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Silicon, GaN and SiC: There's Room for All

An application space overview of device considerations

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***Abstract*— The discrete power device marketplace is estimated between 15 and 22 billion dollars and is comprised primarily of transistors and diodes in a variety of voltage, current, packaging and power ratings. It is an area of intense focus as new technologies such as wide bandgap emerge and new applications such as electric vehicles emerge. Decision makers from Engineers to CEO's are faced with the same decisions they have always faced, comparing power, efficiency and size, yet the decisions are more difficult given the fast-moving pace of these emerging technologies. In this paper, several application spaces ranging from consumer to vehicle to motors will be reviewed, comparing the most critical aspects of the applications against semiconductor choices these decision makes have available. Considerations of the appropriate technologies will be reviewed comparing where the technologies have been, are today, and where they will be in the next 5 years.**

Keywords—Wide bandgap, GaN, SiC, IGBT, MOSFET, HEMT, Motor, Electric Vehicle, power supply, wireless power

I. Introduction

Wide bandgap materials such as Silicon Carbide and Gallium nitride have seen wide adoption in the past five years because of the intrinsic benefits of these materials, when compared to Silicon. Table 1 is a commonly used in comparing wide bandgap materials to silicon.

Table 1 – Material comparison of wide bandgap materials to silicon

Material	Bandgap (eV)	Mobility (cm²/V*s)	Permittivity	Vsat (cm/s)	Critical field (V/cm)
Si	1.1	1400	11.8	$1x10^7$	$3x10^5$
GaAs	1.42	8500	12.8	$2x10^7$	$4x10^5$
4H-SiC	3.23	260	9.7	$2x10^7$	$2.9x10^6$
GaN (Bulk)	3.4	900	9	$2.5x10^7$	$3.3x10^6$
GaN (HEMT)	3.4	1800	9	$2.5x10^7$	$3.3x10^6$

Viewing all semiconductor offerings from a simple table such as shown in Figure 1, is, however, presenting the technologies in a very simplistic view. This paper will review key market trends in Automotive, Consumer and Industrial spaces, critical parameters required in these spaces, and detailed technology comparisons with regard to semiconductor solutions. First, a series of common applications are reviewed, with a look at the architectures and those parameters which are critical to those topologies. Secondly, additional criteria for deciding on technologies are reviewed which focus on the business aspects of decision making, including cost, capacity, reliability and future development predictions. Including these very realistic factors into decision making now will help any company to decide on their product's development roadmap. Finally, a look at market trends for each technology will be reviewed in the context of additional feature sets such as integration capabilities, packaging and power limitations, process improvements and capacity predictions. This holistic overview will show that all technologies can and should be considered for inclusion into the next generation of power electronics.

II. Performance Criteria Overview

In this section, semiconductor device considerations are presented not as a function of their material characteristics as shown in Table 1, but instead, the materials are considered in terms of characteristics the system designer will consider, as shown in Table 2. In Table 2, the primary electrical considerations of voltage, current, and Figure of Merit, as well as other performance factors, are compared, with Figure of Merit being the most universally accepted general comparison between technologies, and between different offerings from various semiconductor suppliers.

Table 2 – Application performance comparison of wide bandgap materials to silicon

Parameter	MOSFET	IGBT	SiC MOSFET	SiC MOSFET	GaN EHEMT	GaN Cascode	GaN GIT
BV_{ds} [V]	650	600	1200	650	650	650	600
I_{ds} [A]	29	30	40	29	31	12	15
$R_{ds,on}$ [mΩ]	45	50*	52	120	41	150	65
Q_g [mΩ]	93	167	115	61	8	6.2	11
$Q_g \times R_{ds(on)}$ [nC×mΩ]	4185	8350	5980	7320	328	930	715
Q_{rr} [nC]	13000	920	283	53	0	54	0
C_{oss} [pF]	70	107	150	90	67	133	-

(*) IGBT equivalent on-state resistance R[illegible] = V[illegible] / I[illegible]

The performance criteria of Table 2 can function as a guide to which technology might be a best fit for a system, but requires a detailed understanding of the application, the critical system requirements and more often than not, the impact of other components such as magnetics in the system. This section will therefore look at a diverse family of applications, in detail, such that a better understanding of the value proposition of any given semiconductor material can be understood.

III. APPLICATIONS REVIEW

Semiconductor decision making applications worldwide, in market segments such as consumer, enterprise, industrial and automotive. In order to understand performance-based decision processes when considering silicon IGBT's and MOSFETs, Gallium Nitride devices and Silicon Carbide devices, the following applications will be reviewed in this section.

- Consumer – Adapters
- Consumer / Enterprise – LLC converters
- Consumer – Wireless Power Transfer
- Enterprise / Automotive – Phase Shifted Full Bridge
- Industrial – Low Voltage Motor drives
- Industrial – Energy Storage systems
- Automotive – On Board Charger
- Automotive – Traction Inverters

In each case, general system priorities such as power density, energy efficiency and system cost will be considered and weighed against the properties of the semiconductor devices which apply to these systems.

A. Consumer Adapters

The adapter space from 25W to 250W, covering commercial fast phone chargers to high end gaming adapters will be presented. Power density and cost will be considered the primary design criteria. Solutions utilizing standard flyback, quasi-resonant flyback and Active Clamp flyback will compared with critical semiconductor parameters considered.

B. Consumer / Enterprise – LLC converters

The LLC converter is considered one of the world's most often-used converter technologies, primarily because it delivers very high efficiency at a low overall cost. It will be shown that the choice of semiconductor device strongly effects the overall performance when combined with the design of the main transformer.

C. Consumer Wireless Power

Wireless power is a fast-emerging technology, ranging from 100kHz to 6.78MHz and higher. Since the driving market is consumer based, the comparison of semiconductor choices is typically between MOSFETs and GaN devices. A comparison of several leading architectural choices, and the appropriate semiconductor device choices will be made.

D. Enterprise / Automotive Phase Shifted Full Bridge

With the onset of electric vehicles, and the wide possible ranges of batteries that can be considered, the Phase Shifted Full Bridge topology can be seen as an excellent choice for vehicle DC/DC converters to convert high voltage batteries to lower system voltages such as 12V or 48V. Design considerations and semiconductor choices will be shown to optimize this architecture.

E. Industrial Low Voltage Motor Drives

Low voltage motor drives can consider tradeoffs in bandwidth, noise, size, efficiency, cost and motor-level-integration to choose from the lowest cost silicon devices to high performance wide bandgap devices. The use of GaN devices have been shown to offer significant system level advantages but requires a relatively new look at the overall architecture. The system benefits of higher frequency and higher efficiency operation will be reviewed against semiconductor device choices.

F. Industrial Energy Storage Systems

Energy Storage Systems (ESS) present an emerging market which highly values energy efficiency. When full power considerations dominate, IGBT silicon solutions are often deemed the best to meet ESS price/performance levels. Since ESS typically run at very low load however, the resistive nature of SiC and GaN offer advantages. An ESS system is presented, with system level benefits studied as a function of semiconductor costs.

G. *Automotive – On Board Charger*

The On-Board charger (OBC) operates between 3.3 and 22kW in automobiles worldwide, with higher levels for commercial vehicles. In an automobile, size and power density are the most critical parameter, next to system costs. Comparisons of Si, SiC and GaN based OBC architectures will be highlighted. The Totem Pole Bridgeless Power Factor Correction circuit, a highly efficient PFC technology, will also be shown to be a key part of any OBC

H. *Automotive – Traction inverter*

The high-power levels of the Traction Inverters, ranging from 10’s of kW to 100’s of kW, have traditionally required high power IGBT solutions, with some SiC and GaN technologies emerging. It will be shown that in normal drive mission profiles, while the IGBT solution offers high efficiency at a low cost, a combination IGBT/Wide bandgap solution may offer the best cost performance. Figure 1 shows a comparison at various drive mission profile levels, of a Silicon, a SiC and a Hybrid GaN/Silicon solution, showing that that semiconductor choice is not automatic.

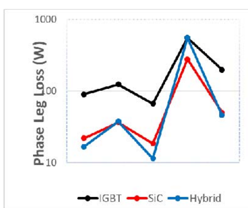

Figure 1 – Historical development of Transistors vs performance

IV. PAST, PRESENT AND FUTURE DEVELOPMENTS

The fact that semiconductors have always evolved should lead us all to realize that semiconductors are now and will continue to evolve. In the power electronics arena, history has demonstrated, as shown in Figure 2, that approximately every 12 years, new technology emerges, evolves and performance is maximized, before new technology emerges. What is not shown in Figure x is that the older technologies do survive long into the marketplace, by either evolving highly specialized versions or by being commoditized.

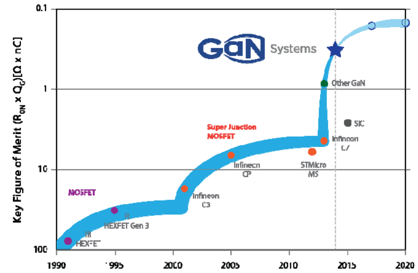

Figure 2 – Historical development of Transistors vs performance

According to IHS [2], the market drivers and inhibitors for the growth of wide bandgap materials is shown in Figure x3. This section will address the state of the semiconductor technologies today and predict where these technologies will go in the next few years. In general, it is assumed that silicon based MOSFET and IGBT technology has fully matured and, as shown by the curves in Figure x, may improve somewhat but dramatically. This section will therefore focus on looking at Silicon Carbide and Gallium Nitride. This analysis will review technology trends that limit or expand the market acceptance of wide bandgap technologies.

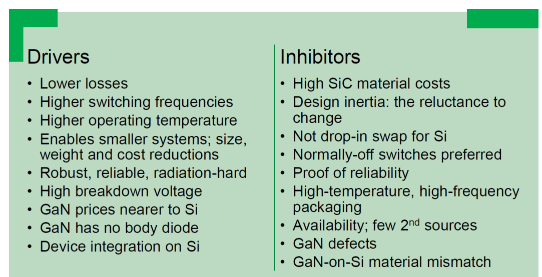

Figure 3 – IHS Market Drivers and Inhibitors

A. *Voltage and current range*

A comparison of voltage ranges for Silicon IGBT’s, MOSFETs, SiC MOSFETs and GaN transistors will be presented showing the breadth of market acceptance by each technology. It will be shown that Silicon MOSFETs, ranging from tens of volts to low kilovolt ranges, compliments Silicon IGBT technologies, that in turn ranges from mid-hundreds of volts to high kilovolt levels.

In a similar way, Gallium Nitride and Silicon Carbine cover the same voltage ranges, with GaN devices dominating from tens to hundreds of volts and Silicon Carbide dominating from approximately one kilovolt to many kilovolts.

Future voltages for GaN devices should range to commercially available 1200V devices to experimental devices to 3300V, while Silicon Carbide devices are now at, and will expand down to 600V.

Current values today show silicon devices reaching into ratings of several hundred amperes, with SiC and GaN devices today limited to just above one hundred Amperes. Both devices show the ability to reach higher currents. Paralleling Silicon, SiC and GaN devices will be quickly compared to show the upside capabilities of each technology.

B. Operating Temperature

Silicon devices have comfortably operated between -55°C to +150°C for some generations now, with high end automotive devices stretching to +175°C SiC and GaN devices have also been able to operate in this same range, but with less proven reliability above +150°C. Theoretical limits of wide bandgap devices show that these devices should be able to be operated at significantly higher junction temperatures but are still limited by yet-to-be-proven reliability and packaging limitations that prevent general acceptance to operating at higher temperatures.

SiC devices in the next several years will continue deliver +175°C rated parts, but will continue to have to prove reliability, and GaN device will remain at 150C for the near time and will lag SiC devices by approximately two to three years.

C. Reliability

Reliability, or the requirement to prove a technology is reliable, has been one of the limiting factors of wide bandgap materials. A summary review of state-of-the-art published reliability data will be summarized, and an overview of the activities of the JEDEC's JC-70 committee will be reviewed, revealing the emerging trends in specifying and proving the reliability of both SiC and GaN Devices.

D. Figure of Merit and Rsp improvements

Performance is generally summarized by the Figure of Merit rating of a technology, while the cost/performance ratio is often compared by studying a technology's specific on resistance, or *Rsp*.

GaN and SiC commercial devices will be summarized with relative performance over the past ten years, with a look to how many more generations are likely to emerge in the next few years.

E. Commercial adoption considerations

The following technology considerations will be summarized and predicted, showing the expected growth of the SiC and GaN technologies.

- Production Capacity and wafer sizes
- Material Availability and manufacturability
- Second Sourcing capabilities
- Market pricing
- Integrated circuit functions

V. CONCLUSION

A wide overview of semiconductor considerations, system architectures, and commercial considerations has been presented to show the complex and ever-changing view of engineers and CEOs alike when choosing a semiconductor technology for their systems. A collection of mainstream high-volume systems has been reviewed with a particular scope of choosing Silicon, SiC or GaN technologies. It has been shown that many factors, both commercial and technical, govern the choice of the perfect device, and the rapid adoption of GaN and SiC devices, the choice is made even harder.

REFERENCES

[1] "Market Forecsasts for SiC and GaN Power semiconductors," IHS Markit, 2018