Market Penetration of Wide-Bandgap SiC and GaN technology in light of Silicon Superjunction and IGBT technology evolution

Anup Bhalla

United Silicon Carbide, Inc., 7 Deer Park Drive, Monmouth Junction, NJ 08852, USA

abhalla@unitedsic.com. Phone: 732 355 0550 X108

Keywords: IGBT, Superjunction, SiC, GaN, Switches, Power Conversion, Motor Control

Abstract.

In this paper, we will provide our view on the market situation facing wide band-gap (WBG) (>600V) switch technology as it competes with continuously improving Si Superjunction and IGBT technology for power conversion and motor control applications. We examine three voltage classes – 600V, 1200V and >1700V, to see where the Si technology is good enough, and where WBG devices can make an impact. We also assess near term cost evolution to get a sense of how great the displacement of Silicon technology is likely to be.

Power Conversion at 650V:

Table 1 shows competing device technologies as they stand today. The current state of the art of Si Superjunction technology is RdsA=10mΩcm^2 [1] at 650V. In comparison, the lateral HEMT GaN (on Silicon) cascode [2] has an estimated RdsA=3mΩcm^2 and the normally-off GaN HEMT is estimated to have an RdsA=4mΩcm^2. SiC 650V JFETs can achieve RdsA<0.8mΩcm^2, and trench MOSFETs [4] have been demonstrated with RdsA=0.79 mΩcm^2. Given the enormous economy of scale advantage enjoyed by Si Superjunction devices and further cost reduction due to the migration to 12inch, the RdsA*Cost Figure-of-Merit clearly continues to favor Si superjunction devices. GaN-on-Si on 6inch <111> device costs are estimated in Table 1 based on epi costs and processing within depreciated 6inch FABs at moderate scales. SiC (JFET/Cascode/MOSFET) devices, currently at 4inch are quite high in cost (assuming low volumes), but are the highest performing technology.

Given the relative maturity of competing technologies, one can project the next technological steps in each space 2-3 years from now. Silicon Superjunction scaling gets more difficult, but new concepts allow scaling to 5mΩ-cm^2 and below, further reducing costs. Batch mode vertical tube based epi tools, or improvements in deep trench epi fill throughputs will at least halve Superjunction costs. GaN devices can be expected to halve in RdsA as well by improving parasitic resistances, the 2DEG and geometry scaling. SiC device RdsA can be improved by increasing channel density, substrate

Device technology	Units	Si Superjunction	GaN Normally-off	GaN HEMT Cascode	SiC Trench MOSFET	SiC JFET Cascode
RdsA	mohm-cm2	10	4	3	1	1
RdsA*Qg	mohm-nC	3720	715	930	Not reported	437
RdsA*Coss(er)	mohm-pF	5840	Not reported	8400	Not reported	2100
Body Diode		Poor	Excellent	Excellent	Higher Vf, low Qrr	Excellent
Substrate type		12inch	6inch Si	6inch Si	4inch 4H-SiC	4inch 4H-SiC
Substrate costs + Starting Epi	Normalized	1	3	3	6	6
Relative processing costs		3.7	2	2	2.5	2
Chip thickness assumed	um	200	200	200	100	100
Target DC (I2R rating)	Amps	20	20	20	20	20
Chip size based on DC rating & Thermal resistance on heatsink (Tj<150C)	mm2	27.5	12.3	9.6	3.6	3.6
Effective Rdson(25C)	mohm	48	43.5	41.6	42	37
Thermal resistance (JC)	C/W	0.2	0.45	0.57	1.17	1.17
Assumed RthJA	C/W	3.2	3.45	3.57	4.17	4.17
Normalized yields		0.95	0.7	0.6	0.7	0.8
GDPW		2282	876	962	1237	1414
Relative chip costs	Relative	2.1	5.7	5.2	6.9	5.7
Package/Cascode costs	Relative	0.2	0.2	0.4	0.2	0.4
Effective part costs	Relative	2.3	5.9	5.6	7.1	6.1
Avalanche capability J	Normalized	1	N/A	N/A	0.6	0.6
Over-current capability A-us	Normalized	1	0.4	0.3	0.2	0.4

*Table 1: Comparison of 650V technology and cost. The WBG options provide lower Rds*Qg, but costs are higher.*

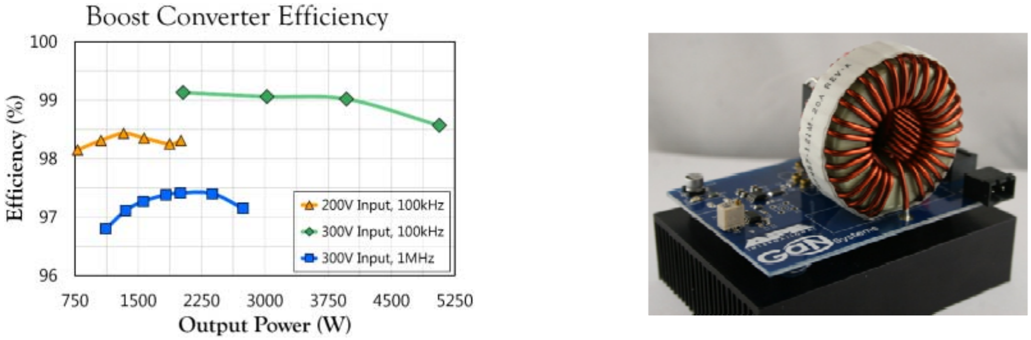


Figure 1: A 5KW boost converter based on GaN HEMTs. At 1MHz, nearly 97% efficiency can be achieved at 2.3KW. Courtesy APEI Inc.

thinning and charge balance methods, along with the impending move to 6inch. These changes will likely reduce the cost differentials between Silicon and WBG technologies (costs can drop 2X-3X), but Silicon devices will still be the lowest cost option (costs dropping slower).

Of the \$1.8B/year discrete MOSFET market, the share of Superjunction devices (10mΩ-cm^2) (\$600M) appears set to grow by steadily replacing standard planar MOSFETs (80 mΩ-cm^2) in many mainstream consumer applications, as the cost has fallen to the point where Superjunction FETs can be offered at lower prices, and efficiency levels for power supplies can meet today's Platinum Energy star regulation levels. Due to the extreme die shrink of the Superjunction devices, the thermal resistance is higher, chip robustness is reduced, so replacing commodity planar MOSFETs is not likely for all applications. Similarly, with WBG devices, cost reduction by extreme die shrink is limited by the need to maintain minimum levels of robustness in avalanche and short-circuit/overcurrent conditions. Discrete Superjunction and WBG devices are currently deployed in standard (TO) packages, and package inductance and EMI constraints limit the maximum allowed dV/dt and dI/dts. This means that the very high speeds of the latest Superjunction technologies can be challenging to exploit without higher EMI costs and reliability risks, and this is also the case with WBG devices. These factors make it quite unlikely that WBG devices will replace generic Si FETs in high volume consumer applications in the next 2-4 years, but will instead be targeted to circuits and systems where their performance benefits fulfill a critical system need, and justify the re-design effort to use them reliably with sufficient system/weight/operational cost savings (e.g. Data Center and Telecom power supplies, Aviation power supplies).

Table 1 also shows the much improved Rds*Qg and Rds*Qoss figures of merits for WBG devices, making them most efficient for hard-switched applications where diode recovery losses play a role, and applications where switching frequencies are high. Figure 1 shows an excellent example (courtesy APEI), of a 5KW GaN-HEMT based boost converter, which can be operated at 1MHz at efficiencies well above what can be offered by Silicon.

The 650V power conversion market, driven by the application it serves, is by far the most dynamic voltage class for transistors. The rapid design cycles combined with short end product life spans will allow new disruptive WBG technologies opportunity to quickly gain penetration where the end user is willing to invest for superior performance. WBG switches targeted at the high performance niches have the highest likelihood of gaining rapid market acceptance.

Motor Control and Power Conversion at 1200V:

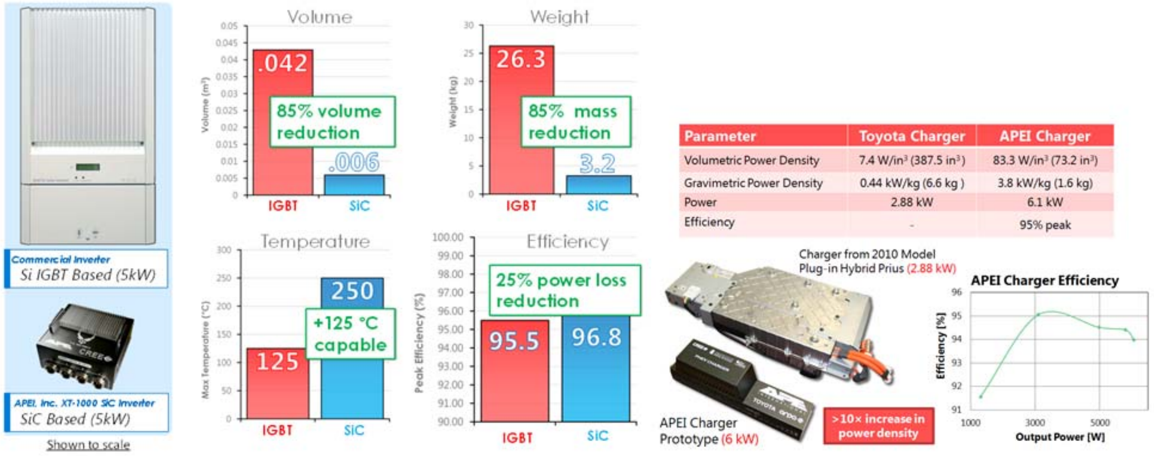
In the 1200V power switch space, the market is dominated by power modules based on Si-IGBTs (\$2-2.5B/yr), with a smaller (\$0.8B/yr) market in discretes. Superjunction technologies are not commonly available at 1200V, due to the excessive number of epi layers needed, and the slower switching speeds commonly used in motor drives. Discrete IGBTs used for power supply applications with good switching speeds are available, but SiC devices (Cree[5], Rohm[5], Infineon, USCi[6], Fairchild) are attacking this space. GaN devices may become available in the next few years, but lateral devices face many challenges in this predominantly high power/high current space with the need to provide large area devices. Table 2 compares the available technologies and relative costs for a given DC rating. While such a rating does not do justice to WBG devices given their much reduced diode recovery and switching losses, and one might be prompted to use even smaller devices, there are limitations based on the need to handle inrush/startup/peak current loads that limit how small the devices can be. The die sizes shown in table 2 account for these factors. IGBTs are currently much lower in cost compared to Si MOSFETs and SiC devices.

Device technology	Units	Si IGBT	SiC Planar MOSFET	SiC JFET Cascode
RdsA	mohm-cm2		4.5	2.3
Vce(sat)		1.6	N/A	N/A
Eoff (hot)	uJ/A	66.5	6	6
Substrate type		8inch	4inch 4H-SiC	4inch 4H-SiC
Starting material	normalized	1.5	7	8
Relative processing costs		2	2.5	2
Target DC (I2R rating)	Amps	20	20	20
Chip size based on DC rating & Thermal resistance on heatsink (Tj<150C)	mm2	16	13	7.3
Effective Rdson(25C)	mohm	N/A	46.3	42.1
Thermal resistance (JC)	C/W	0.3	0.33	0.58
Assumed RthJA	C/W	3.3	3.33	3.58
Normalized yields		0.95	0.7	0.7
GDPW		1684	343	610
Relative chip costs	Relative	2.1	27.7	16.4
Package/Cascode costs	Relative	0.3	0.3	0.5
Effective part costs	Relative	2.4	28.0	16.9
Avalanche capability	Normalized	1	4	2.3
Over-current capability	Normalized	1	0.5	2.3

Table 2: Comparison of 1200V Switch technology.Chip sizes based on current ratings do not capture the operational efficiency or BOM benefits of SiC.

Conversion of motor drives to use inverters for variable speed control can save a great deal of electricity and extend motor life. A significant fraction of consumer appliances and higher power industrial systems remain to be converted to this technology. IGBT based inverters offer high operating efficiencies, operating at PWM frequencies of 5-16kHz, and the main thrust for power savings is to simply get wider adoption of variable speed drives. In most cases, there is limited push to higher operating frequencies, give that space is not a constraint, efficiencies are reasonably high and initial acquisition cost seems to trump operating costs, at least for intermittent applications. Again, higher dV/dts cause problems with insulation and EMI in actual applications, limiting how fast devices may actually be switched.

For these reasons, the first penetration of WBG 1200V devices focus on power conversion applications such as PFC, solar inversion, high power welding, EV chargers etc. where system cost reduction through the use of WBG switches has been demonstrated even at current prices. Figure 2 shows the massive advantage that WBG (SiC) can provide in efficiency and inverter volume, as well as for battery chargers, where the switching loss improvements of the WBG devices are better exploited. With the advent of 6inch fabrication, rapid improvement in 1200V switch pricing is imminent, and this penetration will gain momentum. Introduction of driver circuits which allow synchronous conduction will allow WBG MOSFETs/JFETs to eliminate anti-parallel JBS Diodes, which can significantly reduce solution costs. As processes mature, and high current modules in SiC become more readily available in the next 2-3 years, it is likely that motor-control applications that run 24/7 will use SiC even with somewhat higher initial variable speed drive cost, due to the rapid payback in electricity savings and higher operating reliability by reducing operating temperatures and cooling requirements.

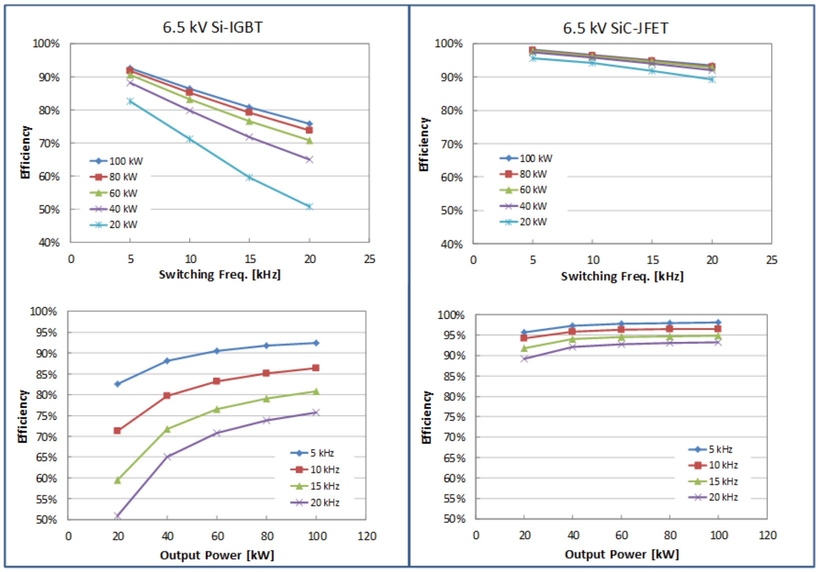


Parameter	Toyota Charger	APEI Charger
Volumetric Power Density	7.4 W/in³ (387.5 in³)	83.3 W/in³ (73.2 in³)
Gravimetric Power Density	0.44 kW/kg (6.6 kg)	3.8 kW/kg (1.6 kg)
Power	2.88 kW	6.1 kW
Efficiency	-	95% peak

Figure 2: A compact 5KW inverter based on SiC MOSFETs, offering compelling improvements, valuable for applications such as avionics. The higher semiconductor cost is also offset by the BOM cost and operating cost reductions. A 6KW battery charger using SiC, with much improved power density. Courtesy APEI & Cree Inc.

>1700V Switches:

For higher voltages, the advantages of SiC devices become quite large compared to IGBT based switches with regard to switching losses. Also, the cost premium of SiC is more readily absorbed in high powered systems 50KW – 5MW. Penetration in this space is limited by the lack of availability of released SiC devices, although many excellent demonstrations have occurred. Commonly used IGBT modules rated for 1700V, 3300V, 4500V and 6500V will likely see a challenge from SiC based modules in the next 2 years. Figure 4 shows the calculated power loss difference of a 3-phase inverter operating with 4KV bus voltage, comparing the best 6.5KV IGBTs with SiC JFETs. Presently, IGBT devices at this voltage rating are limited to 500Hz-1kHz switching. Even targeting just 5kHz operation, the SiC JFET solution offers a large performance improvement, from light load to full load, stemming from its lower switching losses, and the absence of the diode knee in its on-state characteristics. Going forward, the key drivers will be applications where operating costs are reduced much more than upfront installation costs, and long term system reliability is enhanced by reduced losses and lower temperatures. Long distance trains (traction), more electric ships, wind power and data center grid connection are likely candidates. Given the long design and deployment timelines in these markets, actual revenue growth is like to be about 2-3years after product introduction.



a b

Figure 4: Estimated power loss difference between 6.5KV IGBTs and 6.5KV SiC JFETs. Column a (IGBTs) and Column b (SiC JFETs) and compared based on switching frequency (top row) and output power (bottom row). Even at 5kHz, a large improvement is obtained with SiC JFETs.

SiC devices beyond 10KV have been demonstrated as well (IGBTs, MOSFETs, Diodes), but yields in epitaxial technology, very large area devices and many application hurdles must be overcome within the next 3-5 years before these products can be released and see design in success.

It seems likely that the 1.7KV-6.5KV regime is where the transformative effect of SiC is likely to play out in power electronics over the next decade.

REFERENCES:

[1] Infineon Product Brief, New 650V CoolMOS^{TM} C7 series

[2] Commercialization of 600V GaN-on-Si devices, P. Parikh et. al. (Transphorm, USA), ICSCRM 2013

[3] SiC JFET datasheet Semisouth SJDA065R055

[4] T. Kimoto et. al., Physics of SiC MOS Interface and development of Trench MOSFETs, WiPDA 2013

[5] Datasheets of silicon carbide power MOSFET C2M0080120D and SCT2080KE.

[6] A. Bhalla, et. al. The Outlook for SiC Vertical JFET Technology, WiPDA 2013