Substrates for III-nitride vertical power electronic devices

Researchers have in the past few years been exploring the potential advantages of vertical over lateral devices. Mike Cooke reports.

Gallium nitride's wide bandgap has enabled light-emitting diodes (LEDs) to achieve short-wavelength blue and near-ultraviolet radiation for more than 20 years. The material's wide bandgap of 3.4eV also implies a higher critical field, which raises the possibility of creating a range of high-voltage and power devices, and some gallium nitride (GaN) transistors and diodes have become available commercially.

These devices tend to use lateral structures to create high-electron-mobility transistors and Schottky diodes. Lateral structures suffer from a number of reliability and integration challenges

At the heart of such devices is current flow in a 'two-dimensional electron gas' (2DEG) that forms near an interface between GaN and an even wider-bandgap material such as aluminium gallium nitride (AlGaN) or aluminium indium nitride (AlInN) due to different charge polarization properties of the chemical bonds. Of course, the confined electron gas is not truly two-dimensional, but it is restricted to a very thin layer, constricting the amount of flow that can be achieved in small devices.

Vertical devices could be able to handle higher voltages and current with a smaller footprint. Also, vertical devices should benefit from a structure where the peak field is away from the surface of the diode, along with better thermal performance.

A possible drawback is current leakage and breakdown along threading dislocations and other defects. Hence, the performance of vertical devices tends to depend on the substrate used for growth of the GaN and other III-nitride layers. One expects bulk and free-standing GaN substrates to result in lower leakage compared with alternatives due to the lower defect generation in growth with zero lattice mismatch. (Free-standing GaN is grown in a thick layer on a non-GaN substrate that is removed.) The disadvantage of bulk and free-standing GaN is much higher cost than material grown on sapphire or, especially, silicon (Si).

A number of groups have started exploring the vertical option, and a number of reports have been made since the beginning of this year. These include both transistors [e.g. Semiconductor Today, p90, June/July 2015] and diodes. Here, we report on recent work on diodes on different growth substrates. We also report the first claim of Schottky barrier diode (SBD) fabrication on aluminium nitride (AlN) with a bandgap of 6.1eV, almost twice that of GaN at 3.4eV.

Bulk

Avogy Inc of San Jose, CA, USA has used bulk GaN substrates to create vertical p-n diodes with breakdown voltage of more than 4kV and area-differential specific on-resistance of less than 3mΩ-cm^2 [I.C. Kizilyalli et al, IEEE Electron Device Letters, published online 9 September 2015].

The company is developing GaN-on-GaN technology aiming to produce discrete semiconductor devices, modules and systems that increase efficiency and reliability of power conversion while reducing cost, size and weight.

Increasing breakdown to 4kV brings potential application for ship propulsion, rail, wind power, uninterruptable power supplies (UPS), geothermal instrumentation, high-voltage multipliers, military power supplies, and the power grid, according to the researchers.

Avogy has begun with p–n junction devices as a first step towards the realization of more complex vertical junction field-effect transistors (JFETs) and junction barrier Schottky (JBS) diodes, which have lower turn-on voltages (<1V) and lower conduction losses.

The epitaxial structures were grown by metal-organic chemical vapor deposition (MOCVD) on 2-inch bulk GaN substrate with very low threading dislocation density of 10^4/cm^2. "This is four orders of magnitude lower than for GaN films grown in the conventional manner on non-native substrates," according to the researchers.

The researchers designed the edge termination, n-type drift layer and thickness to achieve junction breakdown around 5kV. In particular, the edge termination spread the anode potential to a distance that exceeded the drift layer thickness by a factor of about 4.5. The edge termination involved two implant steps.

The net doping density of the 40µm drift layer was 2–5x10^{15}/cm^3. "Controlling the doping of GaN to these levels by MOCVD is challenging since it is at or below the level of typical unintentional background impurities, particularly carbon," the researchers comment.

The p-region of the diode consisted of heavily magnesium-doped GaN deposited on the drift layer. The contacts were palladium/platinum.

The researchers have found that nominally c-plane oriented devices with a slight inclination towards the m-plane are optimal for reverse leakage performance and reliability. The inclination is achieved by mis-cutting by several tenths of a degree to encourage step-flow growth, avoiding the formation of screw dislocations.

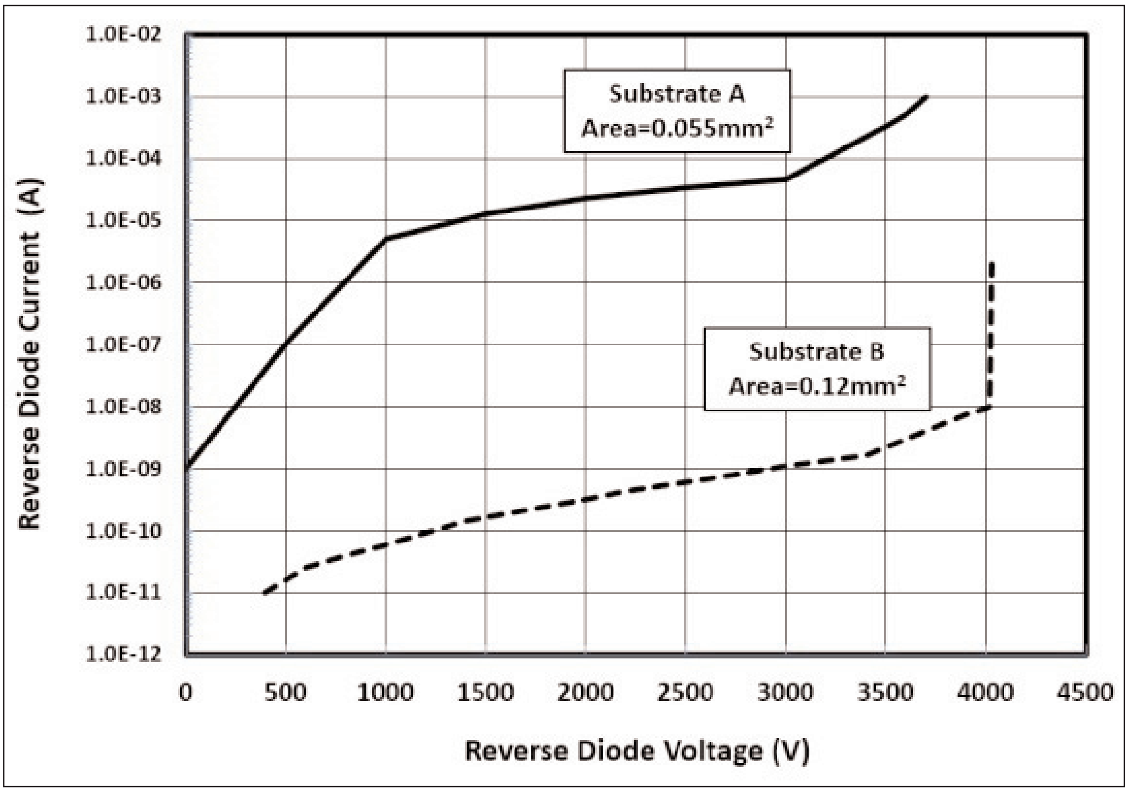

Figure 1. Reverse characteristics at 300K of GaN p-n diodes on optimized substrate B and comparison devices on unoptimized substrate A.

Spiral growth around screw dislocations leads to unwanted large hexagonal hillocks on the GaN surface in on-axis deposition. White-light interferometry gave a mean roughness of less than 20nm over a 1mmx1mm area for an optimized substrate (B), compared with more than 50nm for a sample with lower mis-cut angle (A).

The researchers report: "The implementation of the improved substrate specification results in a marked improvement in the reverse leakage and the first demonstration of a breakdown voltage exceeding 4kV in GaN vertical p–n diodes [see Figure 1]." Last year, Avogy researchers reported devices with breakdowns up to 3.5kV and leakage about 10µA through a 0.055mm^2 effective area.

The team believes that further improvement of the edge-termination should lead to 5kV breakdown. The researchers calculate the field in the drift region at 2.0–2.7MV/cm at breakdown, well short of GaN's critical field of ~5MV/cm. They conclude that the breakdown occurs in the edge termination.

The turn-on voltage is around 3.0V, consistent with GaN's bandgap of 3.4eV. The effective device area was 250µm x 500µm, as defined by the edge-termination implants. The device can handle up to 1A without substrate thinning or packaging.

In 30ms-pulsed quasi-DC operation, the area differential specific on-resistance was 2.3mΩ-cm^2 at room temperature. An increase in resistance with temperature was attributed to reduced electron mobility.

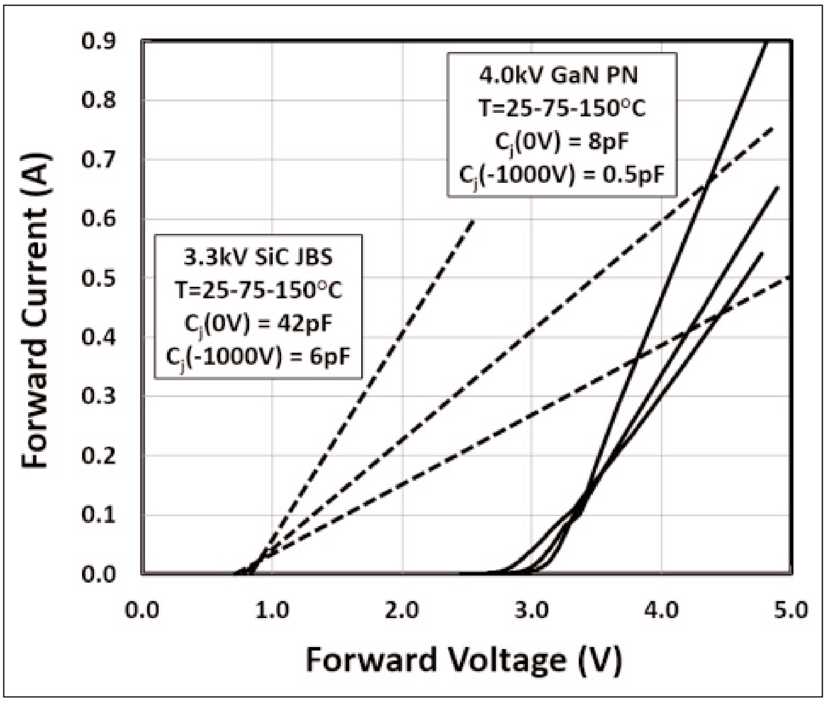

Figure 2. Forward current-voltage characteristics of 4kV GaN p-n diode and 3.3kV SiC JBS diode (dotted line) at 25–75–150°C.

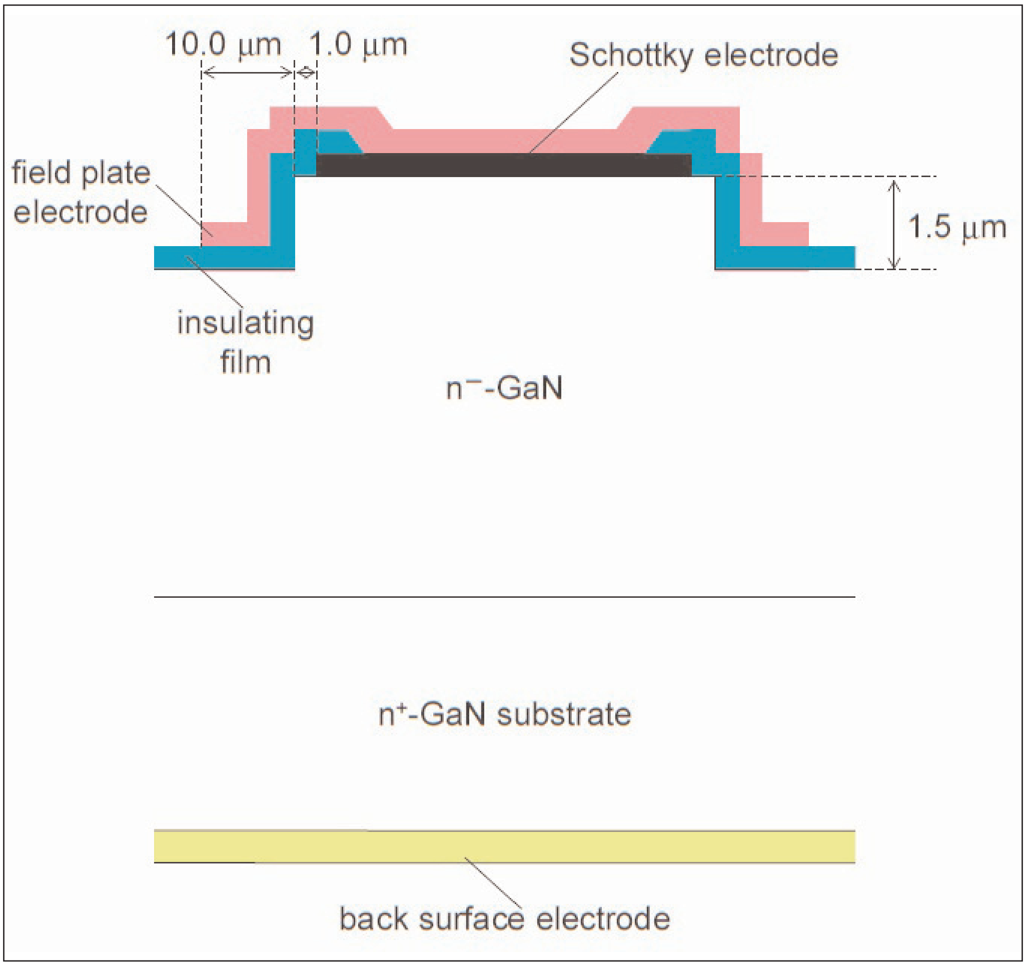

Figure 3. Vertical GaN SBD.

The researchers compared the performance with silicon carbide junction barrier Schottky (SiC JBS) diodes (Figure 2). The junction capacitance of the GaN device was much lower, suggesting lower switching losses.

Avogy has licensing and supply agreements with multiple GaN substrate vendors. The company's equipment base consists of sub-micron lithography, multiple MOCVD reactors, device fabrication, and a full suite of electrical testing and metrology tools. Cleanroom facilities cover 3500ft^2 in a 27,000ft^2 facility.

Free-standing

Japan's Toyoda Gosei Co Ltd has made a number of reports on vertical GaN devices in recent months. These have involved both transistors [Semiconductor Today, p88, June/July 2015; Semiconductor Today, p94, April/May 2015] and diodes. Most recently, the company research team has reported Schottky barrier diodes (SBDs) capable of handling 50A forward current with 790V reverse blocking [Nariaka Tanaka et al, Appl. Phys. Express, vol8, p071001, 2014].

"To our knowledge, the characteristics of operation with a simultaneous high forward current and high blocking voltage are reported for the first time for vertical GaN SBDs on free-standing GaN substrates," the researchers comment.

Toyoda Gosei sees potential applications of high-power GaN rectification and switching in power control units in hybrid cars and for solar power conversion. The company has developed GaN technology for light-emitting diodes since 1986 and began research into GaN power electronics in 2010. Toyoda Gosei's main business is supplying automotive parts, although it also has divisions for LEDs and general industry products (e.g. telecoms, air conditioning, home construction).

MOCVD was used to create a 10µm lightly doped n^--GaN layer on commercially available free-standing heavily doped n^+-GaN substrate. The SBD (Figure 3) consisted of mesa isolation, nickel Schottky anode, insulating film, aluminium-based field-plate, and aluminium/titanium back-contact cathode. The insulating film was 500nm of silicon dioxide and 100nm of aluminium oxide. The field-plate was designed to relieve potential crowding at the edge of the Schottky electrode. Potential crowding increases leakage current and reduces blocking voltages.

A 3mmx3mm device managed a 50A forward current with a bias of 2.05–2.25V. The researchers expect that higher currents can be achieved, since their equipment was limited to 50A. The differential on-resistance above 20A was 25–29mΩ. Since this value was very close to estimates based on the resistivity of the GaN material, the researchers believe the contact resistance of the back-electrode was negligible.

The blocking voltage under reverse bias was 730–790V. Repeat measurements showed the breakdown to be non-catastrophic. The researchers believe the combination of high forward current and high reverse blocking to be a first for vertical SBDs on free-standing GaN.

The reverse blocking was about 200V short of a simple prediction based on thermionic field emission theory. The researchers comment that the difference could be due to potential crowding at the Schottky electrode edge, dislocations, or a combination of the two.

Experiments with different area Schottky diodes showed the forward current density behavior with respect to voltage up to 0.5V to be very similar down to 200µm dimensions. The Schottky barrier height was estimated to be 1.01–1.02eV and the ideality was 1.01, according to the thermionic emission model.

The reverse current density versus voltage was also similar across the different area SBDs. Since the higher-than-expected reverse leakage was thought to be due either to potential crowding or dislocations in the bulk material, the researchers tried to disentangle the effect by seeking the behavior of the leakage according to the perimeter (edge) or area (bulk) of the device. In particular, the leakage at 400V reverse bias was plotted against the perimeter-to-area ratio (Figure 4). Since the effect of the perimeter was small, the researchers concluded that perimeter current was small compared with the bulk current.

The researchers believe that improving the n⁻-GaN growth process will enable the achievement of higher reverse blocking voltage combined with the same high forward current.

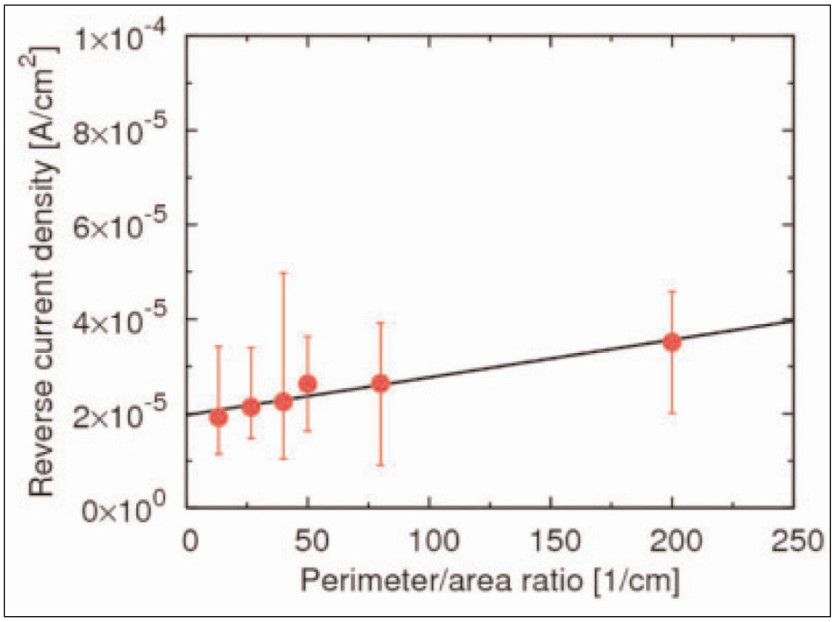

Figure 4. Reverse current density at 400V as a function of perimeter/area ratio.

Cutting leakage on silicon

Researchers in the USA have developed vertical Schottky and pn GaN diodes on silicon with performance comparable to devices grown on much more expensive substrates [Yuhao Zhang et al, IEEE Transactions On Electron Devices, vol.62, p2155, 2015].

The researchers from Massachusetts Institute of Technology, and from Synopsys Inc and Applied Materials–Varian, worked in particular to reduce reverse leakage currents from a number of sources.

The heterostructures for the Schottky and pn diodes (Figure 5) were grown on (111) Si using MOCVD. The devices were fabricated by etching 1.6μm cathode electrodes from the top GaN layers, and depositing cathode and anode ohmic contacts, 200nm silicon nitride passivation and field-plates. Titanium/aluminium were used for the cathode contact ring and field-plates. The circular anode contact consisted of nickel/gold.

The researchers investigated four possible routes of current leakage: "(1) through the transition layers and Si substrate; (2) through the drift layer; (3) along the etch sidewall; and (4) through the passivation layer."

Tests with trench structures suggested that leakage path 1 was negligible. Also, improvements in the silicon nitride passivation at MIT have reduced path 4 currents to a similarly negligible level. The improvement involves using sputtering rather than plasma-enhanced chemical vapor deposition (PECVD) [Semiconductor Today, p72, June/July 2015].

Inductively coupled plasma (ICP) etch damage (giving defects such as nitrogen vacancies) tends to lead to leakage through path 3. Such etches can change a p-GaN surface into a depleted or n⁻-GaN region, giving reverse bias leakage.

To overcome the etching problem, an edge-termination process was developed to repair dry etch damage that combined carbon tetrafluoride or nitrogen plasma

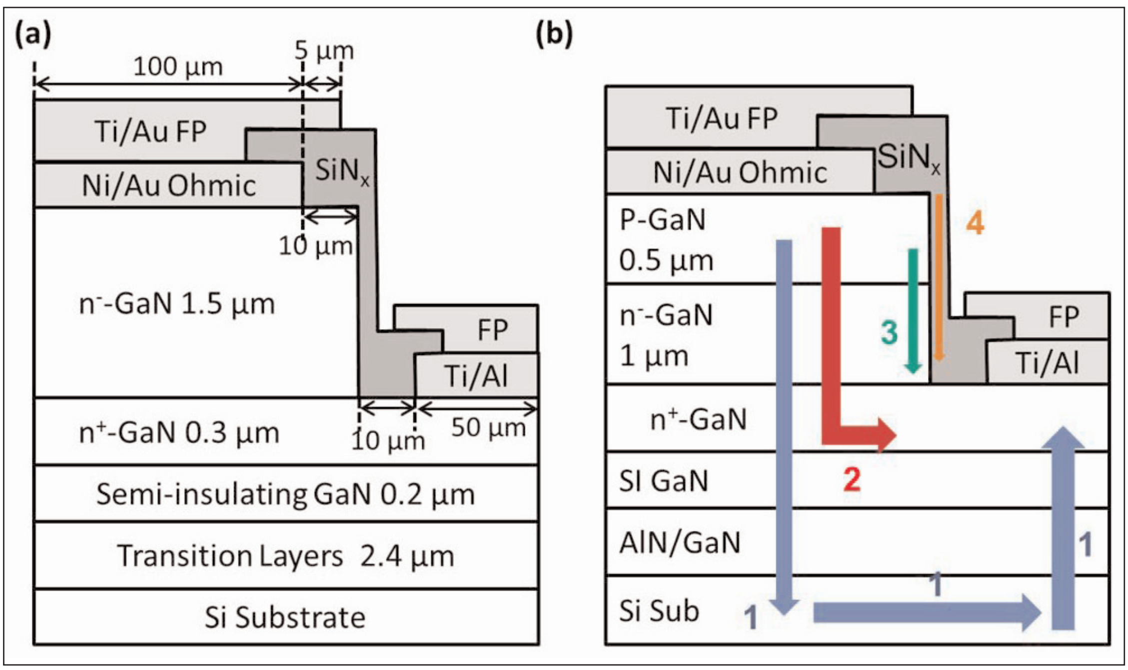

Figure 5. Schematic of GaN-on-Si vertical (a) Schottky and (b) p-n diodes. Four possible leakage paths in GaN-on-Si vertical diodes are shown in (b).

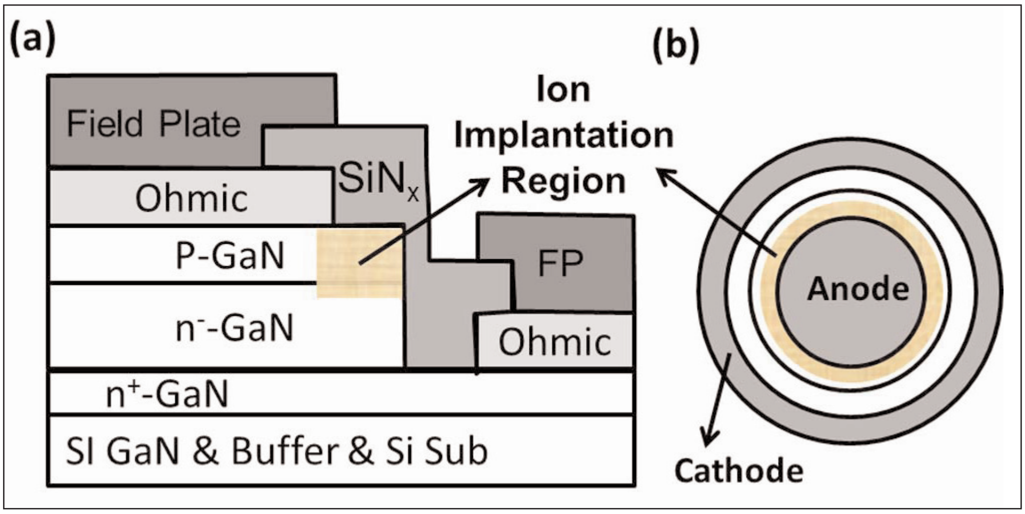

Figure 6. (a) Cross section and (b) top view of the GaN-on-Si vertical p-n diodes with ion implantation regions as edge termination.

treatment, tetramethylammonium hydroxide (TMAH) wet etching, and argon ion implantation. The ion implantation ring isolated the main vertical current from the etch sidewall (Figure 6).

By creating diodes of various diameters, the researchers concluded that the edge-termination process effectively suppressed leakage through path 3, leaving bulk leakage through path 2 as the main contributor.

The reverse leakage in the enhanced pn diodes was reduced by two orders of magnitude, while maintaining a soft breakdown voltage of more than 300V (peak field estimated at more than 2.9MV/cm). The 300V soft breakdown performance is close to the theoretical maximum for a 1.5μm-thick drift layer. Thicker GaN layers should increase the breakdown voltage.

Schottky and pn diodes of 600μm diameter demonstrated forward currents of more than 2A (500A/cm^2) in pulsed measurements with duty cycles up to 1%. The on-resistance for 600μm-diameter Schottky diodes was 6mΩ-cm^2 — for similar pn diodes the resistance was higher, at 10mΩ-cm^2.

The researchers comment: "The relatively high on-resistance of our GaN-on-Si vertical diodes is due to the relatively high contact resistance of ohmic on p-GaN, low mobility of p-GaN (~14cm^2/V-s), and the current crowding near the corner of the etching sidewall. An improvement of the p-GaN material quality is expected to further reduce the on-resistance of our GaN-on-Si vertical diodes."

The researchers compared their device performance with diodes produced on more expensive substrates (Table 1). They comment: "With over 1000x lower substrate cost than the GaN-on-GaN device, our GaN-on-Si vertical devices achieved an off-state leakage current lower than the GaN lateral devices and similar to the one in the state-of-the-art Si and SiC devices."

Aluminium nitride

Researchers based in Japan and USA report fabrication of vertical Schottky barrier diodes (SBDs) on AlN substrates for the first time [Toru Kinoshita et al, Appl. Phys. Express, vol8, p061003, 2015]. The team involved researchers from Tokuyama Corp, Fuji Electric Co Ltd and Tokyo University of Agriculture and Technology of Japan, along with HexaTech Inc and North Carolina State University in the USA.

In addition to its extremely wide 6.1eV bandgap, AlN also has a high thermal conductivity of 3.2W/cm-K, enabling higher power density. The wide bandgap is also attractive for deep-ultraviolet (~200nm) light emission.

One barrier to AlN power electronics is developing n-type conductivity in thick layers so that free-standing substrates can be developed. MOCVD is slow (~1μm/hour). Hydride vapor phase epitaxy (HVPE) is much faster and enables such a development.

The Si-doped AlN HVPE was carried out at 1450ºC on 15mm-diameter highly insulating 10TΩ-cm AlN substrates. The growth substrates were produced in a

Table 1. Leakage and cost benchmarking for the GaN vertical device on different substrates, GaN lateral device, Si and SiC device.

Diode	Leakage current (density) at −200V	I_{on}/I_{off} ratio	Available substrate	Substrate cost per cm^2
GaN-on-Si vertical (this work)	<1μA (10^{-4}–10^{-3}A/cm^2)	~10^6	200mm Si	~$0.08
GaN-on-sapphire vertical	10^{-3}A/cm^2	~10^5	100mm sapphire	~$2.2
GaN-on-GaN vertical	10^{-5}—10^{-6}A/cm^2	~10^9	50mm GaN	~$100
AlGaN/GaN lateral	10^{-2}A/cm^2	~10^5	200mm Si	~$0.08
Si (NTE 588)	5μA	~10^6	200mm Si	~$0.08
SiC (APT6SC60K)	<1μA	~10^6	75mm SiC	~$6
Si power MOSFET (IRHNJ597230)	>10μA (10μA at −160V)	~10^6	200mm Si	~$0.08

physical vapor transport (PVT) process at HexaTech. The Al-polar growth surface was prepared using chemical mechanical polishing (CMP). The average HVPE growth rate was 25μm/hour.

X-ray analysis showed that the crystal quality of the HVPE material was similar to that of the PVT substrate. Secondary-ion mass spectrometry (SIMS) gave uniform values for impurity concentrations of silicon, oxygen and carbon. The silicon concentration of the AlN:Si was $3x10^{17}/cm^3$.

Hall measurements on a 32μm AlN:Si layer resulted in $2.4x10^{14}/cm^3$ net electron concentration, $115cm^2/V\text{-}s$ mobility, and $2.3x10^2\Omega$-cm resistivity. The concentration was the same order as for AlN:Si grown using MOCVD. However, the HVPE mobility was lower than for MOCVD. At the same time, the HVPE dislocation density is estimated to be at least four orders of magnitude lower than for MOCVD. The researchers attribute the counter-intuitive mobility result as being due to a higher number of point defects in the HVPE material.

Temperature-dependent Hall analysis gave a donor density of $2.6x10^{17}/cm^3$, an acceptor density of $1.5x10^{17}/cm^3$, and a donor activation energy of 245meV. The activation energy was similar to values reported for MOCVD AlN. "These results revealed that HVPE can produce AlN:Si layers with n-type conductivity similar to those grown by MOCVD," the researchers write.

Schottky barrier diodes (Figure 7) were fabricated from a 250μm-thick AlN layer, which was subjected to chemical mechanical polishing on the AlN:Si side and mechanical polishing to remove the PVT AlN substrate. The resulting free-standing AlN:Si was 150μm thick.

Annealed titanium/aluminium/titanium/gold on the Al-polar surface was used as the ohmic contact. Several 270μm x270μm Schottky nickel/gold contact electrodes were applied to the N-polar side. The device was mounted ohmic side down on a ceramic AlN carrier with silver paste.

The turn-on voltage was 2.2V. The series resistance was $3.5x10^6\Omega$, much higher than the value expected from the Hall mobility. The researchers suggest that this could be due to high resistance damage from mechanical polishing of the surface on which the Schottky contacts are made. Increasing the temperature to 373K reduced the series resistance to $2.9x10^5\Omega$.

Reverse-bias leakage was less than $10^{-6}A/cm^2$ below 400V (Figure 8). Reverse breakdown voltages for $10^{-3}A/cm^2$ were between 550V and 770V for six devices. Since the thermionic field emission theory breakdown voltage for the device was 200V, the researchers believe that the ionized donor concentration is significantly lower than the silicon concentration. Toru Kinoshita of Tokuyama reports that a mid $10^{16}/cm^3$ value for the ionized donor concentration would fit the 550–770V breakdown behavior.

The researchers comment that the large discrepancy between experimental and theoretical breakdown values might be reduced by suppressing the effect of surface damage and by creating better defined Schottky contacts. ■

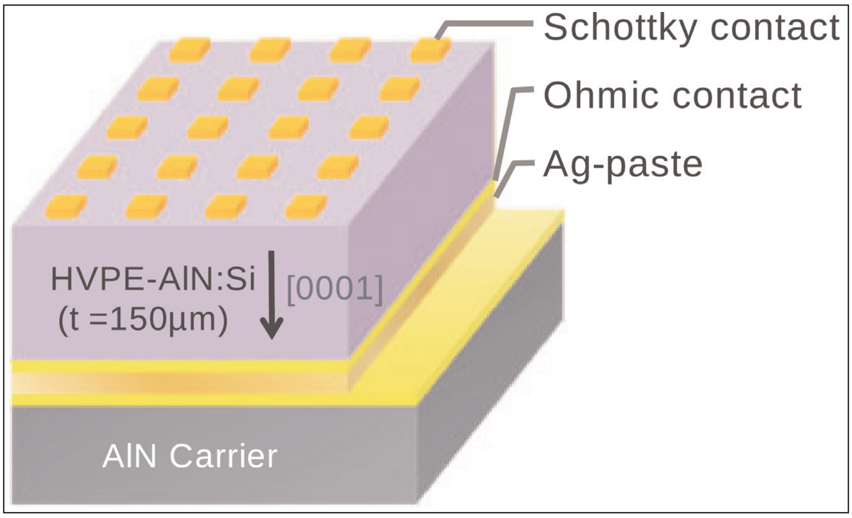

Figure 7. Schematic vertical Schottky barrier diode on HVPE-AlN:Si substrate.

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

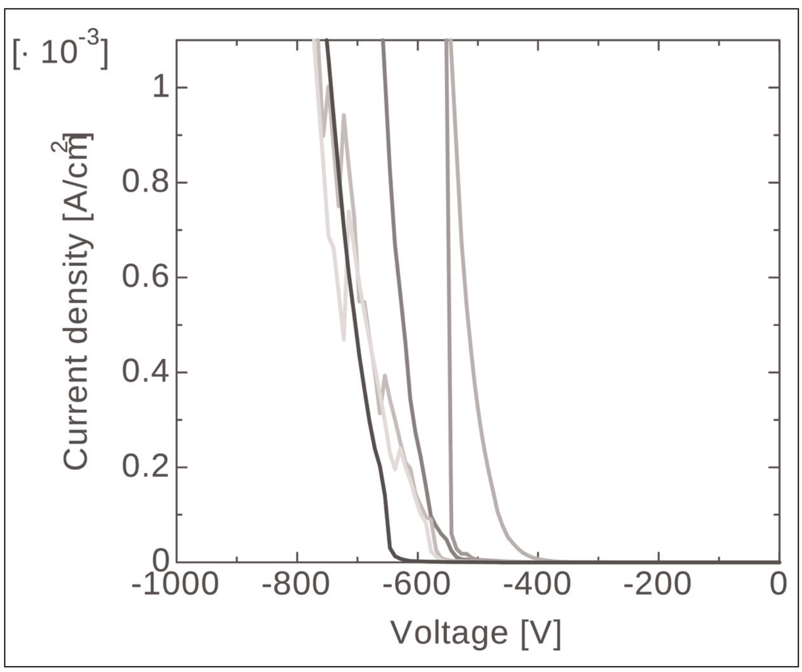

Figure 8. Reverse current–voltage characteristics of vertical Schottky barrier diodes on free-standing n-type HVPE-AlN substrate.