Wide-Bandgap SiC and GaN technology market propects in light of progress of Si Superjunction and IGBT technology

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Abstract.

In this (invited) 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 RdsA=10mΩ.cm^2 [1] at 650V. In comparison, the GaN cascode [2] has an RdsA=3mΩ.cm^2 (given the lateral nature of the device) and the normally-off GaN HEMT is estimated to have an RdsA=4mΩ.cm^2. SiC 650V JFETs can achieve RdsA=1mΩ.cm^2, and trench MOSFETs [4] have been demonstrated with RdsA=0.79 mΩ.cm^2. Given the enormous economy of scale advantage enjoyed by Si Superjunction devices, their further cost reduction due to the migration to 12inch, 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. GaN devices can be expected to halve in RdsA as well by improving parasitic resistances, the 2DEG and geometry scaling. SiC devices RdsA can be dropped by increasing channel density, substrate thinning and charge balance methods.

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 or exceed Platinum 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 WBG devices are currently deployed in Similar (TO) packages, and application/package inductance constraints limit the maximum allowed dV/dt and dI/dts. This means that the very high speeds of the latest Superjunction technologies are hard 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 Si FETs in high volume consumer applications in the next 2-4 years, but will instead be targeted to niches where their 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, Solar, Aviation power supplies).

Motor Control at 1200V:

In the 1200V power switch space, the market is dominated by power modules based on Si-IGBTs ($2-2.5B/yr). Superjunction technologies are not commonly available at 1200V, due to the excessive number of epi layers needed, and the slower switching speeds commonly used. 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. IGBTs are currently much lower in cost compared to Si MOSFETs and SiC devices.

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 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. With the rapid improvement in 1200V switch pricing with the advent of 6inch fabrication, this penetration will gain momentum.

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 temperatures/cooling/ripple currents.

>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 ratings of 1700V, 3300V, 4500V and 6500V Switch technology will likely see a challenge from SiC based modules in the next 2 years. 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. 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 3-5years before these products can be released and see design in success. However, this is the regime where the transformative effect of SiC is likely to play out in power electronics.

[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

Table 1: Comparison of 650V technology and costs

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	?	437
Substrate type		12inch	6inch Si	6inch Si	4inch 4H-SiC	4inch 4H-SiC
Substrate costs + Starting Epi	Normalized	0.9	3	3	7	8
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	2.0	5.7	5.2	7.7	7.1
Package/Cascode costs	Relative	0.2	0.2	0.4	0.2	0.4
Effective part costs	Relative	2.2	5.9	5.6	7.9	7.5
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 2: Comparison of 1200V Switch technology

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