Building up vertical GaN for high-power technology

Devices where currents flow through the substrate material could change the location of peak fields in high-power devices. Mike Cooke reports on research to enable vertical high-power diodes.

Gallium nitride (GaN) has been developed for some time for high-power and high-frequency electronics beyond its original core applications of light-emitting diodes and laser diodes. Electronic devices on gallium nitride have mainly been restricted to lateral structures where charge flow is restricted to one side of the chip. This can be due to the non-conductive nature of the substrate, particularly where sapphire is used.

Recently more research has focused on vertical devices, where current flows from the top surface layers through the substrate to a contact on the back-side. The vertical structure allows simultaneous high current and high voltage with reduced on-resistance and less performance degradation from surface and interface states, compared with more conventional lateral devices.

Progress to vertical technology has been enable by the fast development of free-standing and bulk GaN substrates with low threading dislocation density. Such substrates are more expensive than conventional sapphire, silicon or silicon carbide (SiC) wafers. However, if the performance can be enhanced sufficiently, this may balance the increased (but hopefully falling) substrate cost.

High material quality is needed to avoid premature breakdown through defects in power electronics. Defect densities of GaN on sapphire or on SiC tend to be more than 10^9/cm^2. Using free-standing/bulk substrates can reduce the density to around 10^6/cm^2.

Here we look at some recent research focused on using p-n and Schottky diodes as test vehicles.

High-voltage regrowth

Researchers in the USA have been studying the regrowth of GaN on bulk GaN substrates, claiming the highest breakdown voltage so far for regrown vertical GaN p–n diodes [Zongyang Hu et al, IEEE Electron Device Letters, vol38, p1071, 2017]. “This is the first high-voltage vertical regrown p–n junction ever reported in the GaN system,” according to the team from Cornell University, University of Notre Dame, and IQE RF LLC in the USA.

The power performance is comparable to diodes produced without regrowth (‘as-grown’) on sapphire substrates, the researchers report. They add: “This work serves as an important step towards understanding the conduction mechanism in regrown junctions and improving selective doping technique for high-performance vertical GaN switches.”

Selective doping is needed for current apertures formed from lateral p–n junctions or for embedded p–n junctions in vertical switches.

The n-type part of the device was grown by metal-organic chemical vapor deposition (MOCVD) in the form of an 8μm GaN layer with ~2×10^{16}/cm^3 silicon doping on commercial bulk GaN. The surface was then cleaned with hydrochloric acid before molecular beam epitaxy (MBE) of 400nm ~10^{18}/cm^3 magnesium-doped p-GaN and a 20nm p++-GaN cap.

MOCVD has problems in regrowth such as high leakage in non-planar structures and strong dependence of impurity incorporation on crystal orientation. There are also problems with forming sharp boundaries between p-type and n-type material due to the magnesium memory/diffusion effect. Further, the presence of hydrogen in MOCVD passivates the effectiveness of magnesium doping in creating p-type conduction.

The fabricated diode was a bevel structure etched down to the n-GaN (Figure 1). The anode was palladium/gold and the cathode was titanium/gold. The device was passivated with spin-on glass (SOG). Edge-termination was achieved with an anode field plate that extended outside the mesa edge.

Capacitance-voltage measurements suggested a reduced built-in voltage of the p–n junction (~2.2V), compared with ‘as-grown’ junctions (~3.2V). The researchers tentatively attribute the reduction to band-bending, arising from increased defect density.

The regrown diode further suffered from higher leakage before, and lower output current after, turn-on at more than 3.2V. Reverse-bias leakage in the regrown diode was below the measurement capability of the test equipment for voltages less than 1V, giving an on/off current ratio of 11 orders of magnitude. The ideality factor was greater than 2 at all bias voltages.

The 300–600nm emission from electroluminescence was 30 times lower than for as-grown devices. “This is another direct evidence that the regrown interface

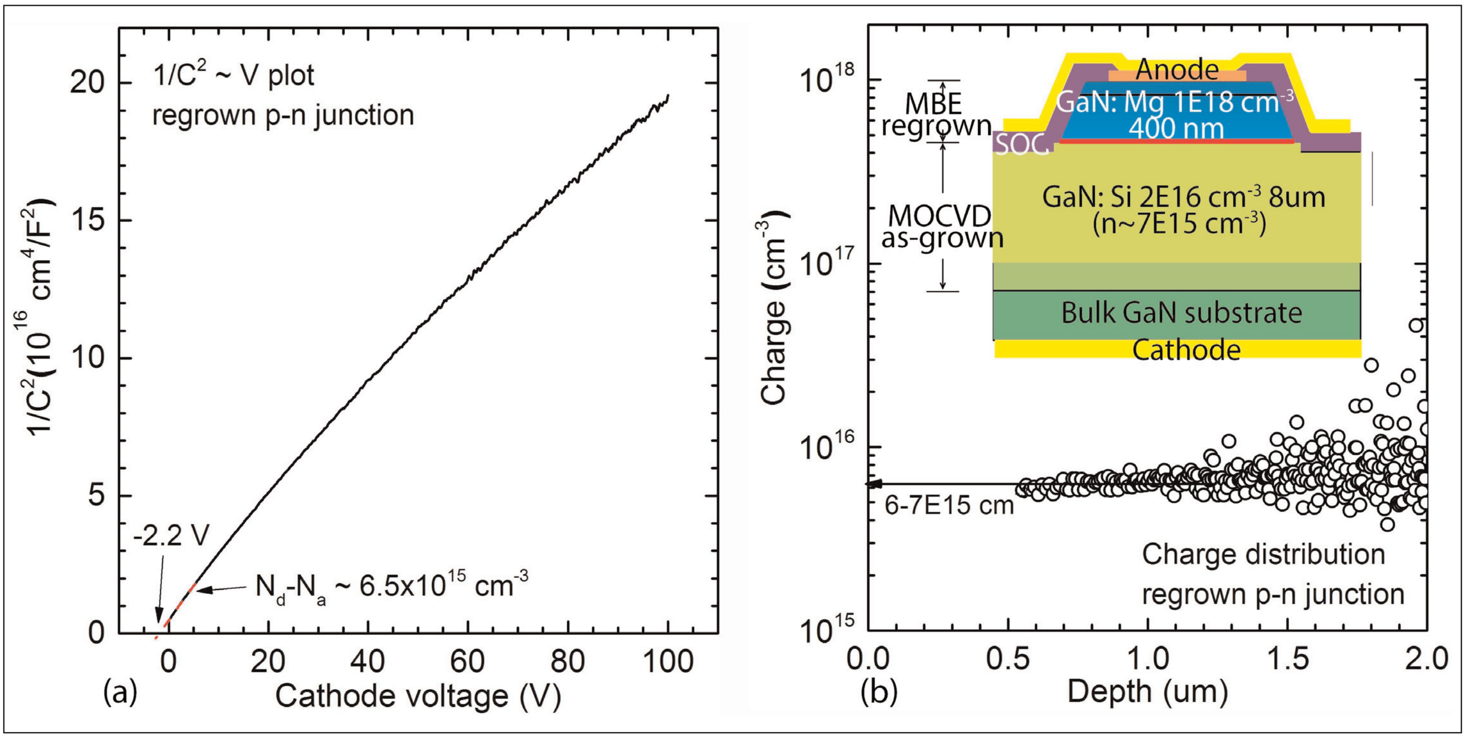

Figure 1. (a) Inverse-square capacitance (1/C^2) as function of reverse voltage measured on regrown GaN p–n diodes and (b) extracted net doping concentration in n-GaN drift layer. Inset: schematic cross section of completed device.

contains much more non-radiative recombination centers than the bulk material," the researchers comment.

The researchers also note that the differential on-resistance (R_{on}) increased with temperature from 25ºC to 125ºC. "This trend suggests that the dominant component of R_{on} in the regrown diode is the n-layer resistance (ρ_n), since electron mobility in the lightly doped n-GaN with low dislocation densities is significantly limited by phonon scattering, thus decreasing with increasing temperature," they write.

At 800A/cm^2 current density, the R_{on} was ~3.9mW-cm^2 for regrown diodes and ~0.6mW-cm^2 for as-grown.

The maximum reverse-bias breakdown of the regrown diodes was 1136V for a 107μm-diameter device. The leakage before breakdown was 0.1A/cm^2. "Most breakdown events were destructive and no avalanche breakdown behavior could be measured, unlike in the as-grown p–n diodes," the team reports.

Study of the current–voltage behavior suggests that Frenkel–Poole field-assisted thermionic emission was the dominant leakage mechanism below 160V reverse bias. This changed to variable range hopping in the depletion region as breakdown approached, it is thought.

Comparing the breakdown voltage (BV) and 800A/cm^2 R_{on} (Figure 2) through the ratio BV^2/R_{on} gives 0.33GW/cm^2 for the regrown diode and 4.1GW/cm^2 for the as-grown device.

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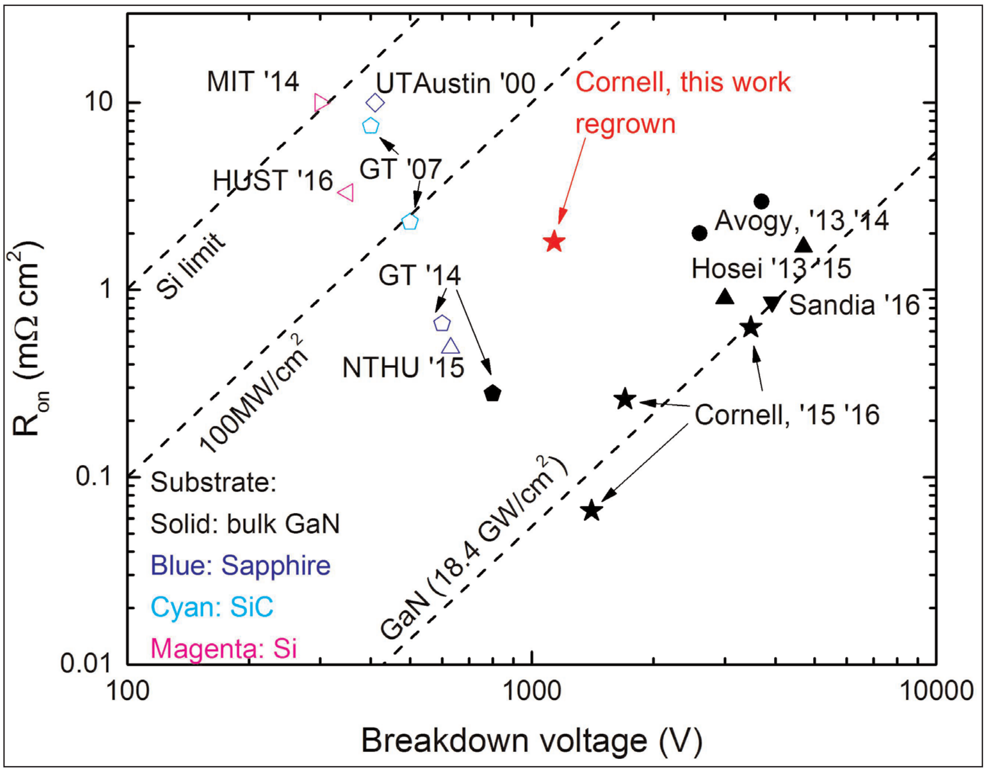

Figure 2. On-resistance versus breakdown voltage benchmark plot of state-of-the-art high-voltage GaN p–n diodes on GaN, SiC, sapphire and silicon substrates.

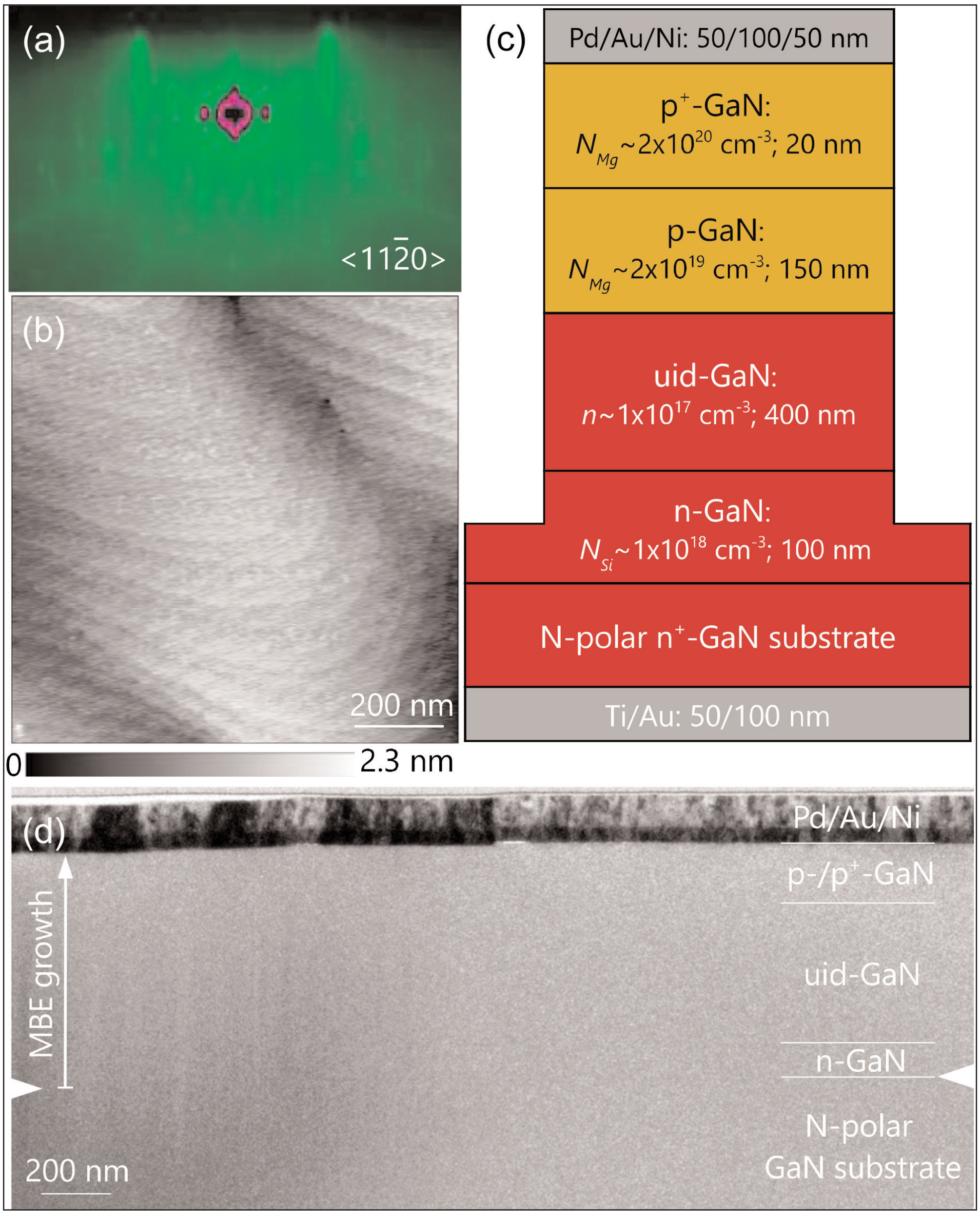

Figure 3. (a) In-situ reflection high-energy electron diffraction (RHEED) pattern showing (3x3) reconstruction characteristic of N-polar surface, and (b) AFM micrograph of MBE-grown N-polar GaN p–n diodes showing atomic steps. (c) Schematic layer structure and (d) cross-section transmission electron micrograph of fabricated vertical p–n diodes. Two white grooves on sides of image highlight the interface between the single-crystal bulk GaN substrate and MBE-grown epi-layers.

Nitrogen polarity

Cornell University in the USA has developed vertical p–n diodes using nitrogen-polar c-plane (000$\bar{1}$) GaN growth [YongJin Cho et al, Appl. Phys. Lett., vol110, p253506, p2017]. The researchers report: "A very low dislocation density leads to a high reverse breakdown electric field of ~2.2MV/cm without field plates — the highest reported for N-polar epitaxial structures." They further claim that their devices are the highest-quality p–n diodes ever demonstrated on N-polar GaN in terms of reverse-bias leakage.

The GaN crystal structure has strong charge polarization in the c-direction due to the ionic nature of the Ga-N chemical bond. The Cornell team suggests that growing material in the N-polar rather than the more common Ga-polar form, reversing the polarization, could lead to new electronic and photonic device opportunities such as ultra-low-power tunneling transistors, buried barrier high-electron-mobility transistors, and interband tunnel junctions. Further polarization engineering is used to create two-dimensional electron gas (2DEG) transistor channel layers and can also be exploited to improve hole densities in p-type regions.

N-polar growth allows higher growth temperatures, since the material is more robust against decomposition. However, bulk GaN substrates are usually prepared in Ga-polar form, and high-quality, low-dislocation, smooth N-polar GaN substrates have only recently become available. The N-polar GaN (000$\bar{1}$) substrate for Cornell's work was supplied by Ammono SA. The n$^+$ doping in the substrate delivered an electron concentration of about 10^{19}/cm^3. X-ray diffraction analysis suggested a dislocation density of 5x10^4/cm^2, much lower than the 10^9/cm^2 typical of GaN material on alternative substrates. Root-mean-square roughness over a 10μm x 10μm field was ~0.4nm, according to atomic force microscopy (AFM).

The p–n diodes (Figure 3) were grown using Ga-rich plasma-assisted MBE on a Veeco Gen Xplor machine. Excess Ga droplets were removed after growth by hydrochloric acid cleaning. Analysis of the diode material suggested that "the high structural perfection of the single-crystal GaN substrate was largely transferred to the MBE-overgrown p–n diodes," according to the researchers. The diodes were fabricated with 600nm-high mesas for electrical isolation.

A 50μm-diameter device had a 3.5V turn-on voltage, close to that expected from the ~3.4eV bandgap of GaN. At 5V forward bias, the current density was 7.8kA/cm^2, and the specific differential R_{on} was 0.1mΩ-cm^2 (Figure 4). The resistance was not corrected for the probe and therefore the actual value is smaller. Under reverse bias down to –6V, the leakage was less than 10^{-5}A/cm^2. The ±5V on/off current ratio was more than 10^9.

Electroluminescence was also observed with photon energy peaks at 3.13eV and 3.39eV with 5V forward bias and 1.5kA/cm^2 current density. The 3.39eV was attributed to near-band-edge (NBE) emission. The 3.13eV emissions were assigned to conduction-band-to-acceptor (CBA) transitions in p-GaN layers. The magnesium doping of p-GaN gives a hole binding energy around 0.25eV.

A very weak broad deep-level transition was also observed around 2.2eV. The team writes: "The presence of the NBE and CBA peaks, and the weak intensity of the broad band peak, indicate a low density of deep point defects in the p–n diodes."

Reverse-bias breakdown was studied using a 20μm-diameter diode. Abrupt breakdown occurred at –76V, just after the current leakage reached 10^{-1}A/cm^2 density. The researchers attribute the breakdown to trap-assisted avalanche effects as opposed to interband Zener tunneling.

Using capacitance–voltage measurements to estimate the electron concentration in the unintentionally doped (uid) GaN layer (9.6×10^{16}/cm^3), the researchers calculated that the peak electric field at breakdown was around 2.2MV/cm, occurring at the edge of the depletion region.

The team comments: "This breakdown electric field, lower than the best Ga-polar GaN p–n diodes of ~4MV/cm, nevertheless indicates the highest value for N-polar GaN p–n diodes and can be significantly improved by sculpting the electric field externally using field-plates as the Ga-polar counterparts. The full performance and true breakdown behavior of the diodes may be accessible by electrically isolating the device regions from edge sidewalls."

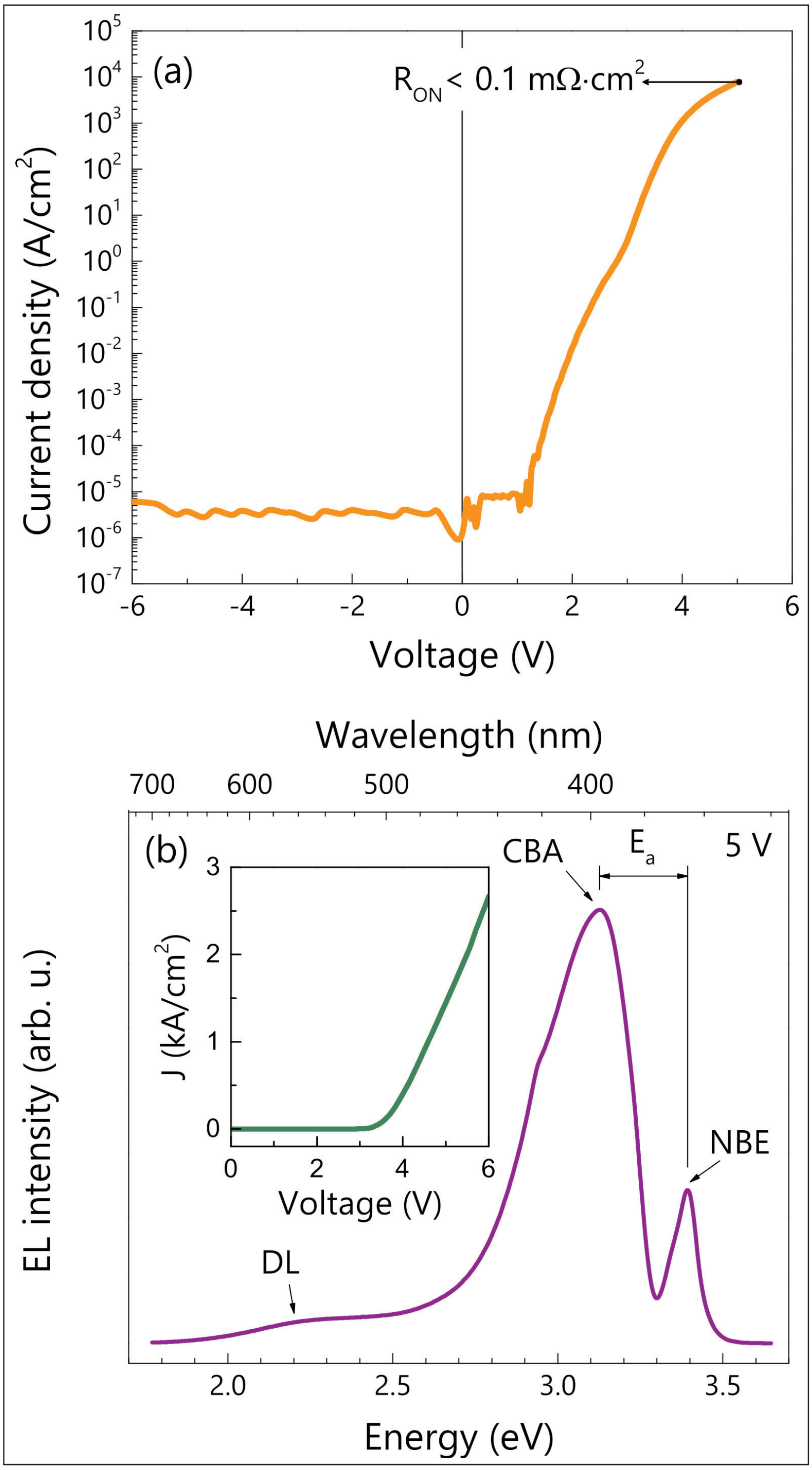

Figure 4. (a) Current density versus voltage characteristics of N-polar GaN single-crystal diodes in semilog scale showing high rectification ratio and low on-resistance. (b) Electroluminescence spectrum measured at 5V forward bias. Inset: linear-scale current density versus forward voltage.

Buffer and drift layer effects

Arizona State University in the USA has been studying the effects of GaN buffer layer thickness and drift layer doping on the material quality and performance of vertical p–n and Schottky barrier diodes [Houqiang Fu et al, IEEE Electron Device Letters, vol38, p763, 2017]. Without passivation or field-plates, some p-n devices reached breakdown voltages of more than 1000V and achieved R_{on} as low as 3mΩ-cm^2.

Samples were created from MOCVD on n-GaN free-standing substrates (Figure 5). The buffer layer was doped with silicon at 2×10^{18}/cm^3 concentration. The buffer thickness was varied at 50nm, 400nm, 1μm, and 1μm for samples labeled A–D, respectively. The 9μm drift layer was unintentionally doped (UID), except for sample D that was lightly doped with silicon (2×10^{16}/cm^3). The p-GaN upper layers were doped with magnesium — 500nm at 10^{19}/cm^3 concentration and 20nm at 10^{20}/cm^3.

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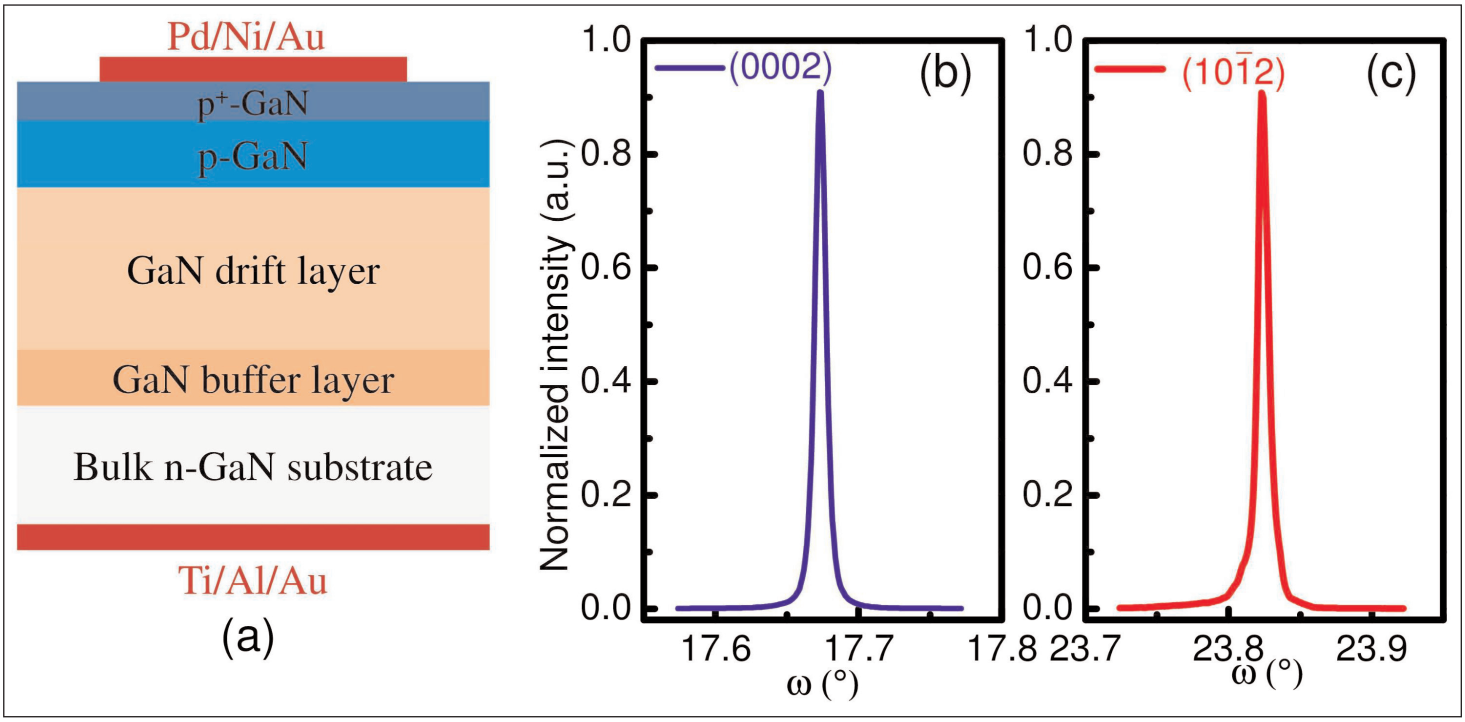

Figure 5. (a) Schematic of GaN p–n diodes on bulk GaN substrate. High-resolution x-ray diffraction rocking curve of (b) (0002) plane and (c) $(10\bar{1}2)$ plane for GaN p–n diodes.

As a result of x-ray diffraction analysis, the researchers comment: "All samples have dislocation densities on the order of 10^6/cm^2, which are significantly lower than that of typical GaN devices grown on sapphire (> 10^9/cm^2)." AFM scans gave root-mean-square (RMS) roughness values in the range 0.5–1.5nm over a 10μm x10μm field.

The p–n diode fabrication began with inductively coupled plasma etch to 1.5μm depth of 260μm-diameter circular mesas. Annealed 200μm-diameter p-GaN ohmic contacts of palladium/nickel/gold (Pd/Ni/Au) were created with electron-beam evaporation. The backside n-GaN contacts comprised titanium/aluminium/gold (Ti/Al/Au).

The p–n diode turn-on voltage for all samples was around 3.1V. The on/off current ratio was of the order 10^{10}. Variations between devices are not believed to be intrinsic, but rather due to inhomogeneous p-contact resistance. The R_{on} was of order 3mΩ-cm^2 at 4V.

Electroluminescence was detected with spectral peaks at 2.2eV, 3.2eV and 3.4eV photon energies. "The strong EL suggests the radiative recombination in GaN p–n diodes and is an indication of high material quality," the researchers write.

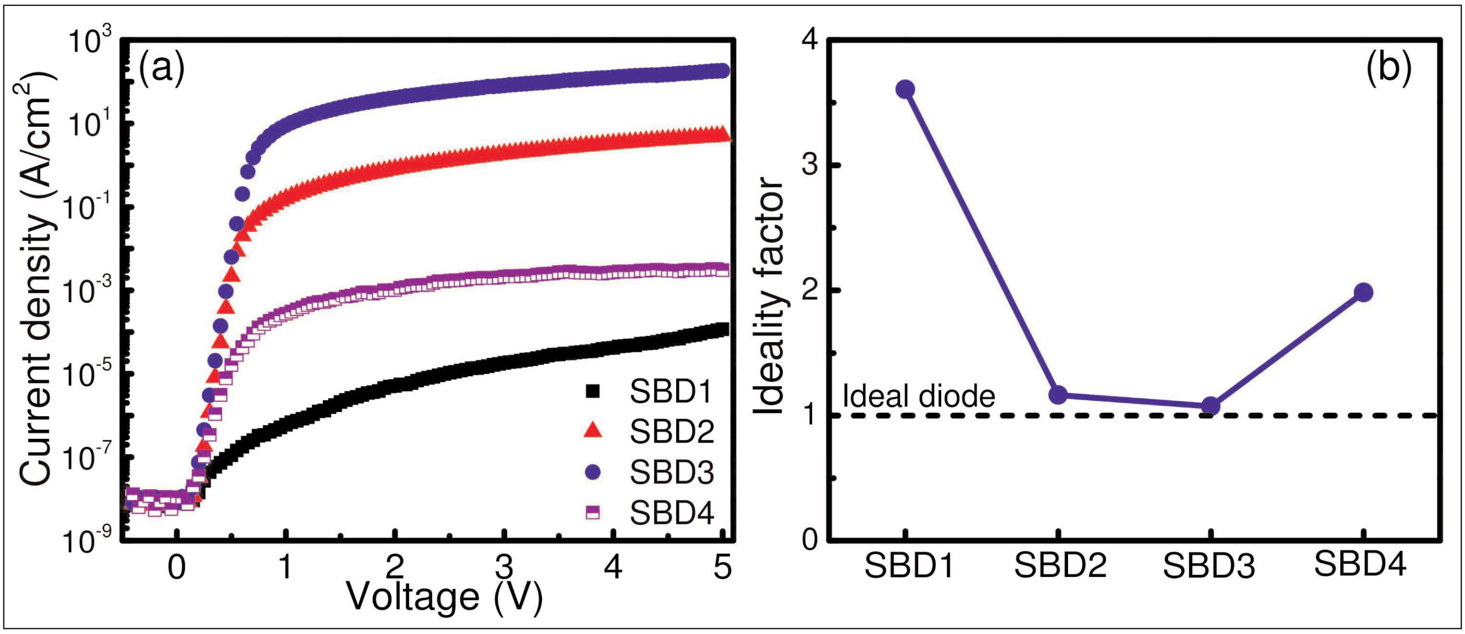

Figure 6. (a) Forward current–voltage I–V characteristics and (b) ideality factor of GaN Schottky diodes.

Table 1. Growth conditions, growth rate, root-mean-square (RMS) surface roughness, and thickness of grown GaN.

Sample	TMG (sccm)	NH_3 (slm)	V/III	Growth rate (μm/h)	RMS (nm)	Thickness (μm)
A	30	10	4057	2.61	0.11	4.36
B	60	10	2028	4.72	0.62	7.95
C	90	15	2028	7.78	1.19	7.78
D	90	10	1352	8.08	—	8.08

The reverse bias breakdown voltage was highest at more than 1000V for the p–n diode on sample C. The other samples in order of decreasing breakdown voltage were B at 772V, D at 687V, and A at 647V. The sample C device had a thicker buffer layer and low drift layer doping.

Some Schottky barrier diodes were also produced with Pd contacts on samples where the MOCVD growth ended with the drift layer. The buffer layer thicknesses were 20nm, 100nm, 400nm and 400nm for SBDs1–4, respectively. The buffer silicon doping was at 2x10^{18}/cm^3, as before. The 9μm drift layer was unintentionally doped, except for SBD4 with light silicon doping (2x10^{16}/cm^3).

The SBDs showed much more variation in on-current, with SBD3 demonstrating the highest (Figure 6). Also, the ideality for SBD3 was near unity at 1.07, indicating high material quality of the drift layer, according to the team. The researchers comment: "With the same UID drift layer, the ideality factor decreases with increasing buffer layer thickness, indicating thicker buffer layer results in better material quality which can result from reduced defect density."

Thinner buffers and intentional drift layer doping gave idealities deviating from near-unity.

Thicker buffers were also found to increase the critical electric field, and hence breakdown voltages. However, the critical electric field was smaller than previous work by University of Notre Dame and Cornell University. The Arizona team attributes the lower performance to insufficient mesa isolation and larger contacts.

The breakdown characteristics of the SBDs followed the trends of the p–n diodes, with the best performance coming from thicker buffers and lower drift layer doping.

One negative side-effect of having thicker buffers was to increase the net doping in the overlying drift layer, which potentially could impact performance, according to capacitance–voltage studies on the SBDs. However, the researchers found that drift layer material quality was more important than doping concentration in achieving high breakdown voltages.

Schottky barriers

Japan's National Institute for Materials Science (NIMS) and Shanghai University in China have developed vertical GaN Schottky barrier diodes (SBDs) with a combination of low turn-on voltage and low R_{on} [Bing Ren et al, Appl. Phys. Express, vol10, p051001, 2017]. The low turn-on voltages obtained are claimed as "the lowest values ever reported for the vertical GaN SBD".

The team used a lowered growth rate to improve the GaN drift layer. The researchers see the technique as a route to high-performance vertical GaN SBDs with low conduction loss and high switching speed suitable for high-power applications.

The GaN drift layer was grown by MOCVD at 950ºC on free-standing substrates with 4x10^6/cm^2 threading dislocation density and 1x10^{18}/cm^3 donor concentration. The precursors were trimethyl-gallium (TMG) and ammonia (NH_3) in a carrier gas that was a mix of nitrogen and hydrogen.

The growth rate was controlled by varying the TMG flow rate between 30 standard cubic centimeters (sccm) and 90sccm (Table 1). The ammonia flow was fixed at 10 standard liters per minute (slm), except for sample C. The NH_3/TMG (V/III) molar ratio was between 1352 and 4057.

Schottky barrier diodes were formed with sputtered Ti/Al/Au ohmic metals on the substrate back-side and evaporated Ni/Au as Schottky contact.

The researchers studied the surface of the grown GaN with AFM. Samples A–C, grown with flow rates 2.6–7.81μm/h, had surfaces with aligned, atomic-level steps. By contrast, the 8.08μm/h fast growth rate of sample D resulted in valley-like defects. The researchers suggest these defects could arise from a three-dimensional growth mode or from the relatively low V/III ratio.

The researchers comment: "Although the step-flow growth was achieved in an optimized growth rate range, the RMS roughness was still rising from 0.11 to 1.19nm with increasing growth rate."

X-ray analysis produced narrow peak rocking curves

Table 2. Key diode parameters extracted from current–voltage (I–V) and capacitance-voltage C–V curves.

Sample	n	Φ I–V (eV)	Φ C–V (eV)	Free carrier density (/cm^3)	V_{on} (V)	R_{on} (mΩ-cm^2)	Mobility [cm^2/V-s]
A	1.04	0.97	0.97	6.35x10^{15}	0.73	0.72	1370
B	1.03	0.93	0.95	2.30x10^{15}	0.68	2.62	975
C	1.04	0.85	0.91	3.10x10^{15}	0.66	2.90	628
D	1.59	0.69	0.71	4.59x10^{16}	0.67	0.86	239

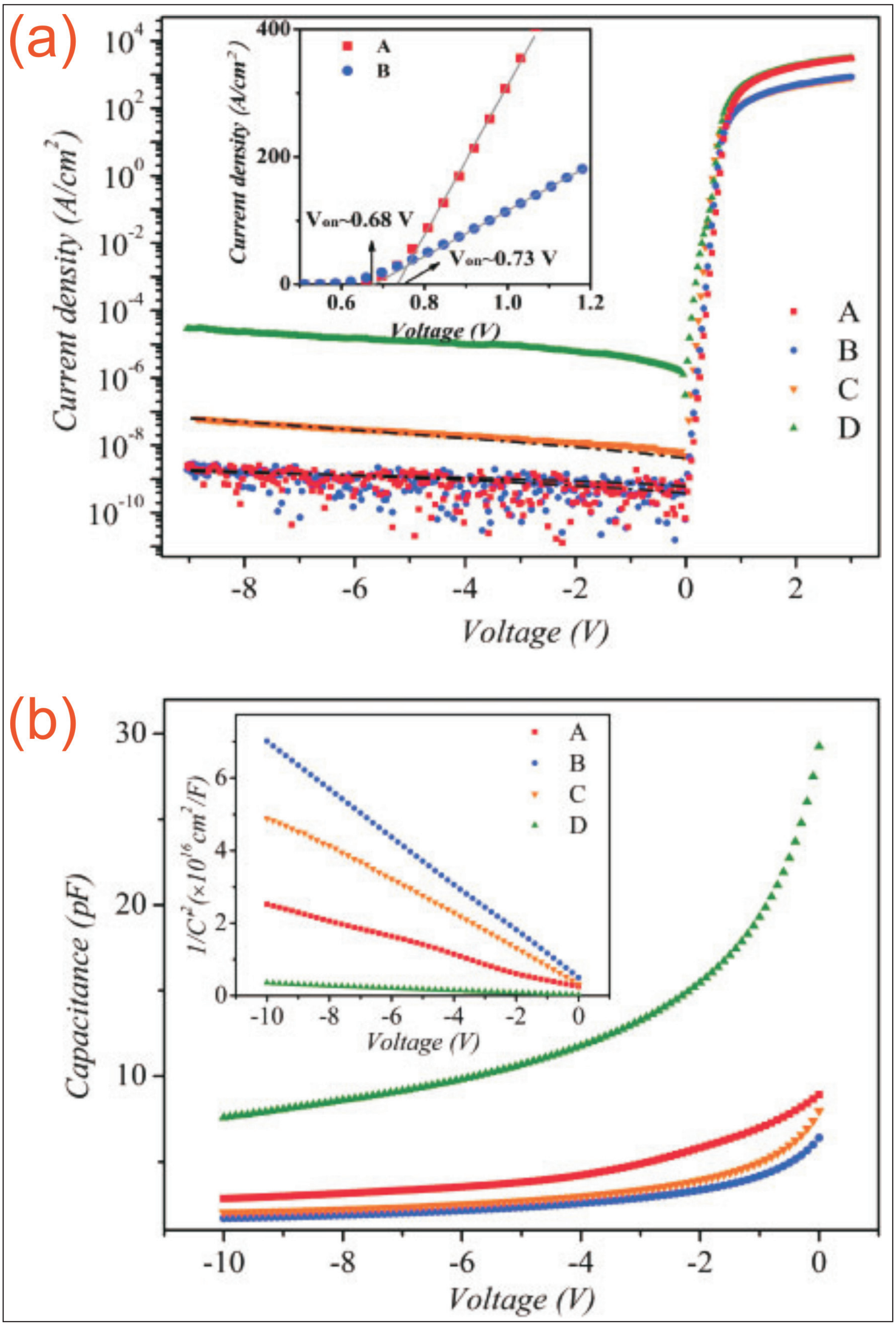

Figure 7. (a) Current density versus voltage, and (inset) detail near turn-on point for samples A and B. (b) Capacitance–voltage measurements at 1MHz, and (inset) inverse-square capacitance versus voltage.

with full-width at half-maximum (FWHM) values similar to that of the underlying substrate. Photoluminescence measurements showed sharp 3.4eV NBE emission and broad ~2.2eV defect-related 'yellow' luminescence. The ratio of NBE to yellow emissions trended downward with growth rate — around 60 for the bulk GaN substrate, and in the range 30 to 5 for samples A–D.

The researchers attribute this to increased carbon incorporation, presumably from the organic TMG precursor. The low carbon incorporation of samples A and B improved the mobility of the SBD drift layer.

Electrical characteristics (Figure 7 and Table 2) were extracted from SBDs with 60μm-diameter contacts. "Although the SBD devices have large Schottky barrier heights, the turn-on voltages were still kept at a low level (0.66–0.73V), which are the lowest values ever reported for the vertical GaN SBD," the team writes.

The SBD based on sample A material gave a combination of low 0.72mΩ-cm^2 R_{on} and high 1370cm^2/V-s mobility, at the cost of a slightly higher turn-on voltage compared with the other devices. Sample A's R_{on} is described as "among the lowest ever reported". "It should be noted that this is the first report of such a low R_{on} together with a low turn-on voltage," the researchers add.

The sharpness of the turn-on, as given by the ideality, is close to 1 (the ideal) for SBDs on samples A–C. The higher 1.59 ideality of sample D is attributed to the poor Schottky contact of the rough surface. Also, SBD sample D suffered from a higher reverse-bias leakage of 10^5A/cm^2, due to trap-assisted tunneling, according to the researchers. The Schottky barrier heights (Φ) from current–voltage and capacitance–voltage analysis of the devices on samples A and B are close to the Ni/GaN theoretical value of 1.0eV. ■

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