoepitaxial β-Ga_2O_3. The researchers suggest that increasing the channel layer thickness in conjunction with gate recessing could lead to lower on-resistance and associated improvement in the power figure of merit.

Schottky barrier diodes

Cornell University in the USA and Novel Crystal Technology Inc in Japan claim the lowest leakage current yet reported for β-Ga_2O_3 Schottky barrier diodes (SBDs), another key device type for power applications [Wenshen Li et al, Appl. Phys. Lett., vol113, p202101, 2018]. The low leakage current density of less than 1μA/cm^2 was combined with a relatively high breakdown voltage of 1232V. The devices used a trench structure to create fins with a metal-insulator-semiconductor (MIS) stack on the sidewalls to reduce surface field effects, suppressing leakage under reverse bias.

The researchers used halide vapor phase epitaxy (HVPE) to create the device layers of the SBD (Figure 5). The fin area ratio was ~60% of the total fin+trench pitch. In simulations, a narrower fin was expected to result in lower electric fields near the top surface. The 10μm drift layer had a uniform net doping of 2x10^{16}/cm^3 that made a significant contribution to the improved performance.

Fabrication began with formation of the back cathode: first reactive ion etch (RIE) was performed to improve the ohmic nature of the contact, followed by evaporation and annealing of the titanium/gold (Ti/Au) contact metal.

The front-side of the epitaxial wafer was patterned, using nickel/platinum (Ni/Pt) as both the hard mask for trench RIE etching and the Schottky contact of the final device. The trenches were etched to a depth of 2μm with the fin channels oriented along the [010] direction. The fin sidewalls are described as being 'near vertical'.

The trenches were lined with atomic layer deposition Al_2O_3. Dry etch through the Al_2O_3 at the tops of the fins exposed the nickel/platinum Schottky contacts. The device was completed with sputtering chromium/platinum (Cr/Pt) on the trench sidewalls.

The researchers also produced Ni/Pt Schottky diodes without the fin structuring, for comparison. The current densities were calculated based on device, not fin, area. The ideality factor of both devices was 1.08. The trench SBDs had a Schottky barrier height of 1.40eV, compared with 1.35eV for the regular device. The increased effective barrier height was attributed to the adjacent metal-oxide-semiconductor junction on the sidewalls of the trenches.

Pulsed measurements were used to avoid self-heating effects. The restricted area of the current flow through the fins resulted in reduced current density compared with the regular device. The specific differential on-resistance of the trench SBD was 15mΩ-cm^2, compared with 6.6mΩ-cm^2 for the regular device.

The trench SBD also suffered from trapping effects in voltage scans not seen in the regular device. The researchers infer that "the trapping must be located at the trench MIS structure". The trapped charge increases

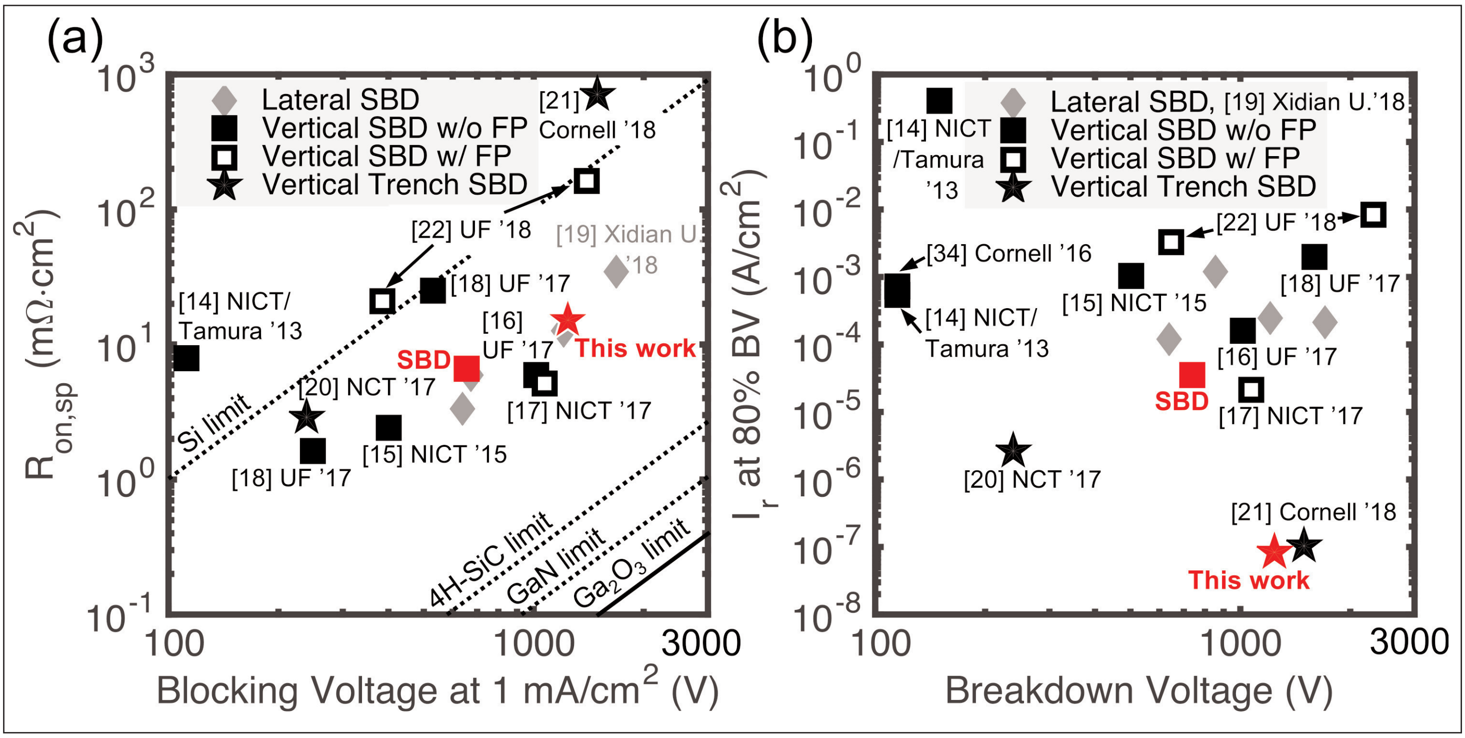

Figure 6. Benchmark plots of state-of-the-art β-Ga_2O_3 SBDs. (a) Differential $R_{on,sp}$, excluding turn-on voltage, versus blocking voltage specified at reverse leakage current density of 1mA/cm^2. (b) Leakage current density at 80% of reported breakdown versus reported hard-breakdown voltage.

the depletion in the fin, constricting current flow. The researchers estimate the extra depletion thickness to be of the order 170nm at zero bias, assuming a trapped electron sheet density of ~8x10^{11}/cm^2.

The team suggests that the trapping could be reduced with a post-deposition anneal (PDA) of the Al_2O_3 dielectric and with improved surface treatment on the Ga_2O_3 surface after the dry etch.

The place where the trench SBD performed better was under reverse bias with breakdown at 1232V, compared with 734V for the regular device. The fins of the best trench SBD were 2μm wide. The leakage current before breakdown was less than 1μA/cm^2, and when the reverse bias was below 1000V the leakage was less than 0.1μA/cm^2, corresponding to power dissipation less than 0.1mW/cm^2. Wider finned devices had higher leakage and lower breakdown voltages.

The team compared the performance of its devices with other reports (Figure 6). The specific differential on-resistance compared with the blocking voltage at 1mA/cm^2 current density showed 'notable' improvement over previously reported trench devices, while also giving comparable performance to the best reported β-Ga_2O_3 SBDs. The team comments: "In comparison with our previous results, the on-resistance is much reduced due to a more uniform doping profile with a moderate level (~2x10^{16}/cm^3) and less carrier compensation."

Comparison was also made between the reverse leakage at 80% of breakdown and the breakdown voltage itself, showing lower leakage in the trench SBDs, compared with regular devices. The researchers claim the lowest leakage reported for the SBDs with 2μm-wide fins. The team's regular SBD showed similar performance to other reports. The lower leakage is therefore likely attributable to the trench structure itself.

The team expects progress toward the theoretical material limit for Ga_2O_3 through reduced trapping in the MIS structure and better field management. ■

The author Mike Cooke is a freelance technology journalist who has worked in the semiconductor and advanced technology sectors since 1997.