Pushing on the vertical limits of gallium nitride power electronics

Researchers at the universities of Notre Dame and Cornell have been developing vertical rather than lateral structures for power applications. Mike Cooke reports.

Applications for III-nitrides such as gallium nitride (GaN) have recently extended beyond the quarter-century-old market for short-wavelength light-emitting devices into high-frequency and switching power electronics. The electronic uses of GaN depend on a high critical field for breakdown, associated with the wide bandgap of the material, while maintaining a relatively high mobility.

Up to now, work on the commercialization of GaN power switching and conversion devices has mostly used lateral current flow in high-electron-mobility transistors and other unipolar transistors on sapphire, silicon carbide (SiC) or silicon. However, vertical structures could avoid problems such as field and current crowding that lead to premature breakdown. Bulk and free-standing single-crystal GaN enables such vertical devices and much progress in this direction has been made in the past year.

The University of Notre Dame and Cornell University in the USA have been at the center of work using molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) on bulk gallium nitride (GaN) substrates to create vertical p–n diode structures. Cornell and Notre Dame, sometimes in collaboration with others, have published a number of papers and conference presentations in the past couple of months.

The researchers hope their work will lead to superior three-terminal GaN power switches using vertical p–n junctions, reaching towards the theoretical limits of GaN's critical field. Present lateral devices that operate in a unipolar manner (that is, not based on p–n junctions) tend to break down through gate leakage and allied effects, and not because of the intrinsic avalanche mechanism that gives the high critical field based on GaN's wide bandgap.

Pushing toward critical field

In [Meng Qi et al, Appl. Phys. Lett., vol107, p232101, 2015], Notre Dame and Cornell researchers report: "GaN vertical p–n junctions with off-state leakage current as low as $3nA/cm^2$, breakdown field E_{br}~3.1MV/cm, and R_{on}~$0.23m\Omega$-cm^2 are achieved in epitaxial diodes. These breakdown and leakage characteristics represent the highest performance metrics in GaN p–n junction diodes grown by MBE."

The researchers used bulk GaN substrates to reduce threading dislocation densities (TDDs). Such defects cause premature breakdown of electron devices. The estimated peak electric field in some of their devices of 3.1MV/cm was derived on the basis of simulations. They comment: "This electric field of 3.1MV/cm is close to the estimated critical field of 3.5–3.8MV/cm for GaN. It is among the highest experimental results reported."

MBE has a number of advantages over MOCVD such as a high degree of control of alloy compositions, high-quality aluminium nitride (AlN) layers and heterostructures, and efficient magnesium (Mg) acceptor doping for buried p-type layers that do not need activation annealing.

A disadvantage of MBE tends to be its slower growth rate compared with MOCVD or hydride vapor phase epitaxy (HVPE). Higher growth rates can be achieved with plasma rather than ammonia MBE, allowing thicker drift layers to be achieved. Thicker layers should lead to higher breakdown voltages (BVs) by reducing the peak electric field for a given potential difference across a structure.

The researchers also observed strong electroluminescence (EL) from their devices, indicating the high quality of the material. They add: "Since we can design for light to carry away a significant fraction of energy out of the diode, it can prove to be a very attractive way for device cooling in power electronics: a technique that has not been possible in indirect-bandgap power semiconductors such as Si and SiC diodes and transistors before."

Si and SiC are semiconductors with an indirect bandgap where recombination in p–n diodes produces heat rather than photons. Schottky-diode-based metal–semiconductor junctions also tend to produce heat rather than light — carrier transport is through thermionic emission of electrons from the semiconductor into the metal. Heat generation in Schottky devices occurs in the metal where electrons dump their energy.

The p–n structures (Figure 1) were grown on GaN substrates with three different levels of threading dislocation density: 1–2x10^7/cm^3, 2-5x10^5/cm^3 and 5x10^4/cm^3. The MBE growth was carried out on the metal-polar (Ga) face of the substrate. An extensive surface preparation cleaning and outgasing procedure was carried out over several hours to remove con-

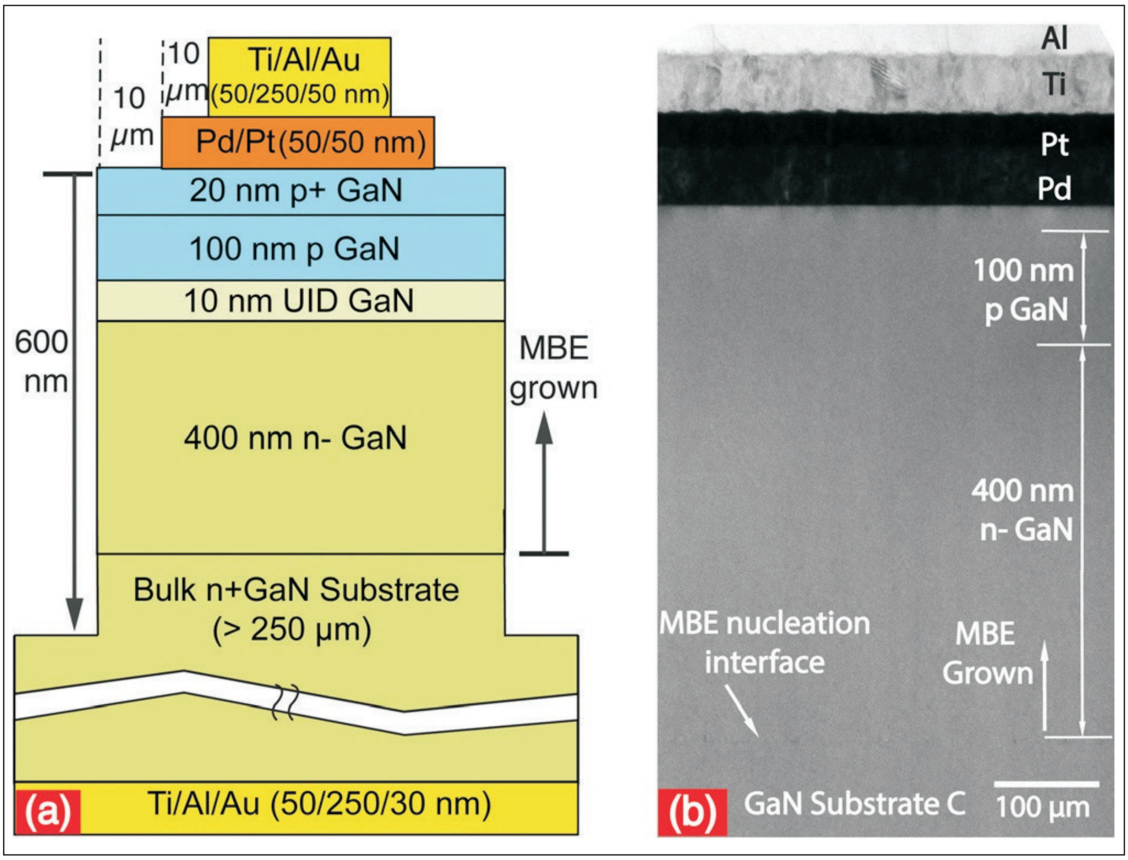

Figure 1. (a) Schematic structure and (b) cross-section TEM of fabricated vertical MBE-grown p-n diodes on low-dislocation density bulk GaN crystal substrate C (TDD~5x10^4/cm^3).

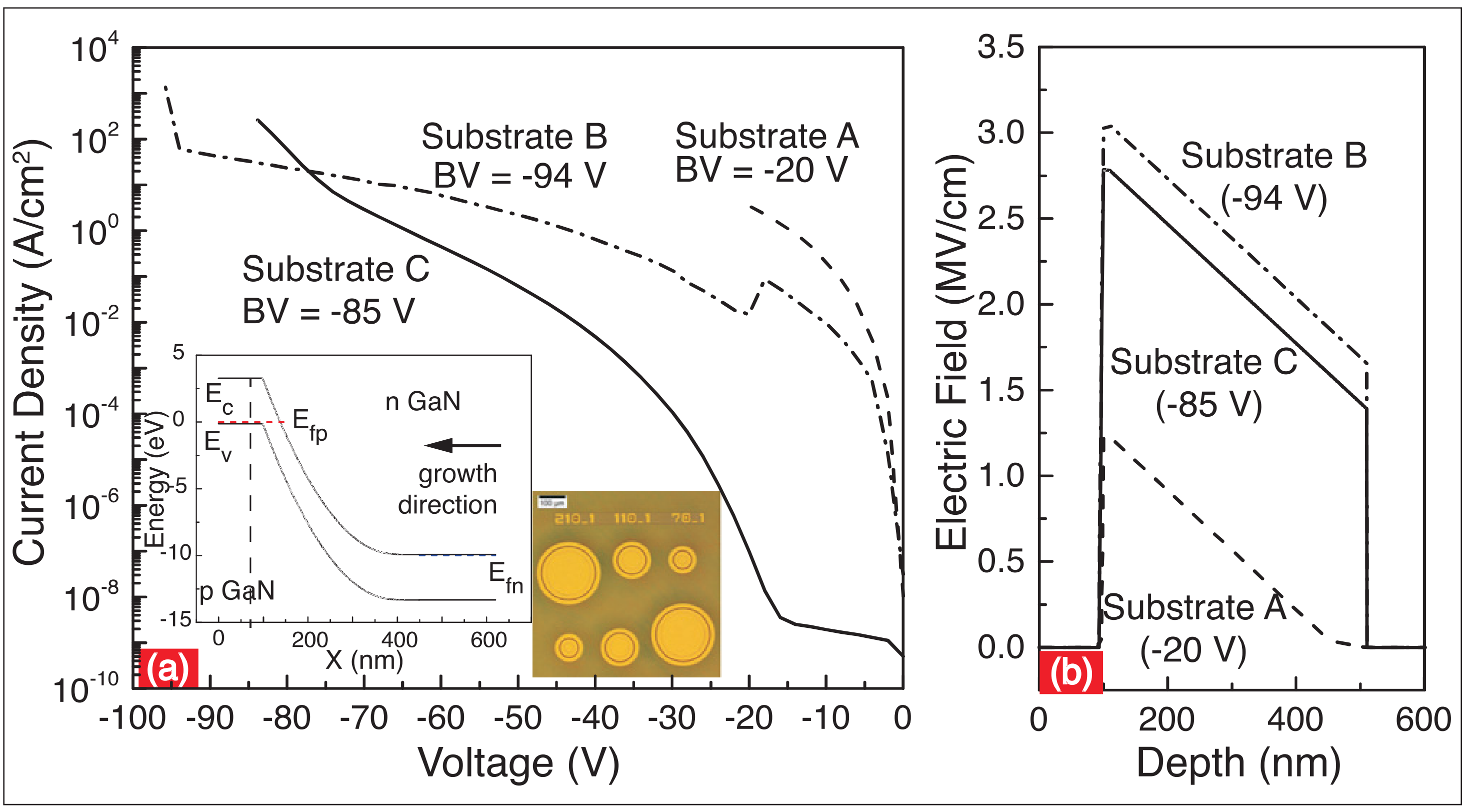

Figure 2. (a) Semilog plot of I–V characteristics with reverse bias voltages until breakdown for three vertical GaN p–n junctions on different GaN substrates. Inset figures show energy band diagram with 10V bias, as well as image of fabricated diodes under optical microscope. (b) Electric field profiles along vertical direction of three p-n junctions on different substrates at corresponding breakdown voltages.

taminants. The MBE began with a pure Ga flux soak to give a Ga-rich surface.

The 400nm GaN buffer layer was grown using plasma-assisted MBE at 720ºC. The nitrogen plasma was created using a 200W RF power source. The Mg and Al cells of the MBE equipment were kept heated at suitable standby temperatures to avoid oxygen out-gasing into the reaction chamber.

Oxygen acts as a donor dopant in GaN. Breakdown voltages in vertical GaN devices are very sensitive to doping density, and the researchers wanted careful control of the unintentional doping (UID) level. In particular, they wanted a high acceptor over donor ratio so that the bulk of the depletion/drift region was on the n-side. The team achieved an acceptor/donor density ratio of about 100.

The 10nm UID GaN layer was grown with the temperature ramping down from 720ºC to 600ºC. At the same time, the Mg cell temperature was increased from 200ºC to 400ºC to prepare for the growth of the p-GaN layers.

Excess Ga drops on the surface of the epitaxial material were removed using hydrochloric acid. Diode mesas were formed with reactive ion etching to a depth of 600nm. The n-electrode metals were applied to the back-side of the wafer. After deposition of the p-electrode metals, the devices were annealed at 400ºC for 10 minutes. The fabrication was completed with the deposition of titanium/aluminium/gold (Ti/Al/Au) metal pads on the p-electrodes.

Electroluminescence for substrate B (TDD 2–5x10^5/cm^3) was found with wavelength peaks around 3.2eV and 2.2eV with 330A/cm^2 injection, +5V bias. The 3.2eV radiation was associated with 3.4eV electron–hole recombination in the depletion region and photon absorption and re-emission from electrons dropping to the Mg acceptor levels ~0.2eV above the valence band in the p-GaN. The 2.2eV radiation was attributed to deep-level transitions.

Diodes on substrate C with the lowest TDD level of under 10^4/cm^3 showed extremely low current densities of less 1nA/cm^2 in the +2V to –5V region (Figure 2). The on/off current ratio for +5V/–5V bias was 10^{13}. Diodes on the higher TDD substrates A and B had reverse current leakage of around 10^{-4}A/cm^2 density and on/off ratio of around 10^8. The highest breakdown voltage of 94V was for substrate B diodes. The low TDD substrate C diode had a slightly reduced breakdown at 85V reverse bias. Details of the mechanism for reverse bias breakdown are still under investigation.

Powering over rivals

Cornell and Notre Dame also claimed a record 'figure-of-merit' (FOM) combination of breakdown voltage and on-resistance (R_{on}) [Zongyang Hu et al, Appl. Phys. Lett., vol107, p243501, 2015]. At the same time, the current–voltage profiles and temperature-dependent modeling suggested a long Shockley–Read–Hall (SRH) lifetime.

The researchers comment: "The long SRH lifetime and low R_{on} in GaN demonstrated in this work indicate possibilities to design GaN p–n diodes utilizing the

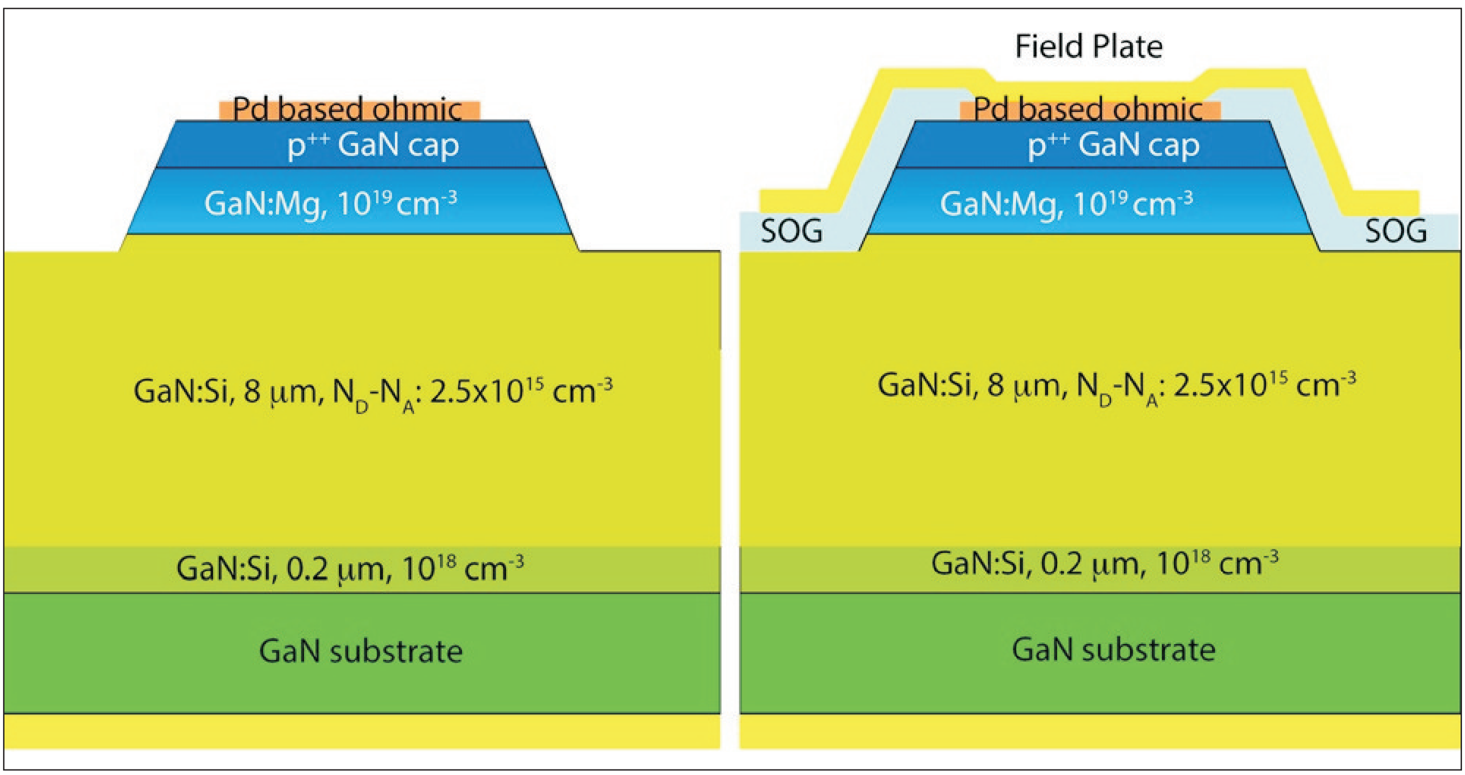

Figure 3. Schematic cross-sections of GaN p–n junction diodes: (left) without passivation/field plates and (right) with field plates.

bipolar benefits of the material. Performance far beyond the unipolar limit predicted by FOM might be achievable in GaN bipolar power devices."

The epitaxial structures were prepared using MOCVD on bulk GaN substrate with defect density ~10^6/cm^2. The upper p-type layers were 400nm of magnesium-doped GaN:Mg and a heavily-doped (p^{++}) cap. Hall-effect measurements determined the hole concentration in the p-type layers at $7\text{x}10^{16}$/cm^3. The hole mobility was 24cm^2/V-s.

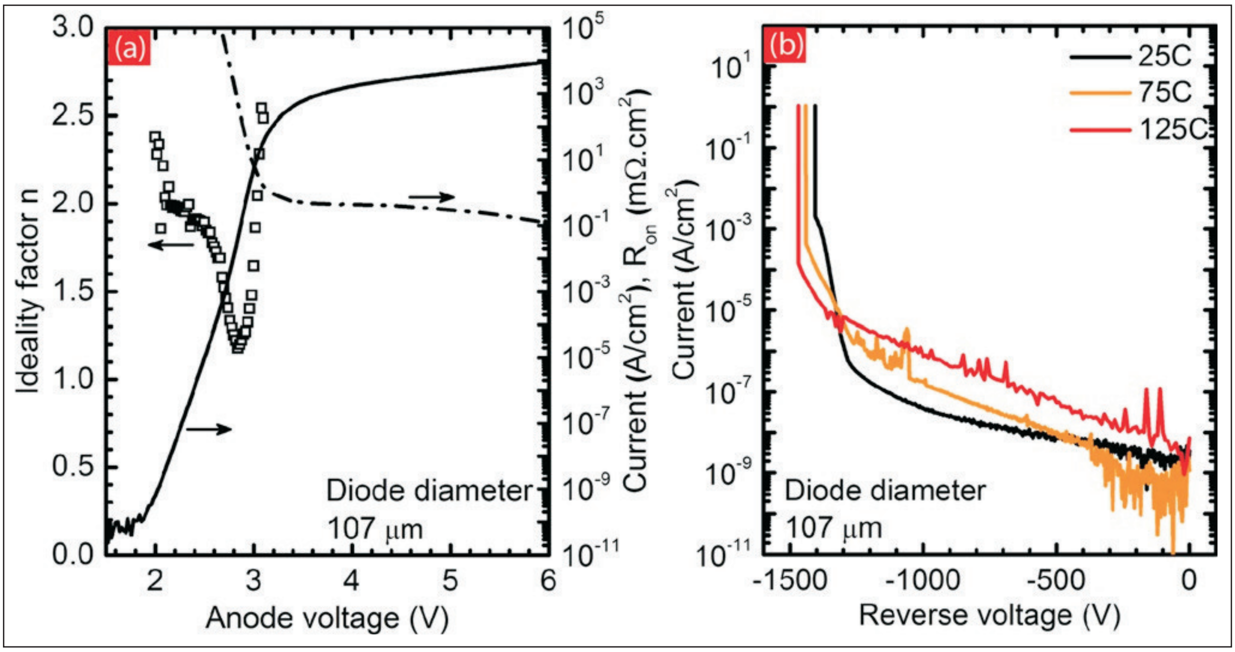

Figure 4. (a) Forward current-voltage characteristics at RT measured on GaN p–n diodes with mesa diameter of 107μm. (b) Temperature-dependent reverse current–voltage characteristics and breakdown voltages.

The diode fabrication (Figure 3) included a circular bevel mesa structure for edge termination to avoid surface leakage currents. Devices were also produced with spin-on-glass passivation and field plates to further improve edge-termination performance and increase reverse-bias breakdown voltages. Devices without passivation or field plates were used in capacitance–voltage analysis of the built-in junction potential and net carrier concentrations.

The forward current density for a 107μm-diameter bottom of the bevel mesa at 6V was "close" to 9.3kA/cm^2, based on a 117μm effective diameter to allow for current spreading (Figure 4). The differential on-resistance was around 0.12mΩ-cm^2.

"The on/off current ratio is about 14 orders of magnitude (limited by our measurement setup), thanks to minimized defects in GaN," the researchers comment. The ideality factor made a transition from around 2.0 at 2.0V to 1.1 at 2.8V. Ideality around 2 suggests domination of non-radiative SRH recombination through charge traps. Ideality factors around 1 are associated with diffusion currents and radiative electron–hole recombination. However, reported radiative recombination coefficients suggest that this effect would have been negligible in the voltage range studied. The SRH lifetime was estimated at around 12ns at room temperature. The recombination center concentration was calculated to be $3\text{x}10^{15}$/cm^3.

"Near-unity ideality factors in GaN observed over a temperature window have never been reported previously," the researchers add. "The near-unity ideality factor is enabled by two primary facts: (1) a small SRH recombination current inside the depletion region due to a long SRH recombination lifetime, i.e. low concentrations of recombination centers; (2) low parasitic resistances allow diffusion current (η = 1) to dominate over a wide bias window."

The reverse-bias breakdown occurred at 1406V at room temperature (300K). This increased to 1442V at 350K and 1470V at 400K.

"The positive coefficient of BV versus temperature is a signature of avalanche breakdown, which is desired for reliable device operation for high power applications," the researchers explain. "The higher leakage current at higher temperatures suggests that trap-assisted conduction is most likely the dominating leakage mechanism."

The team claims a record Baliga figure of merit for all GaN power p–n diodes, or for any semiconductor system ever reported, of ~16.5GW/cm^2 (square of breakdown voltage divided by differential on-resistance).

Avalanche

The team from Notre Dame and Cornell has also worked with researchers based in Japan on vertical diodes on bulk GaN, this time using MOCVD [Kazuki Nomoto et al, IEEE Electron Device Letters, published online 8 December 2015].

The researchers from Cornell, Notre Dame, Quantum Spread Ltd and Hosei University comment: "The textbook-like behavior in our GaN p–n power diodes, with avalanche capability demonstrated in this work, signifies that the quality of epitaxial GaN is now

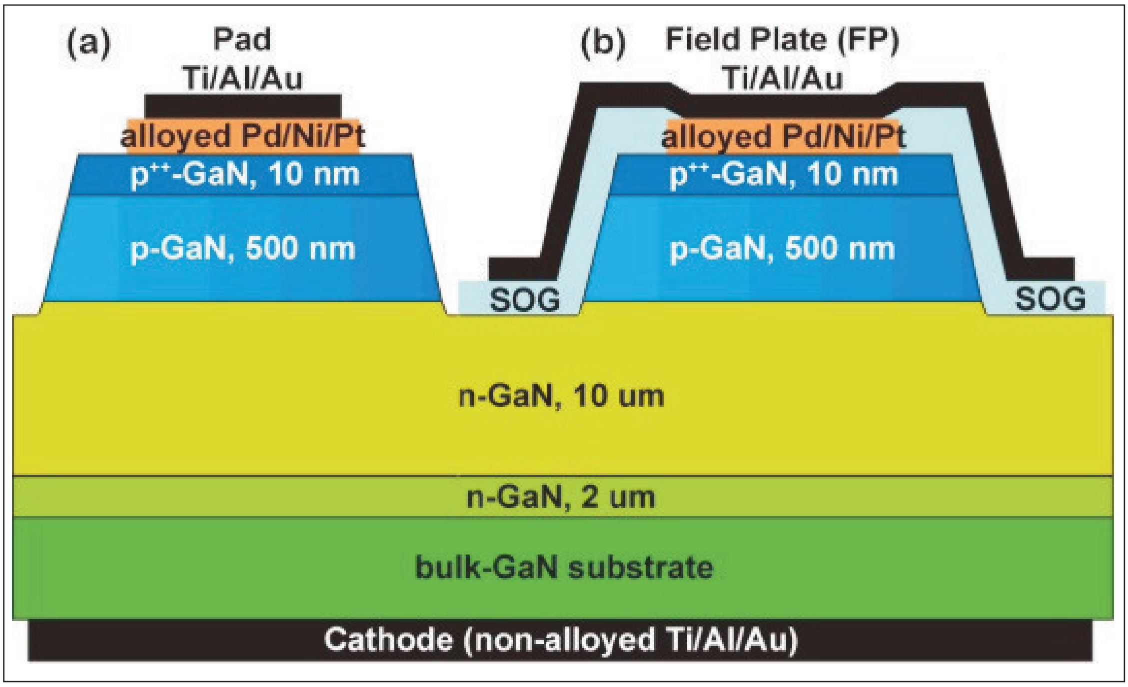

Figure 5. Schematic cross-sections of the GaN-on-GaN p–n junction diodes (a) without (w/o) field plate (FP) and (b) with field plate.

on par with that of SiC while the performance and yield of large-area power devices will most likely improve dramatically with further reduction of threading dislocations in bulk GaN substrates."

The work was in part supported by the US Advanced Research Projects Agency-Energy (ARPA-E) Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES) Program.

The vertical diode material was grown on bulk 2-inch-diameter 400μm-thick GaN using metal-organic vapor phase epitaxy (MOVPE, a form of MOCVD). The n-GaN buffer and drift layers had $2x10^{18}/cm^3$ and $1–2x10^{16}/cm^3$ silicon doping, respectively. The researchers took particular care to restrict carbon and oxygen impurities in the drift layer to $1.2x10^{16}/cm^3$ and $1.7x10^{16}/cm^3$, respectively. The p-GaN and p^{++}-GaN layers had respective magnesium concentrations of $1x10^{18}/cm^3$ and $2x10^{20}/cm^3$. The doping and impurity levels were determined from secondary-ion mass spectrometry on calibration wafers.

Cathodoluminescence indicated threading dislocation densities of $\sim 10^6/cm^2$ in the epitaxial layers, comparable to the level in the underlying bulk GaN. The researchers comment that this level is two orders of magnitude lower than for heteroepitaxial material on non-GaN substrates such as SiC.

After growth, the epitaxial material was annealed at 700ºC to activate the magnesium doping. The hole concentration in the p-GaN was $7.4x10^{16}/cm^3$ with $27cm^2/V$-s mobility, according to Hall measurements at 25ºC.

Diodes with and without a field plate (FP) were fabricated (Figure 5). The FP extended over the whole circular diode mesa. Spin-on-glass (SOG) insulation, 200nm thick, was used to reduce reverse leakage currents. The anode consisted of palladium/nickel/platinum (Pd/Ni/Pt), deposited before the SOG. The curing of the SOG at 425ºC for 30 minutes also affected the composition of the anode metals to give some alloying effect. The cathode on the substrate back side consisted of titanium/aluminium/gold (Ti/Al/Au). This metal composition was also used for the FPs.

The researchers say that they used the best of at least three devices to indicate the potential of GaN-on-GaN technology. Diode sizes were based on the bottom of the mesa diameter. The substrate was not thinned. Thinning would reduce series resistance effects.

The diode's ideality factor between 2V and 2.5V forward bias was ~2.0, indicative of SRH recombination. Above 2.5V, the ideality trends downwards to ~1.3 near 2.8V, indicating a decrease in recombination and an increase in diffusion current across the depletion region. The SRH lifetime was estimated to be 12ns. The turn-on voltage was around 3.0V, close to what would be expected from the 3.4eV GaN bandgap. The current below 2V forward bias was too low to be measured. The current swing was more than 14 orders of magnitude.

The differential specific on-resistance (R_{on}) of a 107μm-diameter diode was ~0.4mΩ-cm^2 at ~3kA/cm^2, or 0.55mΩ-cm^2, including a factor for current spreading that effectively increases the diameter to 127μm. In fact, these values were lower than a theoretical estimate of 0.64mΩ-cm^2. "The difference may be attributed to the underestimated electron mobility or conduction modulation in p–n diodes, demanding further studies," the researchers comment.

The breakdown for 107μm-diameter diodes under reverse bias was around 830V without FPs and around 1706V with FPs. The diode without FP failed near the mesa edge. An increase in leakage current above 500V with FPs was attributed, most likely, to a leakage path introduced by the field-plate fabrication process. The Baliga figure of merit with FP was 5.3GW/cm^2 ($(1706V)^2$/0.55mΩ-cm^2).

The BV was nearly independent of diode diameter for devices without FP. However, with FPs the BV decreases with increasing diameter (~1.2kV with 707μm diameter). At the same time, the R_{on} value increased with diameter.

Based on the drift region thickness of 10μm, the researchers estimate a critical field of more than 3.5MV/cm. This is based on an ideal planar model and assuming 75% of the resultant maximum breakdown to allow for the non-ideal nature of the diode. The estimated critical field is among the best reported, according to the researchers.

The breakdown voltage increased with temperature to 1778V at 125ºC — a signature of avalanche breakdown, according to the researchers. The temperature of the 1706V BV was 25ºC.

A group led by Cornell and Notre Dame also presented record-breaking claim for a Baliga FOM of 12.8GW/cm^2 for MOVPE p–n diodes at the December 2015 International Electron Devices Meeting (IEDM) in Washington DC [session 9.7]. The respective values for breakdown voltage and differential on-resistance were 3.48kV and 0.95mΩ·cm^2. The other contributors to the work were US Naval Research Laboratory, Signatone Corp, Quantum Spread Ltd and Hosei University. Devices with drift layer thickness from 20μm to 32μm resulted in BV values in the range from 2.3kV to 3.5kV (Figure 6).

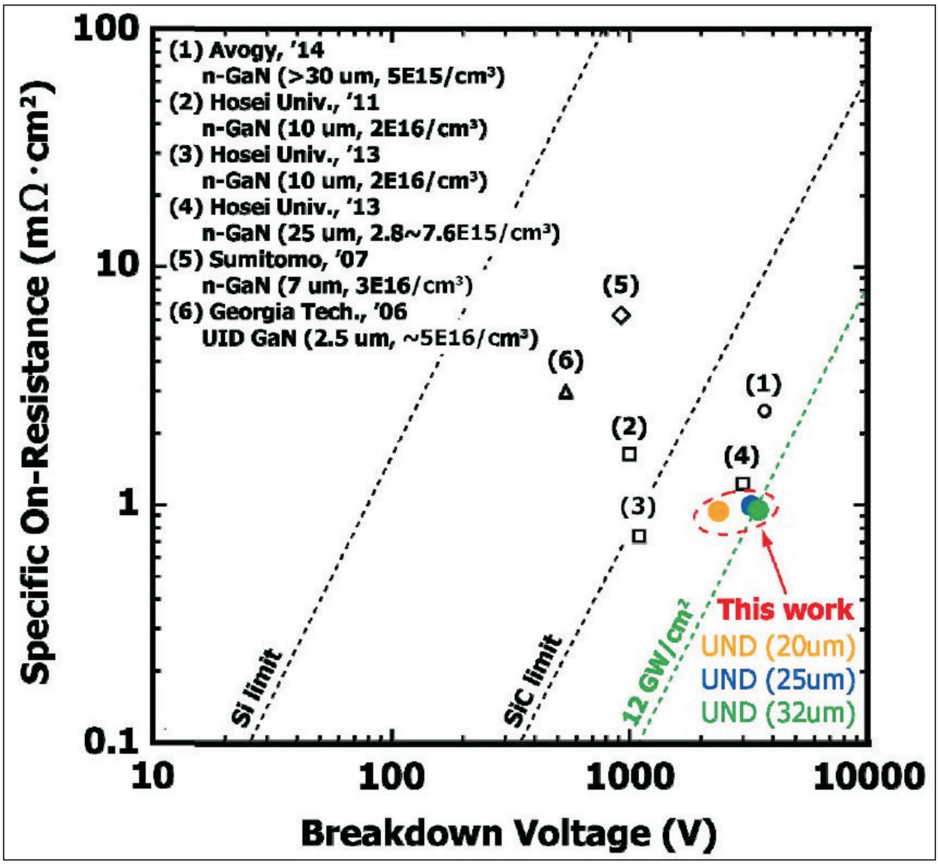

Figure 6. Baliga's figure-of-merit benchmark plot of reported vertical GaN-on-GaN p–n diodes.

The team also claimed a record low range of 1.1–1.3 for the ideality factors of the devices. ■

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