Achieving the Low Cost Structures Needed for the Mainstream Commercialization of GaN

How GaN supply chain dynamics, device packaging options and system-level assembly efficiencies will drive the economies of scale that bring GaN to the masses

By Doug Carlson, Director of Aerospace and Defense Strategy, MACOM

The performance advantages that are achievable with gallium nitride (GaN) technology are well known to all involved with the RF and microwave industry today. GaN delivers as much as 8X the raw power density of incumbent GaAs and LDMOS technologies at high efficiency, with the ability to scale the device technology to high frequency. GaN technology has allowed device designers to achieve broad bandwidths while maintain high efficiency.

GaN technology development has been primarily driven by government funding and R&D to date. GaN on Silicon Carbide (SiC) is being successfully applied in the military domain today for applications including broadband electronic warfare jammers and radar systems, while GaN on Silicon (Si) has been successfully deployed in military communications. This activity has opened the door for GaN's penetration into commercial markets including CATV, cellular infrastructure and other applications. In fact, we are seeing the initial penetration of GaN into these markets.

In order to accommodate the unique price/performance requirements of these diverse commercial applications, GaN will remain segmented into two distinct varieties: GaN on SiC for specialized high performance applications, and GaN on Si for cost-sensitive volume applications. MACOM is uniquely positioned to evaluate these two varieties of GaN as we market a broad portfolio of pulsed and continuous wave products based on both SiC and Si. We find, at the device level, that the performance of GaN/Si and GaN/SiC are essentially identical (Table 1).

Table 1 Comparison of GaN/Si versus GaN/SiC Performance

0.5 µm gate length at 2 GHz	GaN on Si	GaN on SiC
Power Density (W/mm)	7	7
Gain (dB)	17.5	15

Efficiency (%)	>70	>65

SCRATCHING THE SURFACE

Today, we are only at the very beginning of GaN market penetration and adoption. GaN revenue for 2013 was $188.6M according to ABI Research, suggesting that GaN technology today has penetrated less than 1% of the approximate $9.5B overall analog semiconductor market. Given the extensive hype around GaN, this narrow market penetration may come as a surprise to many, especially when one measures GaN's potential impact beyond the RF and microwave market. It's been said that there isn't a single analog function that won't be made better with GaN. Indeed, when GaN's cost structure comes into alignment with incumbent technologies, its disruptive affect on the analog domain will be massive.

There are several critical requirements that must be met in order to propel GaN to mainstream market adoption, many of which are driven by cost of course, others of which pertain to how we as vendors approach customers/system designers with this nascent technology. Among the practical considerations to be mindful of here: any new technology must solve a technical problem which current technologies simply cannot. In this sense, new technologies like GaN do not *replace* older technologies, but rather augment capabilities and expand performance to allow the next wave of innovation. System designers and GaN vendors alike need to understand where GaN fits in the toolbox.

Another important baseline consideration is applications support. System designers, in general, are not experts in semiconductor technologies and capabilities, nor are they expected to be. This means that vendors need to come to the table with more than just product specs, but also the appropriate system and application-level knowledge needed to help the designer build a better product which fully captures the advantages of GaN.

These challenges can be readily overcome with the right combination of designer and vendor savvy. The really major hurdle standing in the way of mainstream GaN adoption and commercialization today is the supply chain.

EFFICIENCIES THROUGHOUT THE CHAIN

The supply chain for GaN will be defined along separate paths for GaN on SiC and GaN on Si, which cater to distinctly different target applications with distinctively different price/performance requirements. Not surprisingly, their respective supply chains look very different as well. As the RF and microwave industry's only provider of both GaN on SiC and GaN on Si devices, MACOM has good perspective on both.

GaN on SiC offers superior thermal properties compared to GaN on Si and is therefore ideally suited for applications with high power density (W/mm^2) requirements. Vendors of GaN on SiC-based devices have demonstrated considerable success via their early efforts – particularly in the electronic warfare domain – and GaN on SiC will remain the specialized GaN flavor of choice for performance-driven applications. But the high attendant costs of producing SiC ensure that this market will be serviced by a select group of high mix, low volume fabs.

By comparison, the silicon industry today does 2000X the volume of the SiC industry, which is driving enormous industrial manufacturing scale. Because Si grows at a 200X or faster rate than SiC, the energy required for manufacturing is much lower and the capital equipment utilization is much higher. This ultimately yields a fundamentally lower cost structure than what's possible with GaN on SiC. And whereas carbide is a relatively new material with a correspondingly short history of use in industrial scale applications, silicon has benefited from more than 60 years of industrialization and development and is arguably the most technically engineered material on the face of the earth. So the supply chain for GaN on Si has a host of natural cost efficiencies aligned in its favor.

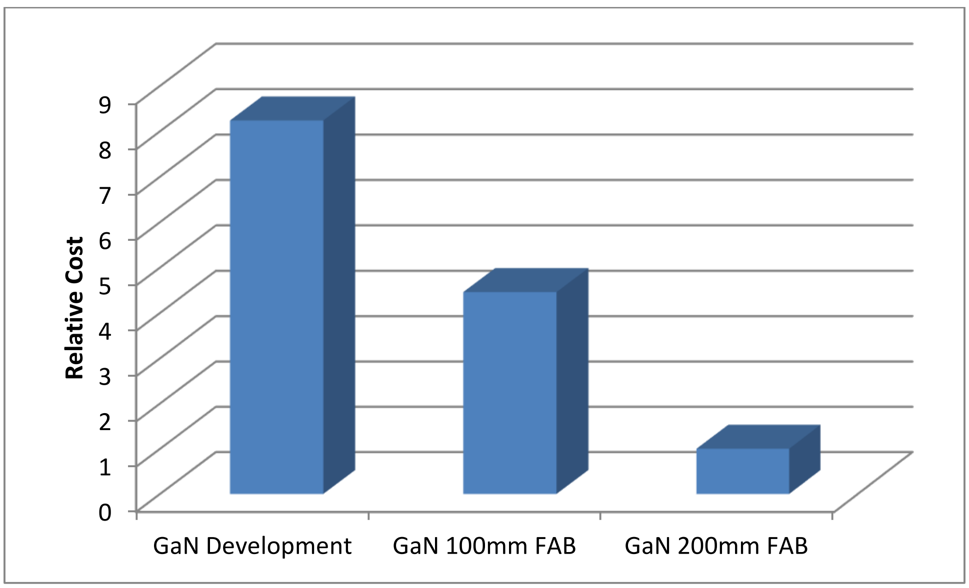
With regard to the GaN epitaxy, cost is directly proportional to the thickness of the epi put on the substrate. For both Si-based and SiC-based devices, the epi thickness is essentially the same so the associated epi cost is approximately equal.

PROCESS DISCIPLINE

GaN on Carbide has been produced mainly by boutique 3" and 100mm compound semiconductor fabs. The main volume application to date for compound semiconductors has been cellular handsets, which today are under attack from CMOS due to the attendant cost efficiencies. SiC-based GaN has no clear viable roadmap to large diameter, high volume production facilities which can drive cost for consumer markets.

The use of silicon on the other hand allows vendors to move to larger diameter fabs with typical volumes greater than 5,000 8" wafer starts per week. Here CMOS process control typically enables line yields that are above 98%. Because of the extreme high volume of the end markets that CMOS is addressing, balancing yield and cost dynamics is critical, and this drives a level of operational discipline that's unheard of in the III-V industry.

At full maturity, we expect that the GaN on Si cost structure in mainstream silicon fabs will be reduced significantly from today's GaN on SiC structure. As shown in Figure 1, scaling GaN from small diameter GaN development fabs to 200mm silicon fabs achieves an almost 10X reduction in cost. This cost advantage is further multiplied by the very high volume of a CMOS facility. To achieve significant GaN volumes at 8", RF demand will be augmented with the volume GaN on Si production that will be driven by the DC power market. This market may be as much as 10X larger than the RF and microwave market. With upwards of 95% of GaN unit volume going forward tied to GaN on Si, both the DC power and RF domains will likely be serviced by the same 8" silicon fabs.



To fully realize the commercial promise of GaN, there must also be surety of supply to promote stability and resiliency – to say nothing of economic efficiency – across the GaN supply chain.

ADVANCED PACKAGING

GaN supply chain optimization will be driven in parallel by process efficiencies and customer demand, the alignment of which will ultimately yield significant cost reductions for all involved. Manufacturing efficiency gains drive reduced production and product costs, which drive volume demand, and so on.

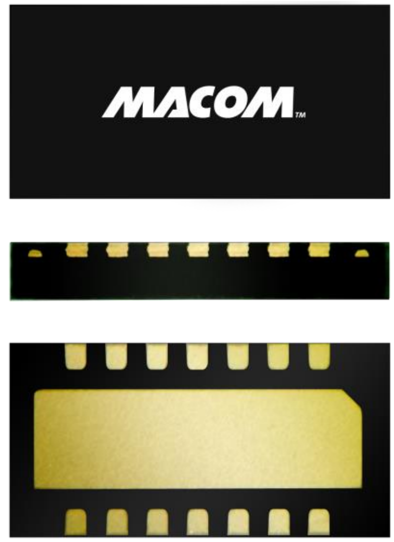


Figure 1: Plastic DFN Package – 3x6mm

But system designers in the RF and microwave domain are of course no strangers to these dynamics, having already seen this evolution in previous technology deployments.

A plurality of packaging options, which support end market applications, is the next critical performance and cost factor which must be considered for a complete product solution. MACOM, for decades, had led the adoption of organic packaging technologies into RF, microwave and millimeter wave applications, extending the functionality and frequency of performance of plastic packaged parts. Recently, MACOM has focused on the introduction of surface mount plastic packaging for high power devices. Plastic packaged high power GaN enables designers to adopt conventional surface mount manufacturing approaches which lead to system size and weight reductions. In this way, the adoption of GaN in plastic facilitates system manufacturing cost reduction together with test efficiencies associated with high volume plastic packaging. The arrival of GaN in Plastic devices has given system designers newfound flexibility to reach power levels up to 90W without the size or weight penalties typically associated with -packaged transistors.

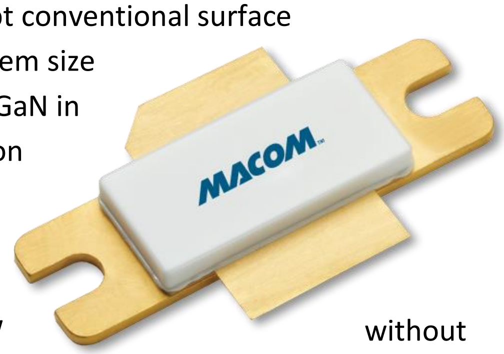


Figure 2 Ceramic Flanged Package

GaN on Ceramic remains the packaging option of choice for devices that must be hermetically sealed in order to ensure reliable operation in environmentally challenging conditions. Ceramic-packaged GaN devices are also capable of managing much greater power output levels than plastic-packaged alternatives available today.

When measuring the value/useful applicability of ceramic- versus plastic-packaged GaN transistors, the target lifecycle for the end system is often the deciding factor. Military radar system designers have higher expectations for environmental ruggedness than designers of many consumer products. Ceramic-based GaN devices are ideally suited for systems that are expected to deliver extremely high reliability for long periods of time with minimal maintenance, and are often less sensitive to cost pressures than commercial-caliber systems.

Here again with the packaging and assembly of GaN-based devices, the RF and microwave industry can leverage the best practices achieved by the broader electronics market to drive down the costs of GaN. Just as we leverage high volume silicon fabs to achieve low cost structures for compound semiconductors, we can leverage packaging and production efficiencies – also enabled by silicon – to help achieve the mainstream commercialization of GaN technology.

###

Dr. Douglas J. Carlson received his ScB in Electronic Material from Brown University in 1983 and his ScD in Electronic Materials from the Massachusetts Institute of Technology in 1989. Dr. Carlson subsequently served on the research staffs of MIT and Bell Laboratory, Murray Hill, NJ. His research focus was on fabrication and characterization of semiconductors and superconductors for microwave applications. In 1990, Dr. Carlson joined MACOM in its Advanced Semiconductor Division. In his career at MACOM he has held engineering, operations and product management positions. Dr. Carlson's current position is Director of Aerospace and Defense Strategy. In this role, Dr. Carlson is focused on advanced technology development and specifically is pioneering the application of commercial manufacturing practices for phased array radar. Dr. Carlson has published over 40 articles in peer reviewed journals. He has authored numerous invited papers and invited presentations on the topics of advanced semiconductors, packaging, low cost manufacturing and phased array radar.