Automotive Opportunities for Power GaN

This article includes studies of the market opportunity, current performance and projected performance of very large area GaN devices that have applicability to the automotive market. Comparisons are made regarding the performance differences between SiC, GaN, and IGBT devices. A yieldable large area 650 V/100 A GaN device is described. **Girvan Patterson, GaN Systems Inc, Ottava, Canada**

Large GaN power devices are currently at the introduction phase. Very rapid market growth is expected within the next five years leading to sales exceeding $500 million by 2020. Yole has published a market research report (June 2014) that identifies EV/HEV applications as being a key element of the market opportunity. Ramp-up will be quite impressive starting in 2016, at an estimated 80% CAGR (see Figure 1).

There are clear incentives for the automotive industry to consider GaN power devices [1, 2, 3, 4, 5, 6]. The possibility of obtaining a reduction of electrical power conversion losses leads to consideration of the value of increasing the number of EV/HEV units within the automotive manufacturers product mix. Clearly imposed fleet emission limits are the prime incentives; however range anxiety, battery and cooling system cost, also relate to power conversion efficiency (see Figure 2).

GaN devices built upon Silicon substrates will meet the needs of the automotive industry in terms of voltage and current rating. The suggested ratings [1] for a GaN e-Mode power transistor are a voltage blocking capability 600 V and minimum single-die current rating of 100 A. To directly compete with Silicon, and allowing no premium for higher performance (efficiency), the GaN transistor would have to be priced at less than $10/cm^2$ [1]. The future use of 8-inch (200 mm) wafers, on-chip drivers, and redundancy schemes to increase yields plus the removal of the need for anti-parallel reverse conduction diodes and the absence of massive heat removal systems and powerful drivers will help towards achieving the overall system cost target. The device cost target will become far less problematic.

Cost is however very closely related to production volume. The EV/HEV penetration of the total automotive market is currently very small. The battery cost is the primary factor that determines the EV/HEV manufacturing cost. The growth potential for EV/HEV cars will be greatly improved as battery costs fall below $400/kWh. This close relationship has been recognized and an intense effort, as shown in Figure 3, is being made to reduce battery costs even further. As shown, the EV/HEV combined sales are forecast to reach 30 million units annually by 2025.

While light EV/HEVs constitute the dominant the potential market area for GaN power switch devices there are other related applications. Figure 4 shows the forecast for the relative value for various sectors of the Electrically Powered Vehicle market. By 2025 it is expected that the light EV/HEV will make up 33 % of the market, while Buses, Military and Forklift vehicles will each hold approximately 13 to 16 % of the market. Diversity will ensure that there will be a large variety of power semiconductor types required.

The automotive market opportunity is possibly the largest that can be addressed by GaN devices. The current market is being served by IGBTs, which are low cost and well understood

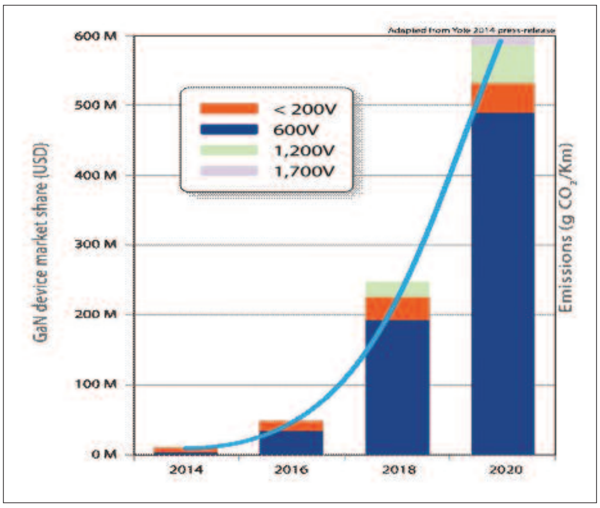

Figure 1: Market opportunities for GaN power transistors

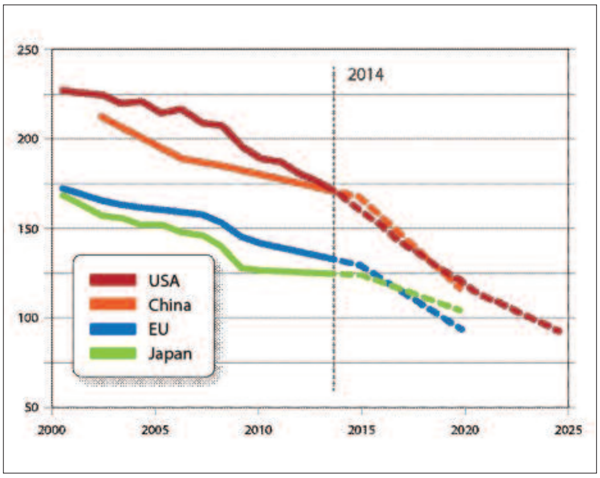

Figure 2: Fleet emission limits by region

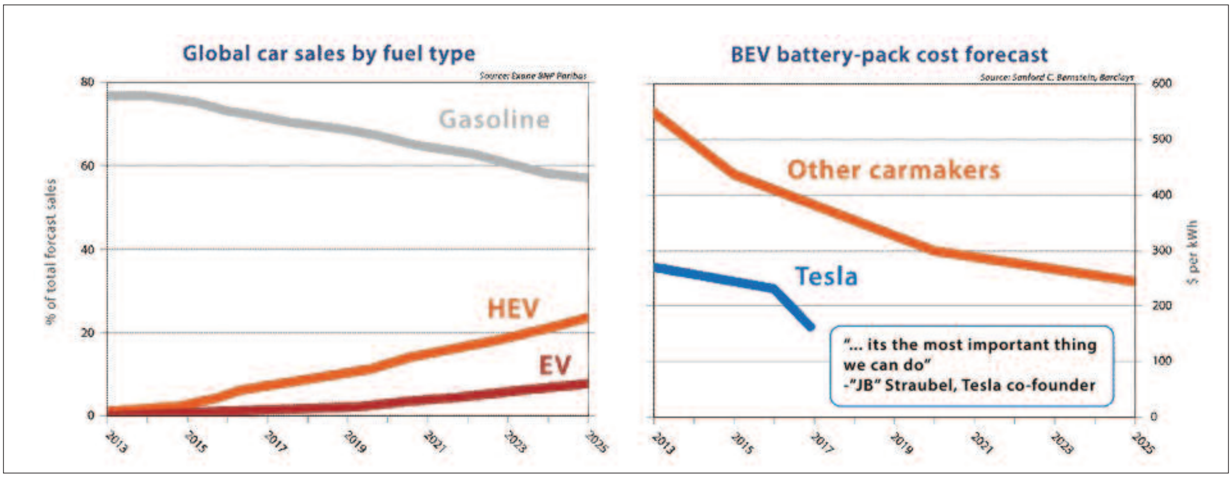

Figure 3: Global car sales by fuel type and BEV battery-pack cost forecast

devices. Displacement of IGBTs will be achieved only when the efficiency improvements and reliability of GaN are well established.

EV/HEV power and operating voltage

Figure 5 shows the power and blocking voltage requirement of the various types of EV/HEVs introduced in the 2010/12 time period [7]. It is expected that future EV/HEVs will have wider range of requirements. Already SiC devices are expected to be introduced that are optimized for 900 V operation and GaN devices will also follow this path.

The potential competitive threat offered by SiC is real because the SiC devices offer excellent thermal performance in terms the variation of on-resistance with temperature. It is however the Device Value in terms of Performance versus System Cost that is critical. The 6-inch starting wafer cost for a GaN on Si device is $25 - 50 while a SiC wafer cost can be $5,000. Even under extremely adverse thermal conditions, 175°C junction temperature, large area GaN devices can have lower on-resistance than a SiC device, smaller chip area, and far smaller switching losses. The lateral nature of current GaN devices allows for the inclusion of on-chip drivers, the achievement of very low capacitance - lower gate charge, and the use of yield enhancing schemes.

Battery voltage levels for hybrid and electric cars range from 100 V to 450 V. A boost converter is normally used where a higher fixed voltage is required. Over voltage provisions dictate that GaN devices rated for a blocking voltage of 650 V will need to safely withstand 850 V and a 900 V device will need to safely withstand 1200 V. Figure 6 shows the leakage current and incipient breakdown characteristics of a GaN e-Mode transistor that has a 6 micron epitaxial layer deposited upon a silicon substrate. Figure 6 shows that this 650 V rated device is able to withstand 1000 V. At 650 V the leakage current is 0.1 μA/mm of gate width. This means that a 1000 mm device that is suitable for use at 100 A could potentially has a total leakage current of just 0.1 mA.

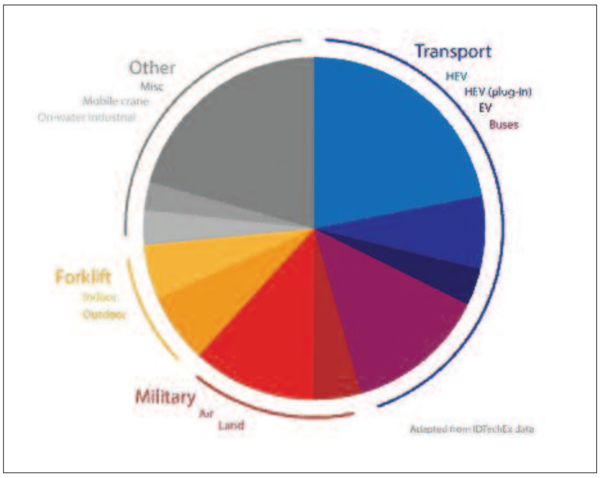

Figure 4: Relative value of electrically powered vehicles in 2025 by application

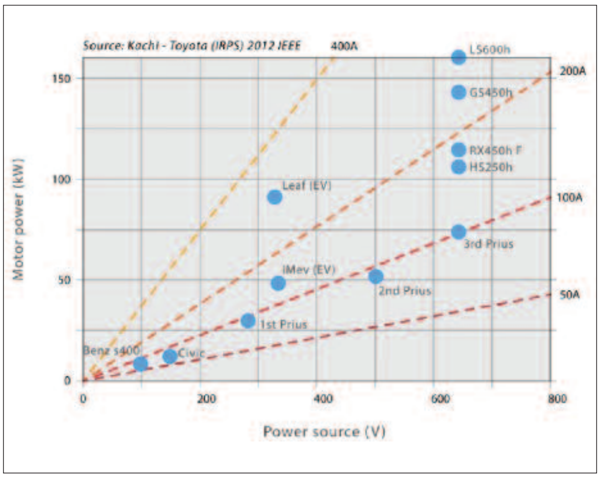

Figure 5: Motor power and operating voltage of EV/HEVs

Specific on-resistance and figure of merit

Figure 7 compares the specific on-resistance of all the common power devices. The GaN device starred is a 1.6 mΩ·cm², 1900 V transistor resulting from the research work of Prof. Medjdoub and his team at IEMN (France) [4]. If this work results in practical devices it is possible to show an estimated performance which is better than 1 mΩ·cm² at 1200 V leading to a safe blocking voltage of 900 V.

Charts, such as that shown in Figure 7, can be misleading because only the active device area is usually used to

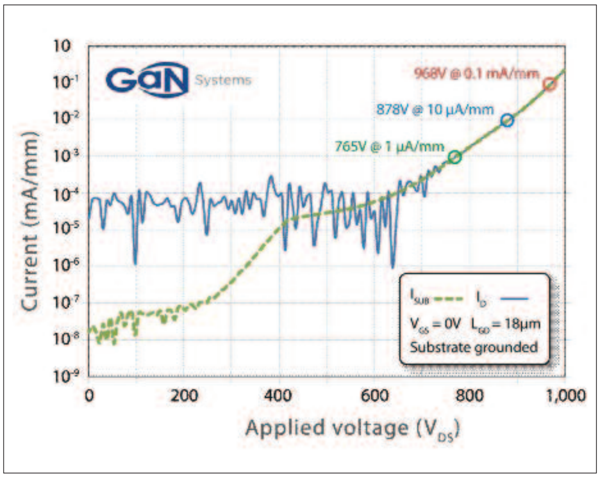

Figure 6: **Leakage current of a 650 V GaN device**

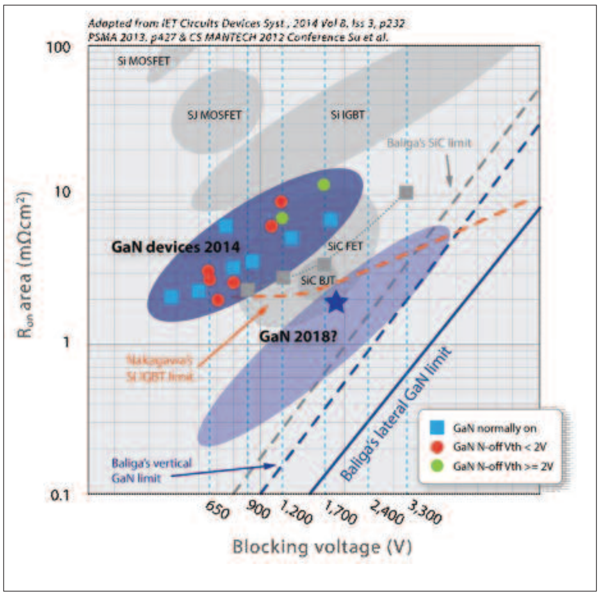

Figure 7: **Specific on-resistance**

provide the basis of calculating the specific on-resistance. Real devices have an overhead interconnect area additional to the active area. Also, fabrication cost is, of course, not simply related to device area.

Another method of assessing the potential performance of the very large devices needed for automotive power switches is to examine the datasheets of smaller parts currently in the market. Large area devices are simply made up of the same structural blocks as smaller devices within the family type. The Figure of Merit (FOM) is then constant across the family while other key loss parameters such as Q_{RR} simply scale with current. Table 1 shows the conventional FOM and the FOM Hard Switching (FOM_{HS}) [8]. The QRR is related to the diode loss that is present in bipolar structures. The data shown is based upon calculations made using the following datasheets: GaN e-Mode GS660506, GaN Cascode TPH3006PS, Si MOSFET FCP190N60E, and Si IGBT STGB20V60DF [8].

The devices, presently being used in EV/HEVs, are IGBTs. These are low cost well established, well understood devices. Freescale Semiconductor has examined the possibility of using GaN devices as replacements for IGBTs [9]. Using the assumption that a 1m? GaN device is achievable it is possible to construct Table 2.

This table was developed using IGBT data and a GaN device model, based upon experimental devices that correspond to the 2018 projected performance of GaN transistors shown in Figure 7. The losses shown greatly favor the GaN transistors. In this simulation four 4 m[2] 650 V/100 A GaN transistors are connected in parallel to achieve the 1 m? performance shown. The power loss reduction is better than 3.5 : 1 at 400 A and 10 : 1 at 100 A.

Large GaN transistors

Transistors capable supplying 100 A and 200 A are shown in Figure 8. These are 650 V (blocking voltage) devices, include an on-chip gate driver, and use redundancy to improve yield, to achieve 1.6 A/mm[2]. They have a maximum on-resistance of 16 mΩ and 8 mΩ respectively. The photographs show the dies before they are post processed using an additional copper metal system that greatly increases the current handling capability.

The schematic circuit shows the on-chip drivers of the 100 A device. Two additional small transistors (Q1, Q2) are provided. These provide very secure direct drive to the large device D3. This scheme greatly simplifies the required pre-driver circuitry. The post processing element of the production sequence plays a vital part of the achievement of producing viable, yieldable, very high current, very large area, lateral GaN power devices. GaN devices that are lateral have limited current handling capability because of the limited thickness of the aluminum metal that is deposited in conventional foundries. It is, therefore, vitally important to augment the original metal system with a high conductive copper super-structure metal system as shown in the Figure 8 schematic.

Additionally the yield of very large GaN devices can be seriously affected by the typical foundry defect density. This issue is also remarkably easy to address by using post processing. Using a proprietary isolated island structure

Parameter	GaN e-Mode	GaN Cascode	Si MOSFET	Si/FRD IGBT
FOM: $Q_G \cdot R_{on}$ (pC·Ω)	375	1,400	10,000	17,000
FOM_{HS}: $(Q_{GD} + Q_{GS2}) \cdot R_{on}$ (pC·Ω)	185	550	4,400	7,300
$Q_{RR\ Diode}$ (400 A) (nC)	0	2,000	190,000	6,000

Table 1: **600/650 V device comparison**

25 °C, 400 A Typ. values	IGBT	GaN Simul.	
V_{cesat} : V_{on} (V)	1.45	0.4	Voltage drop at full load 400 A
P_{sat} : P_{on} (W)	580	160	Conduction loss at full load
E_{off} (mJ)	13	0.25	Switching off energy
E_{on} (mJ)	2.9	0.42	Switching on energy
V_F : V_{on} (V)	1.55	0.4	Forward voltage drop (reverse current)
P_{VF} : P_{Von} (W)	620	160	Reverse conduction loss
E_{REC} : E_{Roff} (mJ)	3.6	0.9	Reverse recovery loss
V_{cesat} : V_{on} @ 100 A (V)	1.0	0.1	Voltage @ 25 % load
P_{sat} : P_{on} @ 100 A (W)	100	10	Conduction loss @ 25 % load

Table 2: **IGBT/GaN power loss**

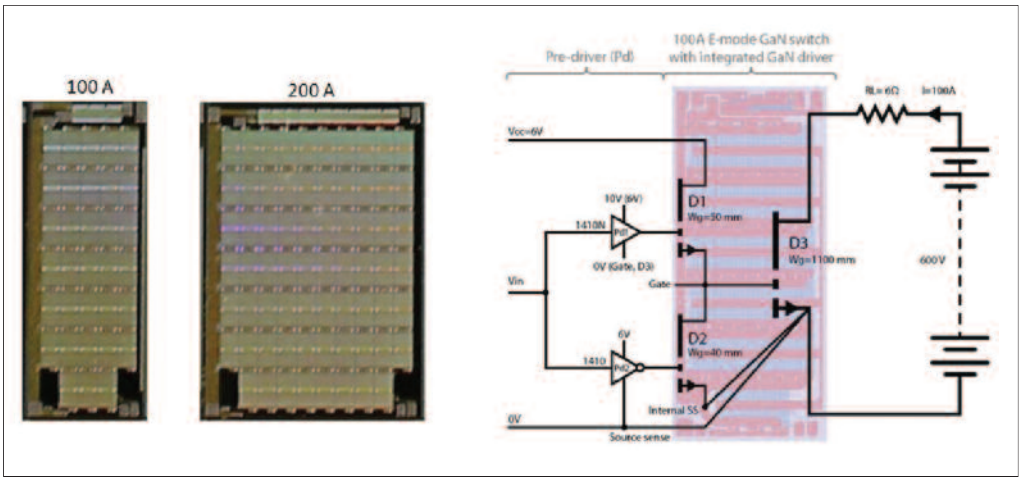

Figure 8: **Die photographs and schematic circuits of large area GaN transistors**

the defective islands can be totally isolated by providing no interconnect to any islands affected by the defects. It is therefore possible to select only the best performing islands. This greatly improves the overall device performance and yield.

Conclusion

The potential for very high volume use of GaN transistors in automotive applications has been described. The lower losses are attractive but GaN devices that meet the demanding requirements of the automotive industry are at an early stage of development. However the interest of the automotive industry is palpable. The actual acceptance of GaN devices into automotive applications will be determined by the achievement of the high volume production of reliable devices. It is likely that the automobile industry will generally be among the later adopters of the technology. The consumer electronics industry is currently moving very rapidly to develop new products using GaN e-Mode 650 V devices. The clear motivation is simply the desire to achieve an overwhelming performance advantage over their competitors. The early adopters within the automotive industry are also those who are the most innovative and competitive [10].

Literature

[1] M.Su, C. Chen, L. Chen, M. Esposto, and S. Rajan, "Challenges in the Automotive of GaN Power Switching Devices", CS MANTECH Conference, April 23rd -26th, 2012, Boston, MA.

[2] T. Kachi, et al, "GaN Power Device and Reliability for Automotive Applications", Reliability Physics Symposium (IRPS), 2012.

[3] S. Araujo, M. Kazanbas, M. Wendt, T. Kleeb, and P. Zacharias, "Prospects of GaN Devices in Automotive Electrification", in PCIM Europe 2014, pp.1033-1040.

[4] K. Boutros, B. Hughes, "GaN Power Electronics for Automotive Applications", IEEE, 2012.

[5] J. Roberts, "Lateral GaN Transistors - A Replacement for IGBT Devices in Automotive Applications", in PCIM Europe 2014, pp.310-317.

[6] T. Kachi, "Recent Progress of GaN Power Devices for Automotive Applications", Japanese Journal of Applied Physics, vol. 53, 2014, pp.100210-1-100210-9.

[7] N. Herbecq et al, "1900 V, 1.6 mΩ cm² AlN/GaN-on-Si power devices realized by local substrate removal", App. Phys. Express, Feb. 2014.

[8] A. Lidow et al, "GaN Transistors for Efficient Power Conversion", Wiley, 2015, pp.228.

[9] C. Assad, and H. Mureau, "GaN-over-Si: The Promising Technology for Power Electronics in Automotive", CIPS 2012, March, 6-8, 2012, Nuremberg/Germany.

[10] G. Patterson, "The Automotive Market Opportunity for GaN", PEE Special Session PCIM 2015 "Power GaN for Automotive Applications".