

Left: The UR26K can accommodate ten 6-inch wafers or six 8-inch wafers

Developers and manufacturers of all of these devices are working with different types of substrate for chip production. Sapphire is the most common platform for the LED, but savings are promised by switching to large area silicon substrates that enable chip processing in under-utilised, depreciated silicon fabs. Silicon substrates are also popular within the III-N power electronics industry, but in both this sector and in that of the LED, if native, low-cost substrate were available, they would be widely used. In fact, a small proportion of the world's LEDs are already being manufactured on GaN, while some groups pioneering ultraviolet LEDs are using AlN substrates for device development.

However, regardless of the substrate employed for making their nitride-based devices, engineers are searching for excellence from their MOCVD tools in three areas: control of the gas-phase reaction for high aluminium concentration and high growth rate; control of carbon doping, from low to high doping densities; 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 MOCVD reactors featuring a 'horizontal three-layer' design and growth at atmospheric pressure. Our smaller tools have an enviable reputation with the R&D community, and our large-scale production machines share the same design philosophy, making it easy to transfer recipes from one type of machine to the other.

Although many know of us through our supply of industrial gases – this activity dates back to the founding of our company in 1910 – we have a strong track record in MOCVD, with efforts commencing in 1983. We initially launched systems for the growth of materials based on the InP and GaAs families of materials. However, by the late 1980s, we started to develop our range of GaN MOCVD systems. They now meet the needs of every customer, from those wanting to carry out research on a single-wafer 2-inch system, to those requiring a large-scale machine for volume production that is capable of accommodating up to six 8-inch wafers or ten 6-inch wafers (see Table 1).

The majority of GaN MOCVD reactors employ either a vertical or a horizontal gas flow. Our reactors adopt the latter approach, with precursors supplied from a nozzle upstream of the substrate holder, which is a part of the machine that is also referred to as the susceptor. Materials are consumed along the direction of gas flow, so rotation of the wafers is required to ensure a uniform thickness of film growth. In a single-wafer tool the wafer is rotated about its centre. Meanwhile, in multi-wafer reactor, planetary motion is used, with accurate control resulting from a carefully chosen gear and ball bearing system. One distinctive feature of our reactors is their three-layered gas ejection nozzle. Materials are injected into the reactor via high flow speeds through this nozzle, to enable good control of organometallics and ammonia, and ultimately the deposition of high-quality GaN, AlN, and AlGaIn at high growth rates.

Faster, better III-N film growth

MOCVD reactors equipped with three-layer nozzles and operating at atmospheric pressure can produce growth rates and doping ranges that manufacturers of GaN power electronics and ultraviolet LEDs are looking for.

By KOH MATSUMOTO FROM TAIYO NIPPON SAN SO

THE III-N CHIP generates billions of dollars every year, with revenues continuing to grow. Sales in this sector are currently dominated by InGaN-based LEDs, which are backlighting many screens and driving a revolution in LED lighting. But other significant markets are emerging: ultraviolet LEDs, which are attractive replacements for mercury lamps, thanks to superior robustness, longer lifetime and portability; and power electronics based on GaN that offers a step up in efficiency compared to silicon incumbents.

GaAs, InP		
Model	Type	Wafer
HR-3000	Horizontal / Face up	3" x 1
HR-4000	Horizontal / Face up	2" x 3
HR-6000	Horizontal / Face down	2" x 6 or 3" x 3
HR-8000	Horizontal / Face down	3" x 6 or 2" x 18 or 4" x 4
HR-10000	Horizontal / Face down	4" x 5 or 3" x 10

GaN		
Model	Type	Wafer
SR2000	Horizontal / Face up	2" x 1
SR4000	Horizontal / Face up	2" x 3 or 4" x 1
SR6000	Horizontal / Face up	2" x 6 or 3" x 3 or 6" x 1
UR25K	Planetary / Face up	4" x 11 or 6" x 7
UR26K	Planetary / Face up	6" x 10 or 8" x 6

Table 1: Taiyo Nippon Sanso produces a wide range of MOCVD tools that meet the needs of R&D groups and high-volume manufacturers of compound semiconductor chips

In our small-scale machines, the nozzle is positioned in the upper-flow section of the susceptor, but in large-scale mass production systems, it is located in the centre of the susceptor, so that gas spreads out from there. A resistance heater raises the temperature of the substrates to that required for growth. The heating system is zone-controlled to realise the optimum temperature distribution on the susceptor. The number of zones varies with the size of the reactor, from just one for the smallest R&D tool to six for our biggest mass-production machine.

Another feature of our systems is continuously controllable pressure, which can be varied from 10 KPa to 100 KPa. Thanks to well-controlled gas phase reactions, adjustments in pressure can tune the material properties, which depend on growth pressure.

Quartz is used for the flow channel components. One merit of quartz is that it is easy to clean – and that is a big advantage for growth of GaN on silicon, because component cleanliness is critical for reproducible growth. Note that mass production machines are equipped with an automated component exchange robot, making it relatively easy to carry out maintenance on the tool.

Higher growth rates

The capability of our reactors is highlighted by the high quality of various epiwafers produced by them. This includes electronic devices based on AlGaIn and GaN that can be formed by high-speed growth and feature a very wide range of carbon doping levels; high-voltage GaN-on-GaN diodes with well-controlled, shallow silicon doping levels; and AlGaIn films with a high aluminium content, which can be used for producing ultraviolet LEDs.

Growth of high-quality, wide-bandgap electronic structures on silicon demands a multi-layer buffer structure incorporating GaN, AlN and AlGaIn. And if a HEMT is to offer high-voltage power-switching, this buffer must be thick enough to enable a high breakdown voltage.

One downside of any thick layer is that it adds to growth times and thus reduces the number of epiwafers that can be



The Taiyo Nippon Sanso UR26K is the company's biggest MOCVD reactor

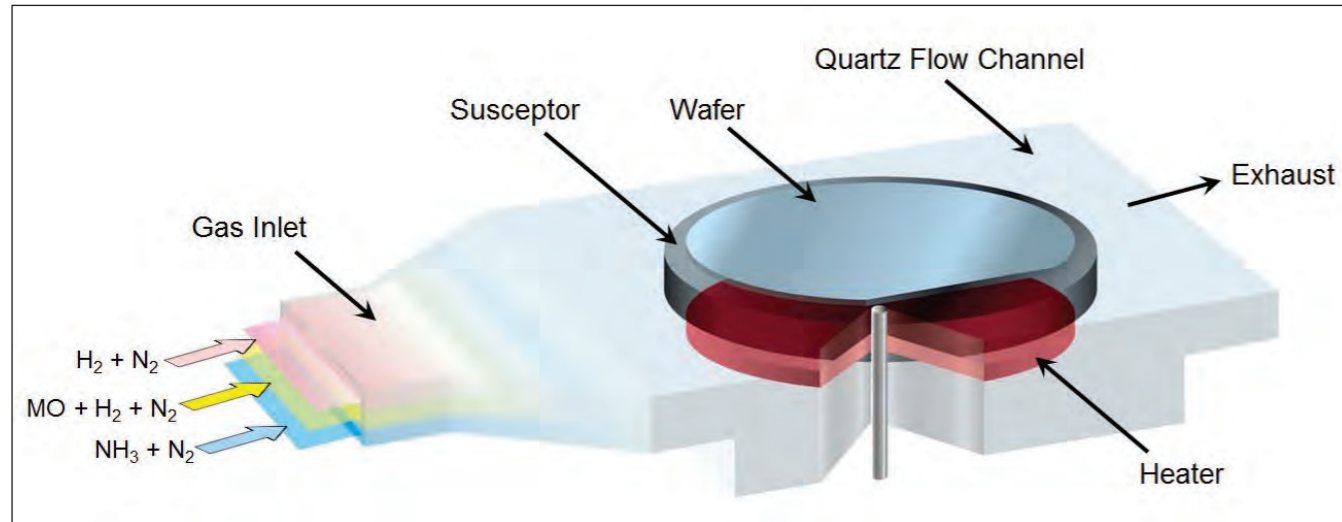


Figure 1: Process gases enter the horizontal flow reactor through a three-layered gas-injection nozzle

produced per day from an MOCVD system. With a conventional reactor, the growth rate for the buffer is limited to 1 - 3 $\mu\text{m/h}$ due to parasitic reactions.

However, with our systems, far faster growth rates are possible, thanks to the combination of a laminar high flow velocity and a specially designed three-layer-flow, gas-injection nozzle. Equipped with these attributes, engineers using our tools have a better control over vapour phase reactions and can realise shorter process cycle times.

Growth rates for III-Ns depend on the constituents, with maximum values of 27 $\mu\text{m/h}$, 3.8 $\mu\text{m/h}$, and 11.4 $\mu\text{m/h}$ for GaN, AlN and AlGaIn, respectively (see figure 2). Employing a very high growth rate, we have deposited a 3 μm -thick HEMT test structure on 6-inch silicon, using a growth rate of 8.5 $\mu\text{m/h}$ for the AlGaIn/AlN strained layer superlattice and 7.5 $\mu\text{m/h}$ for GaN. The net time for film growth, which excludes temperature ramping and reactor purging, is only 41 minutes, compared to 88 minutes for our standard growth time.

This trimming of the growth time by just over 50 percent did not lead to a significant deterioration in electrical properties. According to Van der Pauw measurements, in the high-growth-rate epiwafer the typical electron mobility was $1530 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at a sheet carrier density of $8.9 \times 10^{12} \text{ cm}^{-2}$. It is possible that further optimisation of the growth process could enable even shorter growth times, and thus deliver an additional hike in the productivity of III-N wafers for electronic applications.

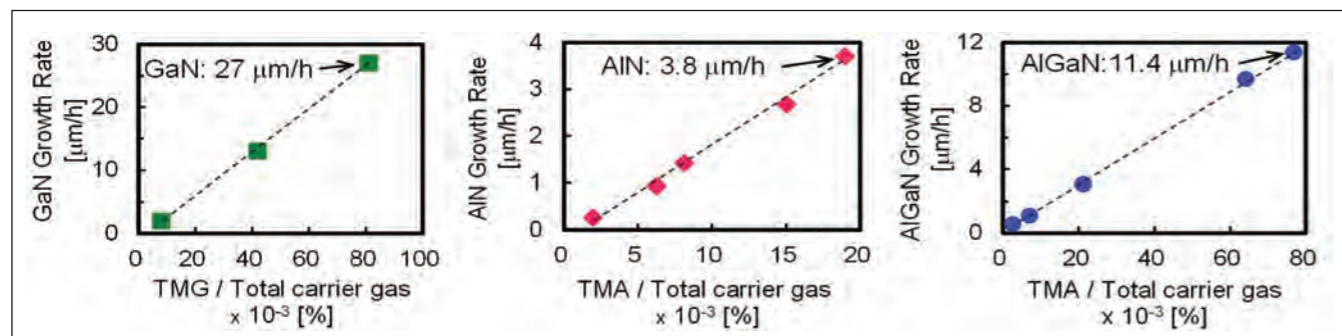


Figure 2: Growth rates for III-N binary and ternary films deposited in a Taiyo Nippon Sanso reactor

Superior doping control

For a power switching device, the usual approach is to heavily dope the GaN buffer layer with carbon so that it is highly resistive, while employing a pure (undoped) GaN layer for the channel. Research groups have shown that increasing carbon concentration boosts breakdown voltage, while increasing growth pressure cuts yellow luminescence in GaN and suggests suppression of current collapse.

With conventional reactors, the range of carbon concentrations at a given growth rate is held back by the limited range of V/III ratios and growth pressure. It is possible to deposit GaN layers with very low carbon concentrations, but this requires low growth rates, and that leads to long growth times. In stark contrast, with our tools the range of V/III ratios and growth pressures that can be used is far wider, and this allows engineers to obtain the carbon concentration they wish at a high GaN growth rate. For example, it is possible to produce GaN films at carbon concentrations from 10^{16} cm^{-3} to 10^{20} cm^{-3} with growth rates in excess of 3 $\mu\text{m/h}$ (see Figure 3).

An alternative, attractive architecture for GaN-based electronics is the vertical diode. This device, which offers easy wiring and packaging and high area efficiency, consists of *n*-type and *p*-type GaN layers that are grown on a conductive GaN substrate. Challenges for manufacturing this device include: a reduction in growth time, because the *n*-type GaN needs to be tens of microns thick; and uniform silicon doping of GaN from concentrations of 10^{15} cm^{-3} to 10^{19} cm^{-3} . Producing films with

low doping concentrations is not easy, requiring control of the very diluted SiH_4 gas supply and a low level of carbon impurities, so that it is possible to produce low compensation *n*-type GaN.

Realising GaN films with these attributes requires a suitable reactor design and a good growth process. As previously stated, the growth rate of GaN in a conventional reactor leads to device deposition times that can be 10 hours or more. But with our system, because it is possible to cut carbon concentration via atmospheric pressure growth, *n*-type GaN growth rates can be very high, leading to runs of just several hours for epiwafers production.

The carrier concentration in *n*-type GaN grown on 6-inch sapphire depends on the ratio of SiH_4 to tri-methyl-gallium (see Figure 4). Uniform doping at $5 \times 10^{15} \text{ cm}^{-3}$ is possible under growth rates as high as 3.6 $\mu\text{m/h}$, indicating that our reactor is very suitable for growth of nitride-based vertical diodes.

Ultraviolet LED structures

Essential ingredients for the ultraviolet LED – which can be used for curing, money checking, and air purification – are the growth of AlN and high aluminium composition AlGaIn. These layers are normally deposited on sapphire, and when conventional equipment is used, within-wafer uniformity and crystal quality are hampered by an excessive gas phase reaction. This impacts productivity and yield.

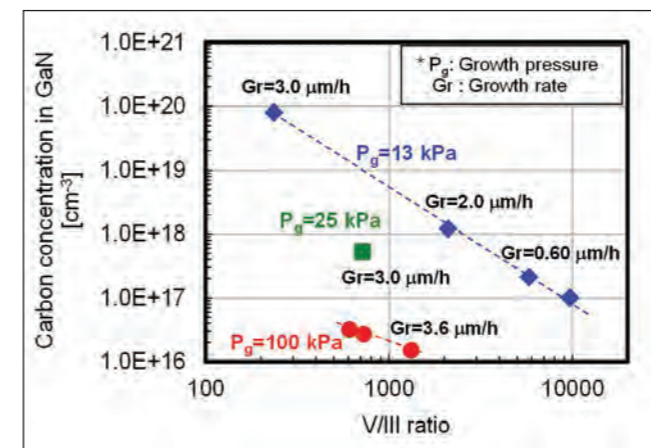


Figure 3: Increasing the growth pressure leads to faster growth rates with a low carbon concentration

However, if engineers use our tool, the parasitic reaction is controlled and high-quality, uniform AlN and AlGaIn films can be grown at high growth rates. For example, it is possible to deposit AlGaIn with an aluminium content of about 60 percent on 4-inch sapphire at 6.4 $\mu\text{m/h}$. Photoluminescence measurements of an InAlGaIn multi-quantum well structure produce intense emission at 330 nm, and a high level of uniformity in the peak emission wavelength across the wafer (see Figure 5). These results demonstrate that our reactors have the capability to increase productivity for manufacturers of ultraviolet LEDs, just like they can do for the makers of electronic devices based on nitride materials.

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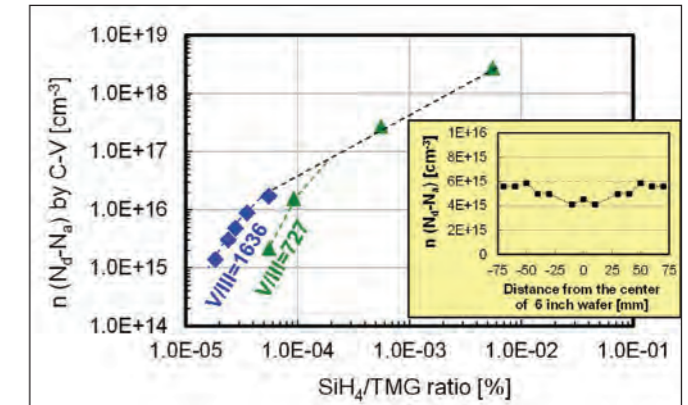


Figure 4: The carrier concentration in *n*-type GaN depends on the ratio of SiH_4 and tri-methyl-gallium and the V/III ratios. The inset reveals the uniformity of doping across a 6-inch epiwafer

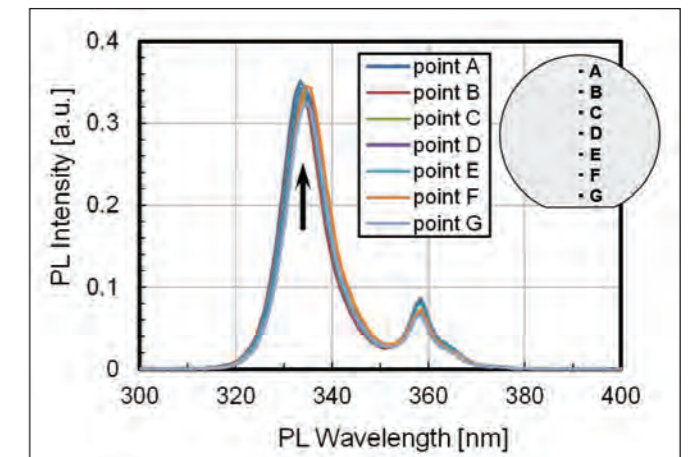


Figure 5: A high level of uniformity of peak emission wavelength indicates the potential of the Taiyo Nippon Sanso reactor for ultraviolet LED production.

Further reading

- K. Matsumoto *et al.* Proc. SPIE. **8262** 826202 (2012)
- H. Tokunaga *et al.* Phys. Stat. Sol. **5** 3017-3019 (2008)
- Y. Yano *et al.* Jpn. J. Appl. Phys. **52** 08JB06 (2013)
- Y. Yano *et al.* Taiyo Nippon Sanso Technical Report **32** 27-28 (2013) (in Japanese).
- S. Kato *et al.* J. Cryst. Growth **298** 831 (2007)
- J. Selvaraj *et al.* Jpn. J. Appl. Phys. **48** 121002 (2009)
- A. Fujioka *et al.* Appl. Phys. Express **3** 041001 (2010)