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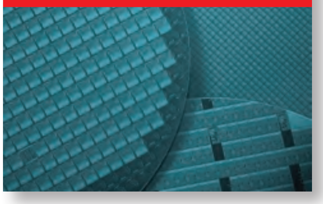

Smart options for the infrared LED

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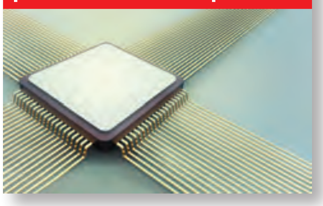

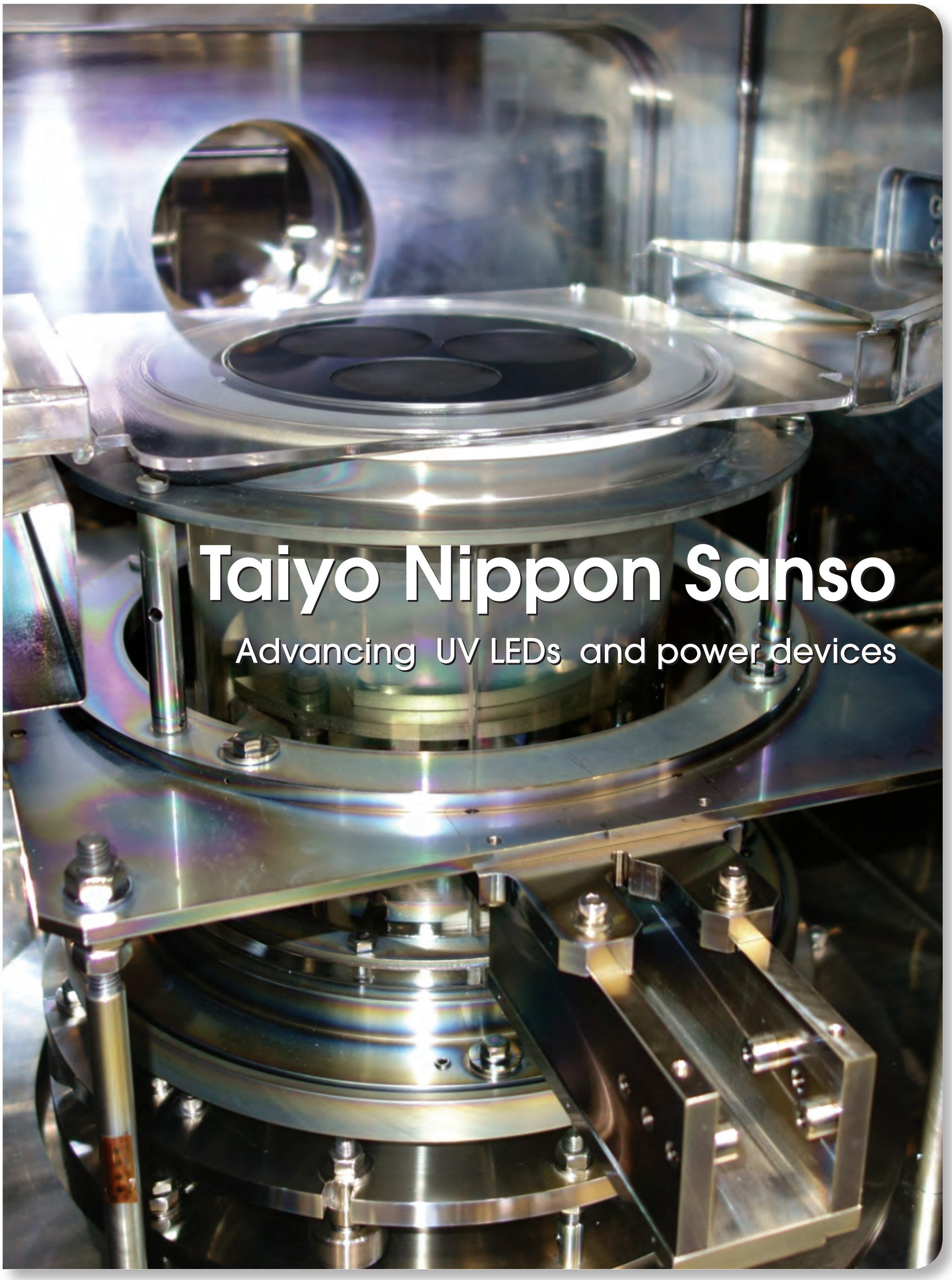

Taiyo Nippon Sanso

Advancing UV LEDs and power devices

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AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

Driving diversification in GaN device production

MOCVD reactors that deliver fast production of aluminium-rich epiwafers with carefully controlled doping profiles can drive a growth in shipments of UV LEDs and vertical power devices

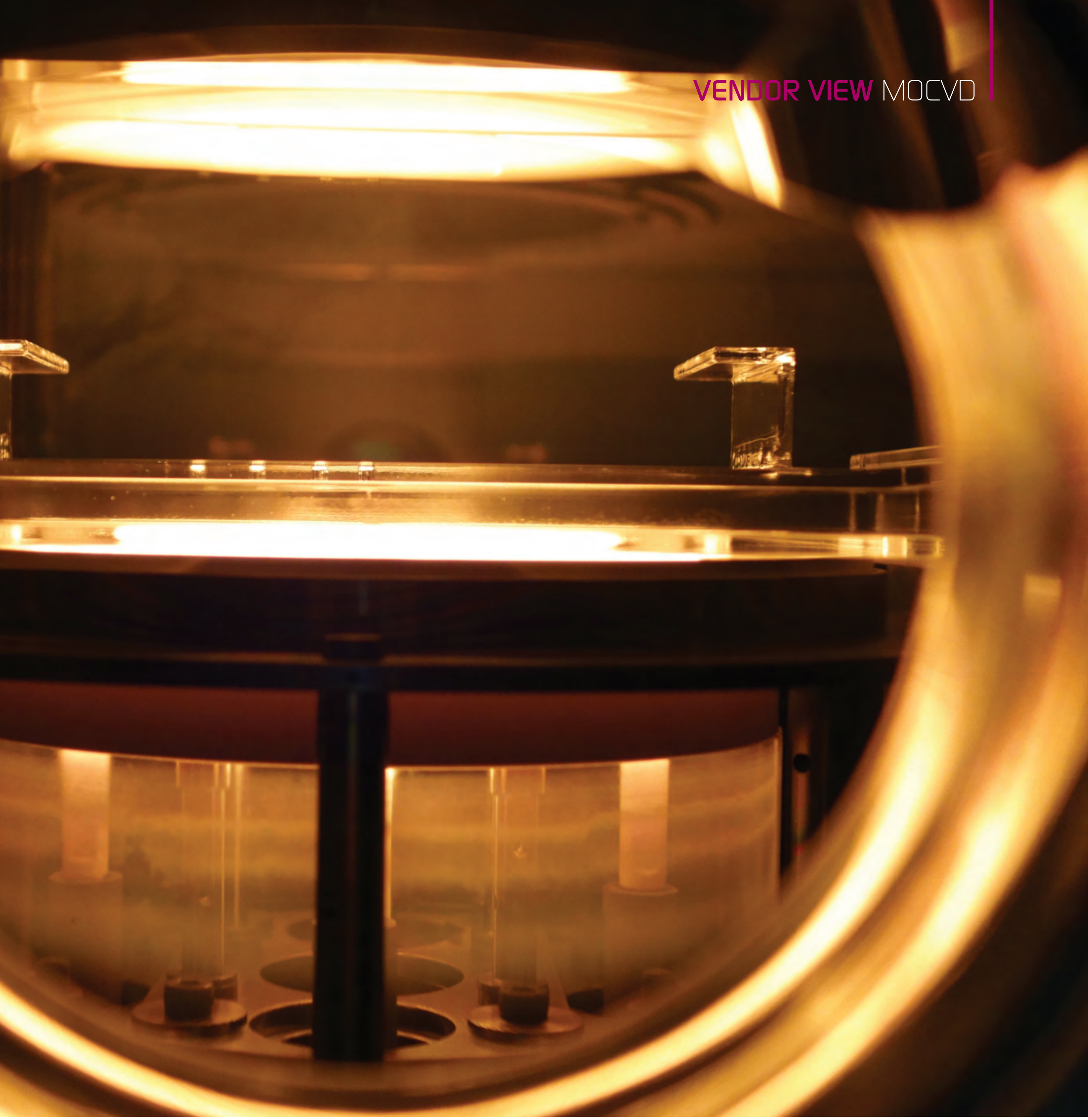
BY KOH MATSUMOTO FROM TAIYO NIPPON SANSO

BY FAR the biggest selling GaN chip of today is the LED. It is backlighting countless screens and fuelling a revolution in efficient, solid-state lighting.

Revenues for GaN LEDs will continue to grow throughout this decade, but could plateau soon after. So, if GaN chip sales are to continue increasing in the long term, the LED will have to be joined by new breeds of device delivering significant commercial success.

Two of the most promising GaN-based candidates are the UV LED and the vertical electron device. The former is an attractive replacement for mercury lamps, and could be used for various applications, including sterilizing viruses, purifying water, optical processing, curing resins, degrading environmental pollutants and preventing hospital infection. There are many good reasons for replacing mercury lamps with UV LEDs, including: increasing the lifetime of the lamp; enabling the introduction of a broader, wavelength-tuneable, more powerful source; boosting wall-plug efficiency; trimming the size of the unit; and reducing environmental impact.

Meanwhile, commercial introduction of competitive, GaN-based power devices could take market share from the incumbent silicon devices, which are held back by a smaller bandgap, a slower electron velocity and a lower breakdown electric field.



THE SR4000HT can reach wafer temperatures of 1300°C or more, thanks to an effective heat shield, a high-power input and an improved inner reactor design.

Many of the researchers that are working with wide bandgap power electronics are developing vertical GaN electron devices that are grown on bulk GaN substrates, because this simplifies wiring and enables the device to be housed in a small package.

To enable UV LEDs and power devices to generate significant and increasing revenues, it is essential for MOCVD tools to provide: control of gas-phase reactions at high aluminium concentrations; control of carbon incorporation; and deposition of high-quality layers at high growth rates. At Taiyo Nippon Sanso of Tokyo, Japan, we satisfy all these requirements with a portfolio of reactors featuring a 'horizontal three-layer' design and growth at atmospheric pressure. Our latest innovation is the introduction of a high temperature element to our GaN MOCVD tools, which have a rich history – the development of the first-generation of these reactors can be traced back to the late 1980s.

One of the biggest challenges with UV LEDs and vertical GaN power devices is the growth of high-quality layers of AlN and high-aluminium-content AlGaN. Particles tend to form, due to a gas phase reaction between trimethylaluminium (TMA), trimethylgallium (TMG), and ammonia. To overcome this issue, a few years ago we introduced a high-flow-rate MOCVD tool, the SR4000, which we described in the March 2014 edition of *Compound Semiconductor*.

Item	Detail
Wafer size	3 2 inch, 1 4 inch
Wafer Temperature	Up to 1300 °C
Growth pressure	From 10 kPa to 100 kPa
Gas flow	Three layered horizontal laminar flow
Safety standard	Correspond to UL regulation
Options	In-situ monitor, gas concentration monitor, etc.

Table I Specification of SR4000HT.

The high-temperature element is present in our recently released SR4000HT, which is capable of reaching wafer temperatures of 1300 °C or more, thanks to an effective heat shield, a high-power input and an improved inner reactor design (see Figure 1 for temperature uniformities on the susceptor surface). Higher temperatures are ideal for forming thick, aluminium-rich layers, which are needed when fabricating UV LEDs and GaN power devices. The latter device can have an epitaxial stack with a thickness of tens of microns, while the high temperatures are beneficial for the baking of the reactor in between growth runs.

Our SR4000HT shares many of the hallmarks of our SR4000, which has proved our most popular machine for R&D and a small-scale production of InGaN-based lasers and GaN-based electron devices (the specification of the SR4000HT is summarised in Table I). The SR4000HT retains the original features of the three-layered gas ejection nozzle, wide controllability from low pressure to atmospheric pressure, and a high-flow-rate of carrier gases. Production capability per run is either three 2-inch wafers, or a single 4-inch wafer.

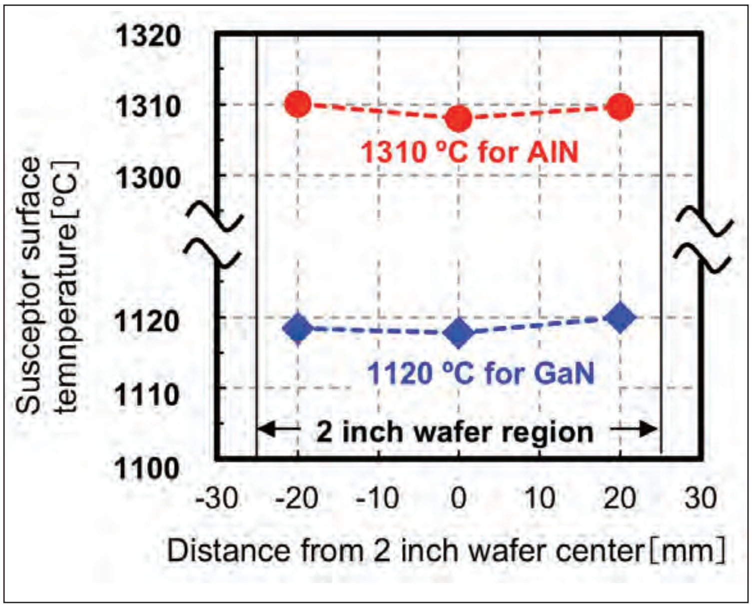


Figure 1. The SR4000HT produces an excellent degree of temperature uniformity across the susceptor surface in the 2-inch wafer region.

Making high-quality UV LED epiwafers

We have demonstrated the capability of our SR4000HT by using it to grow AlN and AlGaN films. Scrutinising the epilayers indicates a very high quality of material produced by our reactor. UV LEDs have an underlying buffer layer of AlN, plus high-aluminium-content AlGaN, so the ideal substrate is bulk AlN. However, the lack of a mature production technique for the growth of this material has led to widespread use of sapphire as a foundation for the UV LED.

Growth of high-quality AlN and AlGaN layers on sapphire demands higher growth temperatures, which enhances the migration of aluminium atoms on the growing surface, but also a parasitic vapor phase reaction. Our SR4000HT meets this need and can realise growth rates of 10.6 µm/h for AlN and 7.2 µm/h for $Al_{0.6}Ga_{0.4}N$ (see Figure 2 for growth rates at various TMA and TMG supply concentrations). The growth rate for AlGaN is almost constant for growth temperatures spanning 1000°C to 1160°C (see Figure 3), indicating that the gas-phase reaction is controlled well.

It is possible to use our SR4000HT to produce AlN template wafers, and to also carry out AlN regrowth on these engineered substrates. We have re-grown 3 µm-thick AlN films on AlN-on-sapphire templates, which were annealed at high temperatures under a mixture of nitrogen and carbon monoxide, and prepared by reserachers at Tohoku University and Mie University. X-ray rocking curve measurements on the template produce a full-width at half-maximum (FWHM) of 64 arcsec for AlN(002) and 191 arcsec for AlN(102). Similar values are obtained for a 3 µm-thick film of AlN deposited on the AlN template wafer – in this case, the FWHM is 49 arcsec for AlN(002), and 214 arcsec for AlN(102). These results indicate that high-quality AlN

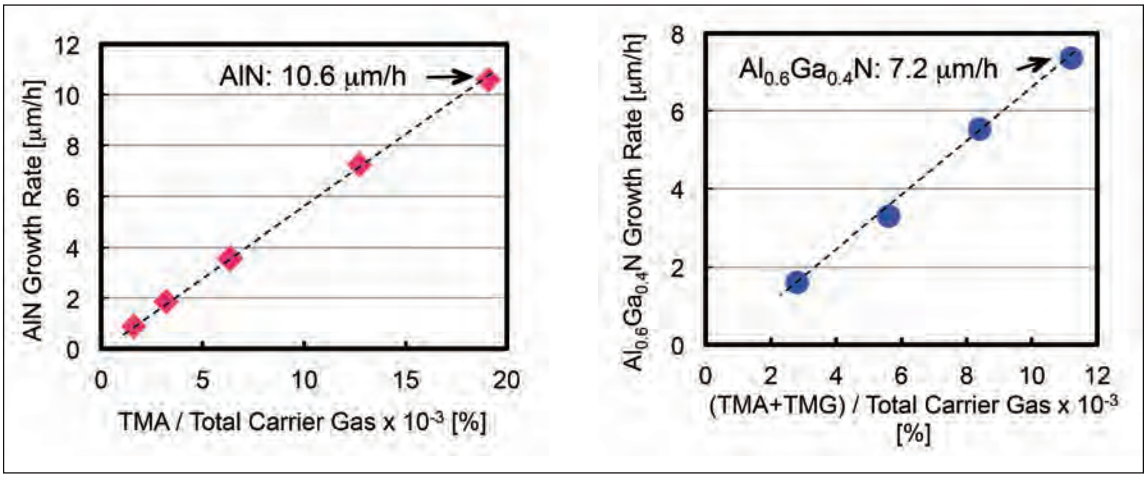


Figure 2. The high growth rates for AlN and $Al_{0.6}Ga_{0.4}N$ enable the relatively quick growth of thick epilayer structures.

with a low dislocation density can be obtained by the combination of these techniques. In addition to the narrow X-ray diffraction FWHM, good quality AlN with an atomic step on the surface was grown at 1300 °C.

Scanning electron microscopy and atomic force microscopy reveal a flat, high-quality surface for the 3 μm-thick AlN layer (see Figure 4). The surface has a root-mean-square roughness of 0.103 nm and features atomic steps, according to atomic force microscopy.

High-performance UV LEDs require *n*-type AlGaN with good electrical characteristics. To grow such a layer, it is essential to reduce impurities that can compensate for donors. Cutting out carbon is crucial, as it can be incorporated on nitrogen sites within GaN, where it acts as a deep acceptor. We have found that the carbon concentration can be reduced from 5.4×10^{18} cm^{-3} to 2×10^{17} cm^{-3}, even for growth rates as high as 7.2 μm/h. This result underlines the capability of the SR4000HT for producing UV LEDs (see Figure 5).

Further proof of the capability of our tool has come

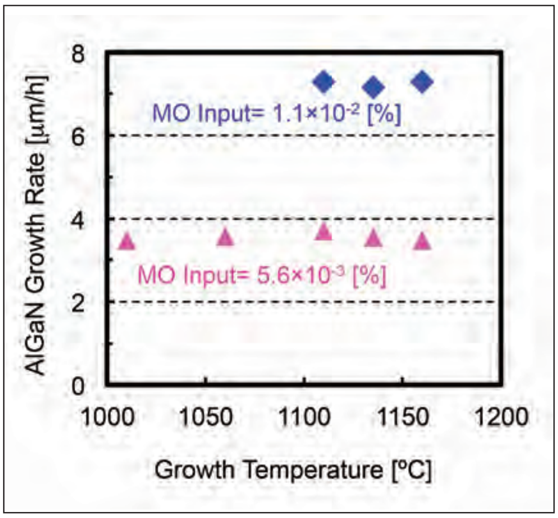


Figure 3. MOCVD process engineers will benefit from an AlGaN growth rate that produces very little variation with growth temperature.

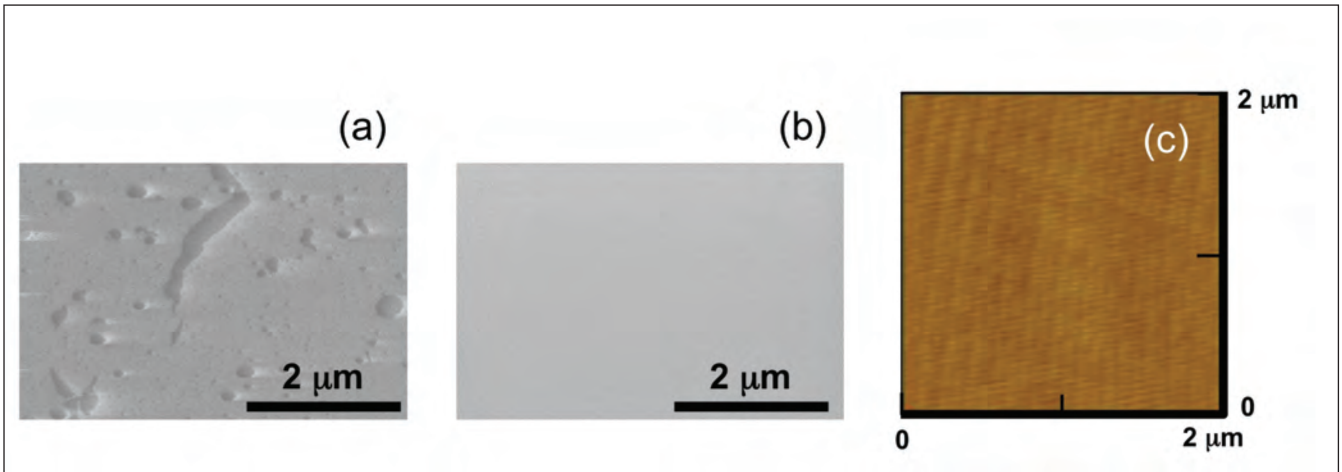
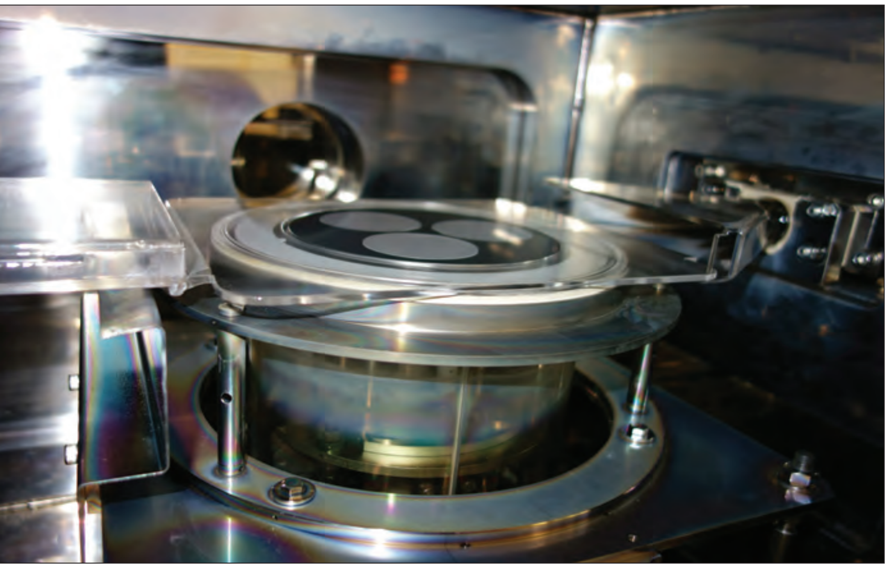


Figure 4. (a) SEM image of AlN template surface annealed at a high temperature after MOCVD growth. SEM (b) and AFM (c) images of an AlN surface re-grown on the template shown in Figure 4 (a).



With the SR4000HT, diode structures can be grown in just a few hours, thanks to low carbon concentrations at high growth rates.

from engineers at the Industrial Technology Research Institute in Taiwan. They have used our SR4000 to produce a UV LED. The electroluminescence spectrum for this device has a peak intensity at 284 nm, a full-width at half maximum of 15 nm, and a very small deep-level-luminescence (see Figure 6).

Improving diode doping

The other leading candidate for driving up GaN chip sales, the vertical electron device, has a superior efficiency over the silicon incumbent, due to a lower on-resistance. Minimising this on-resistance requires careful control of dopant concentration and minimising impurities. Another challenge for MOCVD process engineers is to produce epiwafers using high growth rates, to reduce the time taken to grow the thick layers that are needed for a high breakdown voltage.

Our reactors are ideal for growing power devices, because they accommodate a tremendously wide range of growth pressures, growth rates and V/III ratios. This flexibility equips our tool with impurity controllability at a high growth rate. In the remainder of this feature, we detail the reactor's capability to control carbon and silicon impurities, and dopant concentration, in the growth of a GaN *p-n* diode on a native substrate.

We have investigated the growth of the bipolar *p-n* diode, rather than the mono-polar Schottky barrier diode, because it has a smaller on-resistance. The carrier concentration in the silicon-doped, *n*-type layer of this bipolar device must be controlled over the range 10^{15} cm^{-3} to 10^{19} cm^{-3}, while the carbon concentration is maintained to no more than 1×10^{16} cm^{-3}. For the lower end of *n*-type carrier concentrations, silane must be supplied at a very low flow rate and carbon impurities must be very low. Meeting these requirements depends on the reactor design and growth techniques.

Conventional reactors are often unsuitable for the growth of diodes, because they have a low growth rate for *n*-type GaN that leads to total growth times of several tens of hours or more. With our reactors, however, epiwafer growth can be completed in just a few hours, thanks to the low carbon concentrations at high growth rates (see Figure 7).

At a growth rate of 2.3 μm/h under atmospheric pressure, the carbon concentration can be as low as 3.7×10^{15} cm^{-3}. Lower carbon concentration at high growth rates can be obtained at atmospheric pressure. The far higher carbon concentrations at high growth rates can be also be beneficial in some structures, such as GaN-on-silicon devices, because they introduce high resistivity.

We have used our reactor to produce vertical GaN electron devices with an architecture that has been pioneered by researchers at Cornell University and Hosei University (see Figure 8). Growth rates of

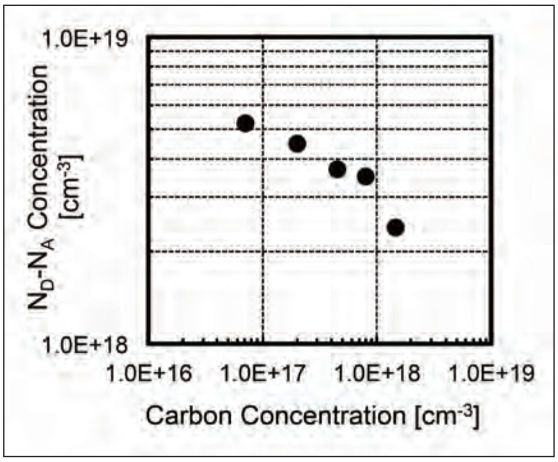


Figure 5. *n*-type $Al_{0.6}Ga_{0.4}N$ with low carbon concentrations are possible, even at growth rates of 7.2 μm/h.

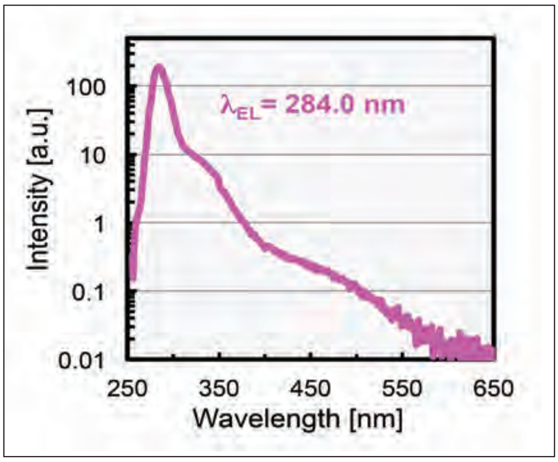


Figure 6. The sharp electro-luminescence spectrum highlights the capability of the SR4000HT for the growth of UV LEDs.

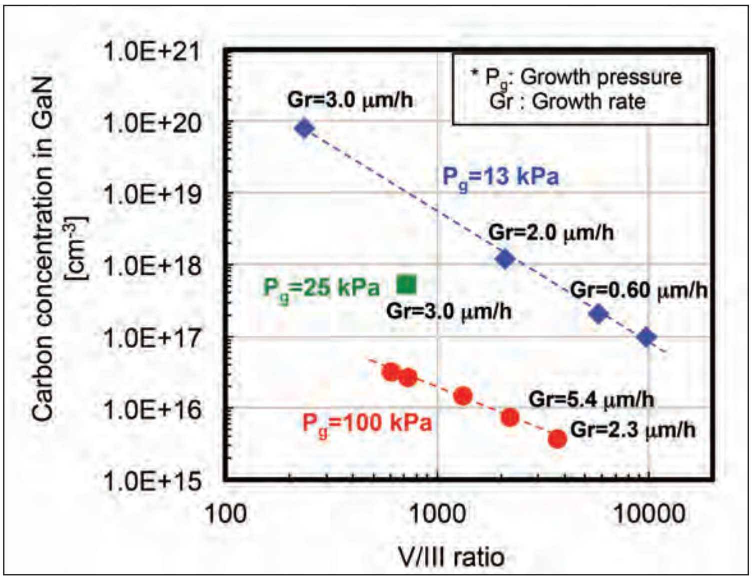


Figure 7. Even at high growth rates, the carbon concentration can be adjusted in the range 10^{15} cm^{-3} to 10^{20} cm^{-3} by appropriate selection of the V/III ratio and growth pressure.

2.3 µm/h for the undoped GaN and 5.4 µm/h for the *n*-type GaN have been used to produce *p-n* diodes on a GaN substrate. These devices have been scrutinised by secondary ion mass spectrometry (see Figure 9). This technique reveals low values for carbon and silicon concentrations in the undoped GaN, and accurate doping of these elements in the *p*-type layers. Note that it took less than four hours to grow the 20 µm-thick *n*-type GaN drift layer.

Our diodes are currently undergoing electrical characterisation. We anticipate that these results will support our case for the suitability of our reactors for growing GaN diodes. And as we have shown earlier, their high-temperature capability makes them a great choice for producing UV LEDs.

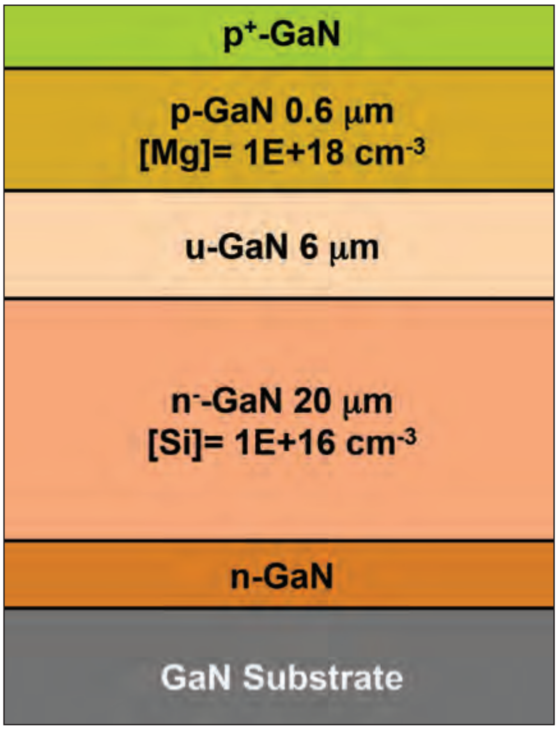


Figure 8. The *p-n* diode structure grown by engineers at Taiyo Nippon Sanso.

Further reading
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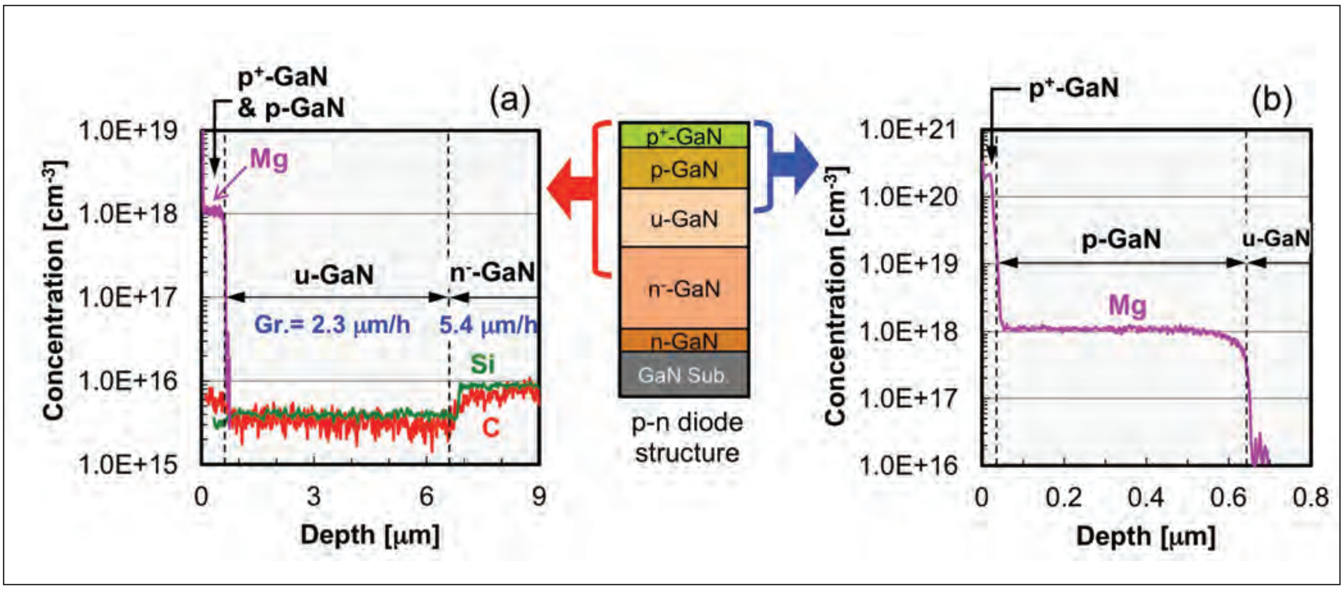

Figure 9. SIMS profiles highlight the capability of the SR4000 tool to realise material with low levels of impurities and carefully controlled doping. (a) SIMS profile to a depth of 9 µm (b) SIMS profile to a depth of 0.8 µm. The detection limits are as follows: 6 x 10^{14} cm^{-3} for carbon, 2 x 10^{15} cm^{-3} for silicon, and 1 x 10^{16} cm^{-3} for magnesium.