GaN – A truly revolutionary semiconductor technology matures

Chief marketing officer Dr Markus Behet and chief technology officer Dr Joff Derluyn of epiwafer supplier EpiGaN discuss the benefits of GaN-on-silicon technology for RF power and power switching applications.

The power management and RF market will experience a major technology transformation in the coming years that will impact the semiconductor industry in a profound way. The benefits of gallium nitride (GaN) as a wide-bandgap semiconductor in power switching, RF power, and sensor applications are evident, and mainstream commercial applications will increasingly start to adopt this revolutionary technology.

A retrospective view

For the past few decades, silicon- and gallium arsenide (GaAs)-based technologies, devices and integrated circuits have paved the way for many power electronic innovations such as 3G, 4G-LTE wireless systems or power switching topologies in converter and inverter systems. Products enabled by these semiconductor technologies such as smartphones, computer power supplies, photovoltaic inverters, variable-speed motor drives — to name just a few — became commercial reality and are taken for granted in our daily lives.

These commercial applications were fuelled by generations of GaAs HEMTs, HBTs and silicon MOSFETs and IGBTs with ever increasing performance characteristics. However, improvements are nowadays only happening in incremental steps, as these incumbent semiconductor technologies are approaching their theoretical limits. Squeezing out an additional dB or Ohm of performance for power devices and systems requires a huge effort by design engineers at continuously increasing development cost.

Technology stagnation is not an option for a modern society. In that sense, Moore's Law of increasing the computing power at an exponential pace has set the pace of innovation and provided guidance for the semiconductor industry for several decades. However, Moore's Law seems to be running out of steam because shrinking traditional silicon transistors below the 10nm node is hitting physical and economical limits. Also, in other application fields (such as power switching) silicon technology has hit the hard wall of its fundamental limitations. Here, III–V semiconductors and especially wide-bandgap GaN-on-Si technology come to the rescue. For the first time a new semiconductor technology combines the capability to significantly outperform the incumbent silicon and GaAs technologies in power switching, RF power and sensors applications while leveraging Si-based economies of scale manufacturing to exploit economic gains. The good news is that next-generation III–V technologies like GaN combined with higher functional integration and new transistor design concepts will help Moore's Law to survive through functional diversification.

GaN promises a bright future

Even if a disruptive technology like GaN offers a very appealing value proposition, it is unfortunately not adopted overnight. Past market studies have proven to be much too optimistic regarding the rate of adoption of GaN technology. The existing market value chains are very complex and many stakeholders at different steps in the value chain need to be convinced before a switch to a new technology is initiated. In addition, unmet needs of end users differ significantly per market application with regard to performance, cost, ease of use or reliability for new technologies.

Nevertheless, the number of applications demonstrating superior performance enabled by GaN technology has increased exponentially in the past years. The initial development focus was on transistors for 600V power-switching applications and lower-voltage, low-loss DC–DC converters. Recently, high-resolution LiDAR, wireless charging, ET (envelope tracking) for 4G-LT, medical or high-radiation applications have appeared and demonstrated the added value from the ultra-fast switching capabilities of GaN HEMTs.

Another big development focus is RF systems for the future 5G wireless communication standard. GaN RF power amplifiers have already demonstrated their capability to boost RF performance significantly compared with incumbent GaAs or LDMOS technologies while also reducing size, weight and power consumption of the overall system. The high breakdown voltage, gain and efficiency at millimetre-wave (mmW) frequencies — combined with a 8–10x higher power density — makes GaN an ideal choice for RF systems. Of all RF power semiconductor technologies, GaN offers the highest output power up to 100GHz. Moreover, GaN RF transistors have a high output impedance, resulting in very good linearity performance and the widest bandwidth, enabling RF amplifiers to support multiple protocols. Additionally, GaN can operate at higher device operating temperatures, which in turn decreases cooling requirements and maintenance costs as well as improving reliability. Two flavours of RF GaN power technologies exist today: GaN-on-SiC for specialized highest-performance applications and GaN-on-Si for cost-sensitive volume applications. With the latest technology improvements for GaN-on-Si, the performance gap for these two technologies for RF power seems to disappear.

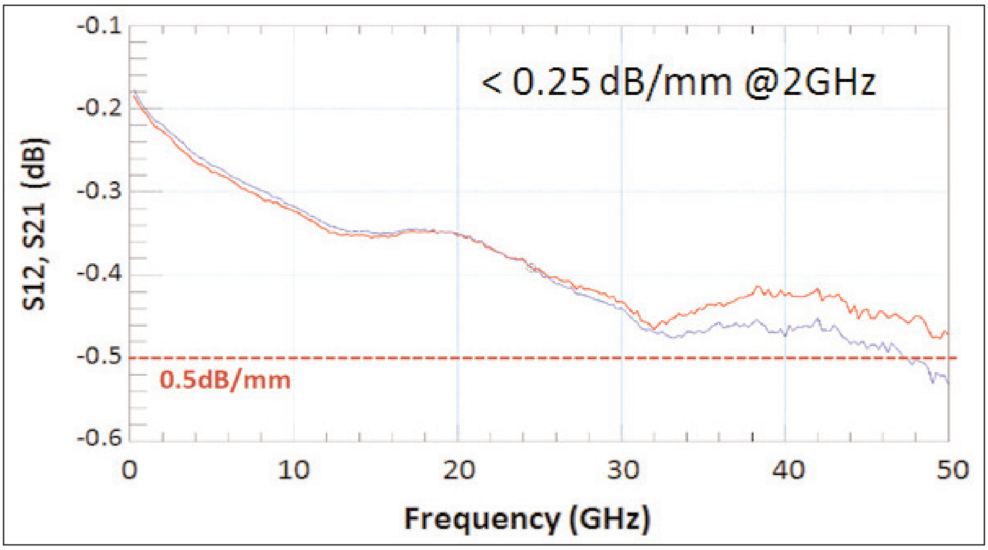

Figure 1: RF losses in dB/mm measured on transmission line structures of an optimized RF GaN-on-Si HEMT structure (courtesy of F Medjdoub, IEMN, Lille, France).

Last but not least, GaN-on-Si technology has begun to attract significant attention for gas- and bio-sensing applications such as air quality, medical (glucose monitoring or cancer diagnosis), and automotive anti-pollution systems for NO_x. The added value that GaN can provide here over Si-based sensors is its unique capability to operate in harsh environments and high temperatures while performing at orders-of-magnitude better sensitivity.

The GaN value chain matures

Typically, new industries are fragmented and consolidate as they mature. We do see this happening today for the wide-bandgap technologies like SiC and GaN. Large silicon integrated device manufacturers (IDMs) that have a mature silicon power and RF product portfolio start adding GaN and SiC technologies. This will give them a big advantage as they now can address any requirement, from the most cost-sensitive to the highest-performance application over the full range of voltage breakdowns. The scale of these formerly silicon IDMs will allow them to also become dominant players in compound semiconductor technology. Furthermore, silicon foundries start adding GaN-on-Si process offerings to diversify their technology portfolio with high-value and high-performance processes. Altogether, these are very encouraging indicators that GaN is at the onset of facing mainstream availability and adoption in many different applications and markets.

These next paragraphs will highlight the latest technical advances in both GaN epiwafer and device technology for power switching and RF power applications. EpiGaN is at the forefront of this research area and has achieved significant technological milestones that will help drive GaN technology into the next stage of commercialization.

Advances of GaN technology for RF power

For GaN-on-Si to compete directly with GaN-on-SiC in high-end RF applications, there are a few technical hurdles to overcome. Some are intrinsic, such as the lower thermal conductivity of silicon compared to SiC, which can be overcome by an aggressive reduction of the substrate thickness during device processing. Another major hurdle is the creation of a conductive interface between the silicon substrate and the III–nitride layer stack during the epitaxial deposition. This parasitic conduction path causes the dissipation of RF signals. Transistors manufactured on such lossy substrates will never be able to attain high efficiencies.

At EpiGaN we have developed a robust interface technology to mitigate this conductive path, reducing RF signal loss on GaN-on-Si at 2GHz from 1.5dB/mm or more to below 0.25dB/mm, which is very close to the performance that can be obtained on the much more expensive GaN-on-SiC material. Even around 50GHz, the RF signal loss stays below 0.5 dB/mm (Figure 1). In the near future EpiGaN will validate the feasibility of high-resistivity 200mm Czochralski (CZ) silicon substrates for RF power applications. This should ultimately drive cost down further for RF power GaN-on-Si technology and will ease its entry in today's mainstream 200mm lines, both at silicon integrated device manufacturers and at silicon foundries.

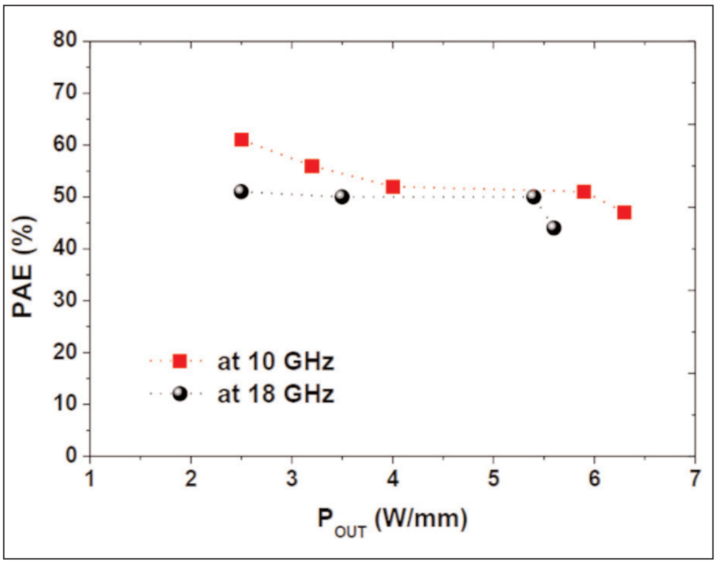

Figure 2: 0.15µm gate-length AlN/GaN-on-SiC power measurements at 10GHz and 18GHz (courtesy of F Medjdoub, IEMN, Lille, France).

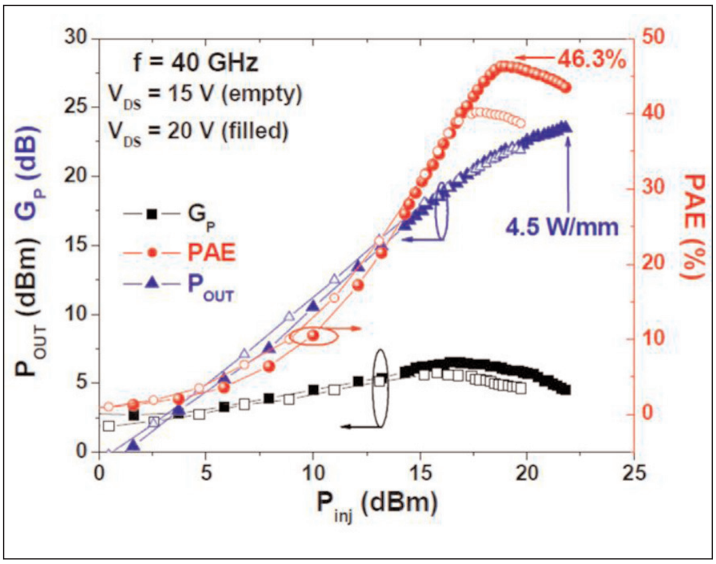

Figure 3: CW power performance of a 2x25µm AlN/GaN HEMT at f = 40GHz with V_{DS} = 15V and 20V (courtesy of F Medjdoub, IEMN, Lille, France).

The beauty of binary AlN barriers

In parallel, EpiGaN has been developing HEMT heterostructures featuring pure AlN barrier layers in combination with an in-situ SiN cap layer to complement and eventually replace their typical AlGaN counterparts. With this configuration, it is possible to reduce the thickness of the barrier from typical values of around 20nm down to only 4nm. This allows bringing the transistor's gate very close to the densely populated channel, thus maximizing the electrostatic coupling between the two (i.e. improved gate control) and resulting in far superior RF transistor characteristics. The so-called 'short-channel parasitic effects' — i.e. reduction of the transconductance due to a poor gate length/gate-to-channel distance aspect ratio (ideally >=15) when scaling transistor gates below 0.15µm — are supressed drastically. In addition, the AlN barrier maximizes the inherent piezoelectric effect in this material system, which leads to carrier densities $>2x10^{13}cm^{-2}$ in the transistor's 2DEG (two-dimensional electron gas) channel. This boosts power densities and, with an appropriate thermal chip layout, significant chip size reductions are achievable.

Collaborators at IEMN–CNRS have manufactured prototype transistors on EpiGaN's GaN-on-SiC RF wafers that show a power density above 5W/mm together with a power-added efficiency (PAE) above 50%, at an operating frequency of 18GHz (Figure 2). This level of performance is even maintained at much higher frequencies: at 40GHz, transistors with 120nm gate length exhibited power gain cut-off frequencies above 230GHz at V_{DS} = 20V. A 2x25µm AlN/GaN HEMT still produced a peak output power density of 4.5W/mm with an associated peak PAE of 46.3% at 40GHz.

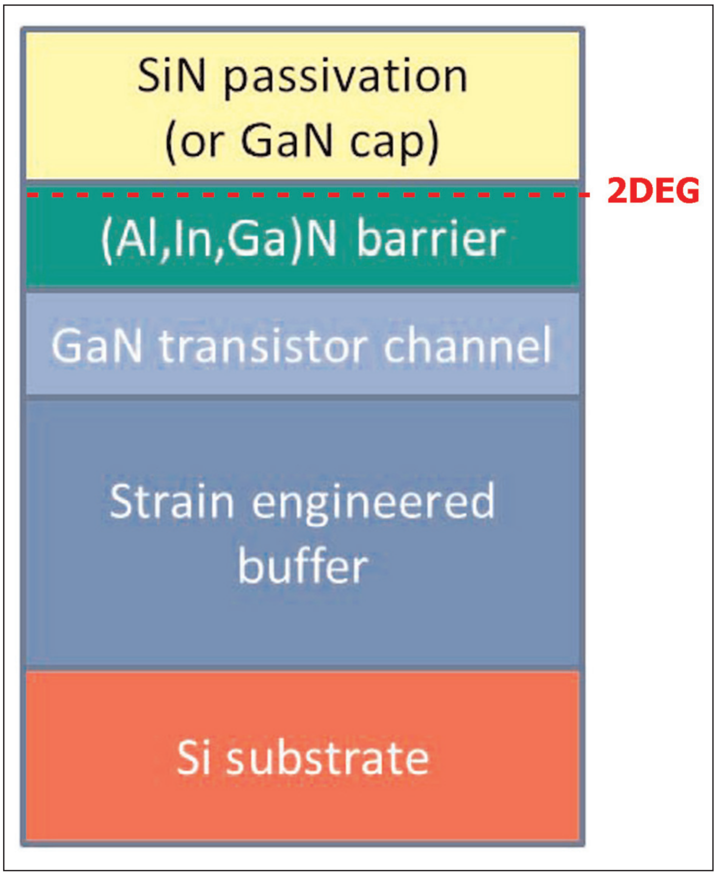

Figure 4: Typical GaN-on-Si HEMT structure.

GaN-on-Si technology for 600V power switching

In power switching applications, GaN is usually introduced to address the 600V node of the market, because there silicon technology has reached fundamental physical limits that can no longer be overcome. A typical layer stack for these applications consists of a buffer stack grown on the silicon substrates, typically several microns thick, covered by an active part consisting of a classical GaN/AlGaN HEMT heterostructure (Figure 3).

Even though it is the active HEMT part that will be processed into switching transistors, the buffer stack fulfils a number of important functions: first it serves as a mechanical absorber to take care of naturally induced stress between the substrate and the GaN material, second it needs to block leakage currents between the grounded substrate and the high-voltage nodes of active switching devices, and last it needs to be free of undesirable charge trapping sites to which the active HEMT devices are very sensitive (and cause an increase in the transistor's resistance while in operation). The latter issue becomes even more severe at higher operating temperatures.

EpiGaN's latest generation of high-voltage buffer technology fulfils all three requirements. The 650V epiwafers are flat, with a bow of less than 50µm. They have negligible vertical leakage currents below 1µA/mm^2 up to 650V, and in both polarities, the latter aspect enabling new on-wafer topologies such as integrated half-bridges (Figure 5). Finally, EpiGaN has recently demonstrated that, even at 150ºC and when operated at 600V, there is no change in transistor resistivity compared to the steady state — thus the dynamic $R_{ds,on}$ effect is completely eliminated (see Figure 6).

New device features enabled with EpiGaN's in-situ SiN technology

In the past few years EpiGaN has developed and optimized a solution for sealing the top of the GaN-on-Si wafers directly after growth by means of an in-situ-grown silicon nitride (SiN) passivation layer. As a consequence, there is no exposure of (Al,Ga)N layers to the fab environment, which will facilitate the entrance of GaN-on-Si technology into silicon CMOS fabs. EpiGaN pioneered this in-situ SiN surface passivation and now applies it to much broader purposes, among them a unique gate dielectric with a smooth and contamination-free surface.

This in-situ SiN capping layer also controls the filling of the surface states during device operation. SiN can provide enough charge to neutralize the surface charge of the AlGaN barrier layer in a GaN-on-Si device so that its surface potential no longer contributes to 2DEG depletion. Another beneficial effect is that the SiN layer adds device stability at elevated temperatures.

In combination with the in-situ SiN deposition it is possible to replace the AlGaN layer with a pure AlN layer without material degradation, as described in the previous paragraphs. For such a SiN/AlN/GaN layer design, sheet resistance falls well below 300Ω/sq. This low resistance enables the fabrication of transistor devices with higher current densities — and hence a smaller device at lower costs for the same current rating.

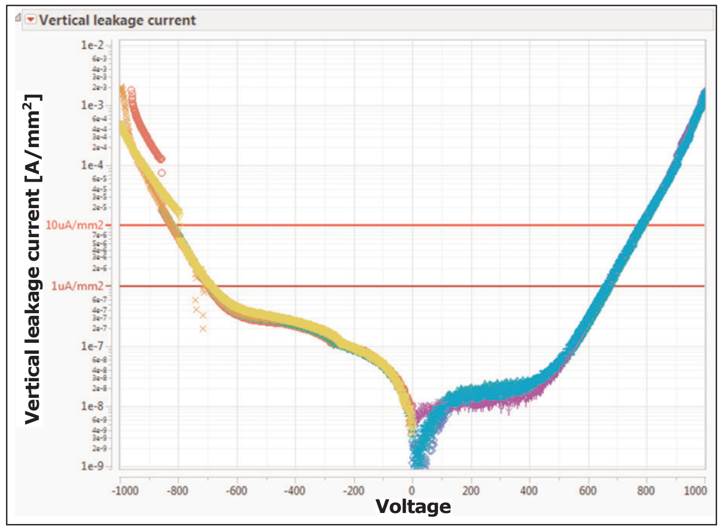

Figure 5: Vertical leakage current of 650V GaN-on-Si HEMT with <µA/mm^2@650V in forward & reverse bias.

Conclusion and outlook

GaN technology will come to the masses — no doubt about that. The value proposition that GaN brings to the table is simply too attractive and it has already started to spur innovations in many existing applications and markets such as RF power and power switching. In parallel, emerging applications will appear for which GaN technology is an enabler, for example in markets such as unique medical and chemical sensors.

Reaching true mass-market adoption of GaN technology will require a mature supply chain and ecosystem that is not in place today. However, the big industry players are positioning themselves to build a solid supply chain for GaN device manufacturing as it becomes more and more evident that GaN owns the future, and incumbent silicon and GaAs will be displaced to a large extent. ■

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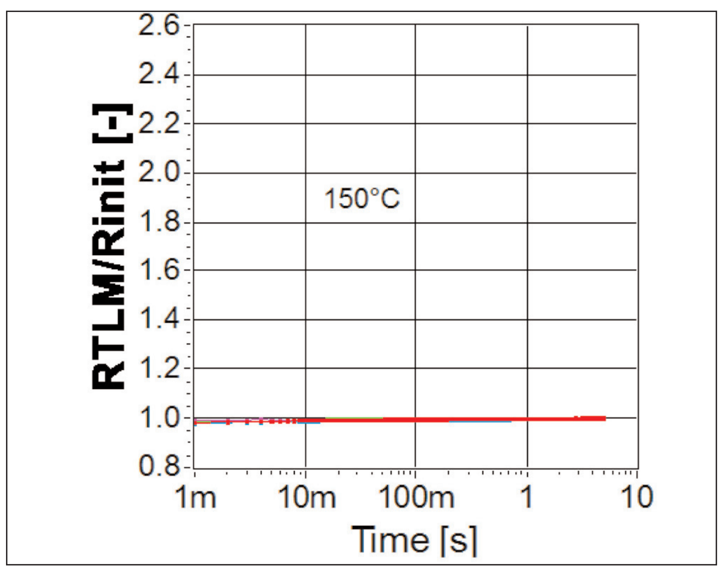

Figure 6: Dynamic $R_{ds,on}$ suppression at 150ºC in latest generation of EpiGaN's HV650 GaN-on-Si products.