GaN-on-Si: best solution for efficient energy management

Belgium-based IMEC spin-off EpiGaN sees huge opportunities for GaN-on-silicon power-up. Mike Cooke talked to CEO Marianne Germain.

Nitride semiconductors have been at the center of new light-emitting applications for some 20 years. In recent years, a new application has been coming to the fore — heterostructure field-effect transistors (HFETs), also known as high-electron mobility transistors (HEMTs), which can handle high power density and high frequency at the same time. A further potential advantage is the ability to run at higher temperature, reducing or eliminating the need for special cooling apparatus. Also, such devices should have reduced switching and conduction losses.

Such capabilities have been developed for high-frequency power amplification, as used in mobile network transmissions from base-station connections to the telecom network. Another recent potential application is power-switching/management applications such as solar power inverters (i.e. DC-to-AC conversion), compact and switched-mode power supplies, smart electric power distribution grids that can handle fluctuating renewable resources, switching between internal combustion and electric power in hybrid electric vehicles, and electric motor control drivers. These devices need a range of different voltage ratings, such as 30–600V for IT and consumer power management and 600–1200V for automotive and industrial power-switching applications.

Whether these options will be taken up depends in large part on competing with low-cost silicon devices. EpiGaN believes that the new challenges presented by the need for efficient energy management in power electronics cannot be fulfilled by silicon-only devices and that GaN grown on silicon offers the best solution. Although the GaN-on-Si process uses (111) silicon, rather than the (100) silicon of mainstream CMOS, additional opportunities could come from the integration of silicon and nitride semiconductor components.

While LED opportunities will come, according to EpiGaN's CEO Marianne Germain, the present focus is on the huge opportunities in power electronics. In the LED sector, there are already a lot of players, and much research and development is still needed to put these devices on silicon. By contrast, GaN power electronics is a new opportunity that can be used today.

EpiGaN was spun-out of IMEC last year with a founding executive team — Germain, Joff Derluyn (CTO), and Stefan Degroote (COO) — that has more than 10 years in IMEC researching GaN epi solutions for device applications. This work culminated in demonstrations of pioneering and industry-leading GaN-on-Si wafer size and quality, as reported in several research papers and patents in the field. The €4m capital for the venture came from Capricorn Cleantech Fund, Robert Bosch Venture Capital, and LRM.

A particular advantage of growing nitride semiconductors on silicon wafers is the possibility of fab and equipment reuse — as the mainstream transfers to larger diameters (300mm, and in the future 450mm), older 6″ (150mm) and 8″ (200mm) facilities become available for other work. But even the smaller silicon substrates usually exceed the diameter of alternative GaN substrates.

EpiGaN can supply 4″ and 6″ wafers now, still in sampling quantities. But, moving to a new production facility in Q1 2012, EpiGaN expects to progress into volume capability next year and deliver its first 8″ substrates, also next year.

The company claims state-of-the-art epilayer quality on standard wafers and low leakage, high breakdown voltage for thinner wafers. Although the surface roughness is specified to be less than 5%, in reality it is always less than 3% (Figure 1). Other features of EpiGaN's product include low RF losses and low-dispersion buffer layers. Products can be designed to handle kV potentials and up to 100GHz frequencies. Nitride layers on silicon carbide substrates are also on offer.

Germain believes that the most important route to process development and optimization is through looking at device results and not just material characterization: dynamic characteristics of these devices intended to operate in switching mode is the key feature. EpiGaN offers such customer support and development of substrates. After all, device performance is the final aim of the work.

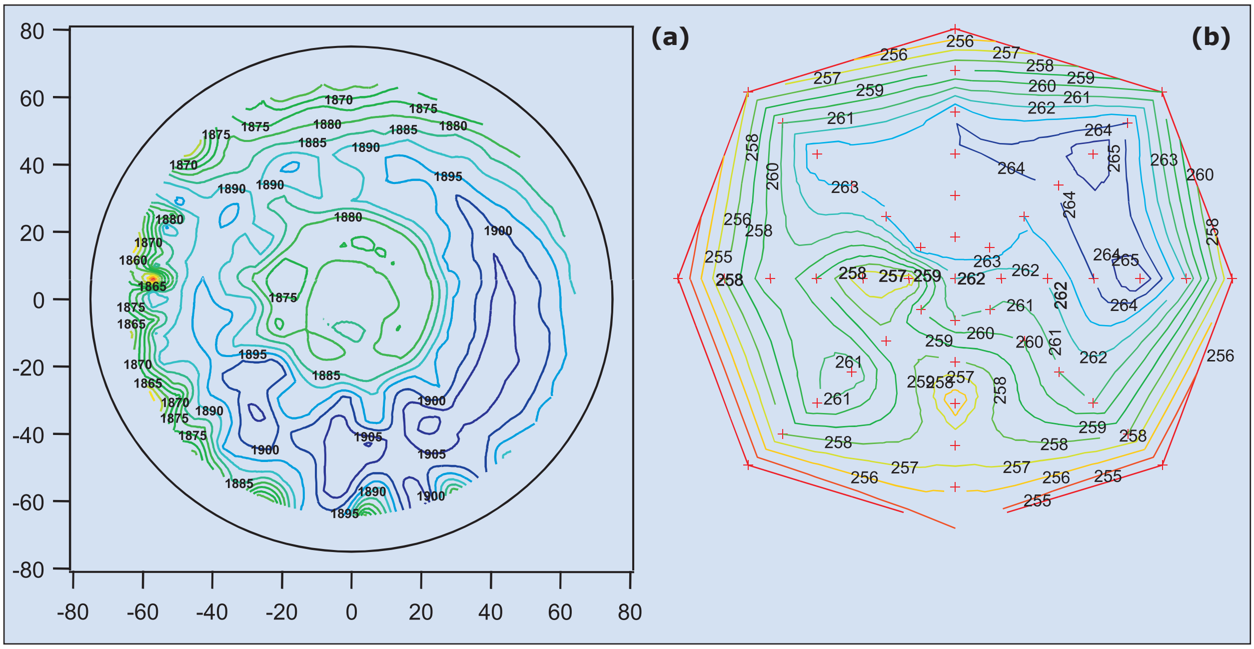

Figure 1. Thickness uniformity mappings for (a) GaN HFET and (b) AlGaN/GaN HEMT epitaxial layers on 150mm (111)Si. The variation in thickness was 0.6% for (a) and 1.3% for (b).

In-situ surface passivation

In the work at IMEC, after having solved the impact of traps in the buffer on device operation, it was found that surface traps were also degrading performance, so in-situ silicon nitride passivation was developed (Figure 2). This 'in situ grown' layer of silicon nitride (SiN) is one of the technologies that EpiGaN licenses from IMEC. The in-situ SiN layer is grown as part of the nitride metal-organic chemical vapor deposition (MOCVD) epitaxy process, rather than separately. The deposition of SiN is usually carried out with plasma-enhanced CVD (PECVD), rather than MOCVD. EpiGaN's in-situ SiN further enhances the robustness of the devices and plays a key role for enhancing device reliability.

In December 2009, IMEC reported on the use of the in-situ SiN technology for making enhancement-mode devices at the International Electron Devices Meeting (IEDM) [Derluyn et al, IEDM 2009, session 7.4; reported Semiconductor Today, p71, March 2010]. In the 2009 research, the SiN layer was used to neutralize a thin AlGaN top barrier surface charge so that it no longer contributed to the depletion of the two-dimensional electron gas (2DEG) conducting layer. This enabled the creation of enhancement-mode (normally-off) GaN double-heterostructure field-effect transistors (DHFETs) on 4-inch (~100mm) silicon substrates.

The importance of enhancement-mode devices is that the current is 'normally-off' and needs a gate potential to flow. Although circuits can be designed to use depletion-mode normally-on devices, normally-off behavior is preferred for power devices that usually need to have fail-safe operation.

Enhanced breakdown

With enhancement or depletion mode devices, the breakdown voltage is primarily determined by the quality and design of the wafer epitaxy. EpiGaN has demonstrated up to kV-capable material. Leakage current at 600V is below 500nA/mm. The breakdown behavior for enhancement-mode devices is consistent with that obtained with depletion-mode DHFETs. This breakdown is explained as being due firstly to breakdown in the top part of the device structure for small gate–drain gaps, but for larger gate–drain distances as being due to vertical conduction down to the silicon substrate. Extended gate–drain distances are used to reduce electric fields in high-voltage devices.

Since that work, EpiGaN has supplied material to different customers and R&D institutes, including

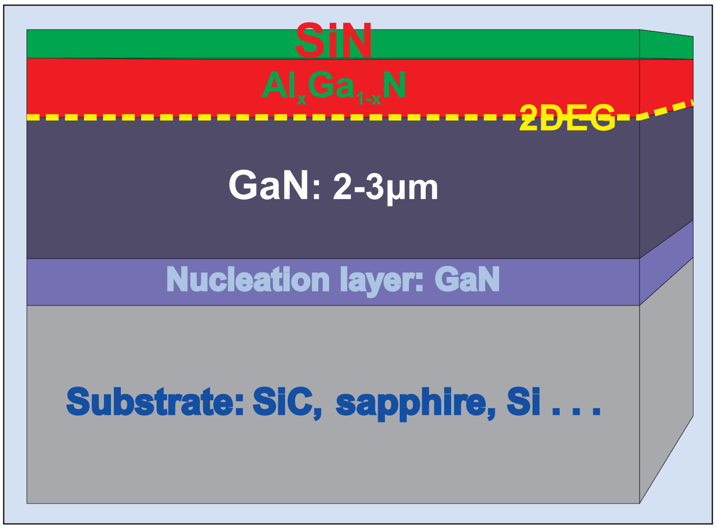

Figure 2. Schematic of in-situ growth of SiN passivation on AlGaN/GaN HEMT epitaxial structure.

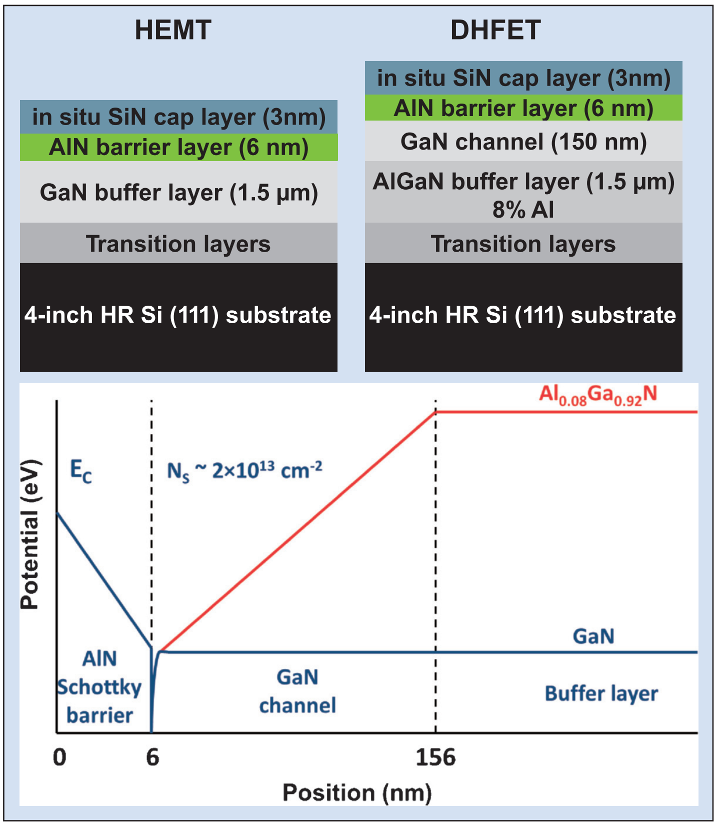

Figure 3. Cross section of fabricated AlN/GaN-on-Si HEMTs (top left) and DHFETs (top right) and schematic of conduction-band diagram of the HEMT and DHFET.

France's Institute of Electronic, Microelectronic and Nanotechnology (IEMN) where the researchers used AlN as the barrier material instead of AlGaN [Farid Medjdoub et al, Appl. Phys. Express, vol4, p064106, 2011; reported Semiconductor Today, p110, June/July 2011]. This allowed the creation of a higher-carrier-density two-dimensional electron gas (2DEG) channel near the barrier–buffer interface, giving drain currents of more than 2A/mm and a record transconductance of 600mS/mm. Farid Medjdoub, the lead author of this work at IEMN, previously worked with the EpiGaN management team at IMEC and is among the authors listed in the IEDM 2009 paper referred to above.

More recently, IEMN has produced devices with back-barriers (Figure 3) to improve RF performance, using material supplied by EpiGaN [Farid Medjdoub et al, Appl. Phys. Express, vol4, p124101, 2011]. The back-barrier overcomes a previous limitation of the drain potential to less than 20V by improving confinement in the channel and thus cutting off a leakage path through the buffer layer. These new IEMN devices achieve a current density of almost 2A/mm together with high-voltage operation at potentials of more than 50V. The gate–drain distance in these devices is 1µm.

"The gate length scaling down to sub-100 nm in the AlN/GaN-on-Si DHFET should undoubtedly open the way for cost-effective millimeter-wave high-power/high-linearity device applications," says IEMN.

Another recent research announcement that includes EpiGaN is the new European Union HiPoSwitch project, targeting more compact and more powerful energy converters for information and communication technology and solar inverters. The leader of this work is the Ferdinand-Braun-Institut, with industrial support from EpiGaN, Aixtron, Artesyn and Infineon. The Slovak Academy of Sciences (Slovenskej akadémii vied), Vienna University of Technology (Technische Universität Wien) and University of Padua (Università degli Studi di Padova) are also involved on the academic side. ■

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Other developments in GaN-on-silicon

A number of other firms are looking to produce nitride-on-silicon substrates, for sale or in-house devices.

Kyma in the USA is expanding its nitride-on-silicon substrate product line with diameters up to 150mm (AlN/Si). Demonstrations have been made for 200mm and 300mm diameters. Kyma uses patented plasma vapor deposition of nanocolumns (PVDNC) and hydride vapor phase epitaxy (HVPE) processes to produce AlN and GaN layers, respectively. GaN-on-Si diameters up to 100mm are available now. The GaN-on-Si is available in semi-insulating form, as is needed for high-frequency FETs. The AlN/Si could be used as an alternative to sapphire for LED production.

Another US company producing GaN-on-Si substrates is Translucent. The company uses a layer of rare earth oxide to bridge the gap in lattice properties between silicon and GaN, targeting products for LED and FET manufacturing. The company also has products available at 100mm and is due to have 150mm and 200mm wafers available next year.

Azzurro in Germany has been offering 150mm GaN-on-Si substrates since 2005 for LEDs and power electronics. The company has plans to offer 200mm GaN-on-Si for LEDs in the near future. It has a new production facility in Dresden due to come online.

Companies producing and developing GaN-on-Si substrates and devices include Nitronex, International Rectifier, startup company EPC, NEC in Japan, and Brigdgelux for LEDs. University of California Santa Barbara spin-off Transphorm (which develops GaN devices for power conversion) has ordered in Aixtron GaN-on-Si tools. LG Electronics in Korea is looking to GaN-on-Si for power electronic devices, aimed at home appliances and electric vehicles.