# Market and Technology Trends in WBG Materials for Power Electronics Applications

Hong Lin

Compound Semiconductor Market and Technology Analyst, Yole Développement, 75 cours Emile Zola, Villeurbannnes , lin@yole.fr, +33 472 83 01 80

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**Abstract**

**With global drivers such as better energy consumption, energy efficiency and reduction of greenhouse gases, $CO_2$ emission reduction has become key in every layer of the value chain. Power Electronics has definitely a role to play in these thrilling challenges. From converters down to compound semiconductors, innovation is leading to breakthrough technologies. Wide BandGap, Power Module Packaging, growth of Electric Vehicle market will game change the overall power electronic industry and supply chain. In this presentation we will review power electronics trends, from technologies to markets.**

INTRODUCTION

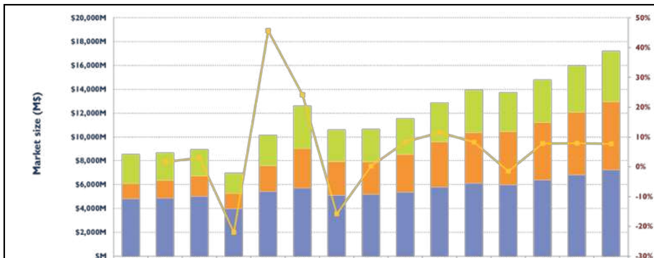
The power electronics industry now deals with conversion and motion, and thus requires lighter/smaller, cheaper and more efficient systems. This evolution starts with improvements at the semiconductor level. There are four technologies which are best suited to handle new system requirements: silicon IGBT, Super Junction (SJ) MOSFETs, Gallium Nitride (GaN) and Silicon Carbide (SiC)-based devices.

POWER ELECTRONIC INDUSTRY

1) Last year, 2014, was a year of recovery for the power electronics market. After two tough years without seeing any growth, in 2014 the market's size increased by 8.4%, reaching $11.5B for power semiconductor devices. The outlook for the years ahead is also optimistic. Market growth will be driven by a significant increase in electric and hybrid vehicle (EV/HEV) sales, as well as the ramp-up of renewable energy and more smart-grid technology implementation. The market will surpass $17B by 2020, representing a compound annual growth rate (CAGR) of 6.9% for the period 2014-2020 (Figure 1).

Power modules, and more precisely IGBTs, will lead this growth. Modules are expected to reach a CAGR 2014-2020 of 10.3%, compared to 5.1% growth for discrete components. This growth in the demand of IGBT modules is due to their improved overall performance in terms of efficiency and thermal conductivity management.

The new wide band gap device market will also drive growth, representing around 5% of the overall market by 2020, even though in terms of units their presence will still be limited.




| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Power IC | $2,458M | $2,335M | $2,218M | $1,708M | $2,562M | $3,587M | $2,690M | $2,744M | $3,007M | $3,278M | $3,573M | $3,287M | $3,583M | $3,905M | $4,257M |
| Power Modules (M$) | $1,280M | $1,489M | $1,709M | $1,286M | $2,181M | $3,298M | $2,828M | $2,730M | $3,173M | $3,805M | $4,262M | $4,458M | $4,845M | $5,267M | $5,714M |
| Discretes (M$) | $4,804M | $4,851M | $5,011M | $3,971M | $5,406M | $5,719M | $5,098M | $5,169M | $5,352M | $5,787M | $6,101M | $5,979M | $6,374M | $6,798M | $7,229M |
| Growth rate (%) | | 1.6% | 3.0% | -22.1% | 45.7% | 24.2% | -15.8% | 0.3% | 8.4% | 11.6% | 8.3% | -1.5% | 7.9% | 7.9% | 7.7% |

Figure 1: 2006 – 2020 power device market evolution

2) In this context the supply chain is evolving. The power electronics supply chain is very diverse and mostly application (and local market) dependent. European and American players will prioritize horizontal integration, keeping proven expertise in a specific level of the value chain. Therefore, partnerships and joint-ventures will be preferred. This paper will review the major mergers and acquisitions of 2014, for instance International Rectifier's acquisition by Infineon, in order to understand their context and purpose.

Some system manufacturers, such as Tesla or BYD, have understood the importance of developing their own power electronics and energy management systems for traction, chargers and batteries in order to offer extended added-value.

Asian companies will prefer to expand vertically in order to be fully integrated and optimize the costs. Japanese players are already vertically integrated and involved in multiple applications simultaneously to benefit from their technologies across different markets. Chinese players are developing this vertical integration in order to create major market leaders in each application segment such as SunGrow in PV, GoldWind in wind and BYD in EV/HEV. This report focusses especially on the details of the Chinese market, which is driven by Chinese Government policies. In this changing environment, western and Japanese players need to bring high added-value solutions to be able to compete with Chinese companies. The strategies of the main players will be presented.

3) The demand for compact products is increasing. Therefore, players are obliged to create partnerships between different industries in order to coordinate and use the synergies of integrated products to offer a smaller and higher-performance solution. Several partnerships are influenced by this trend. In this direction, the concept of the power stack has recently appeared and ever more companies will take part in their development.

Technologically, MOSFETs and IGBTs are and will continue to be the devices in greatest demand, covering low and medium-high voltage applications respectively. New technologies have appeared in the last decade, such as Super Junction MOSFETs, which have brought the MOSFET family into higher voltage segments up to 900V, with better performance. In terms of power packaging, ongoing evolution is driven particularly by the EV/HEV industry.

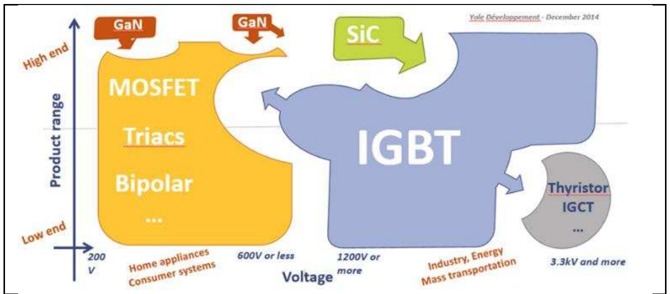



Figure 2: SiC and GaN device positioning among the traditional silicon-based devices

The charge of new wide band gap (WBG) materials is also reshaping the power electronics industry. Silicon carbide (SiC) and gallium nitride (GaN)-based devices are intended for high voltage - especially SiC - high frequency and high temperature applications thanks to their advanced performance compared to silicon devices (Figure 2). SiC technology is more mature than GaN, and so industry segments such as the rail traction and PV inverters have already launched their WBG device systems based on it.

The introduction of SiC into other high voltage segments, such as wind and high-voltage direct current grids is also inevitable. But the big boost for these new markets should arrive with the implementation of SiC devices in electric cars' traction systems. GaN systems are still less present in the market. Some consumer applications, such as laptop chargers, and just-announced PV inverters are going to be the first segments incorporating GaN. Several system manufacturers are also developing further SiC and/or GaN device-based prototypes and thus the next 5 years are going to be decisive for WBG devices' introduction into different markets.

GAN IN POWER ELECTRONICS

1) Overall, 2020 exhibits a projected market size for devices of almost \$600m, leading to approximately 580,000 x 6" wafers to be processed. Ramp-up will be quite impressive starting from 2016 with approximately 80% CAGR to 2020, based upon the scenario where EV/HEV starts adopting GaN in 2018-2019.

From 2015, Power Supply / PFC segment will dominate the business until 2018 where it should represent 50% of the device sales. Automotive will then catch-up.

In the UPS applications, medium power segment is probably much more in line with GaN value proposition as savings at system level is demonstrated. We think GaN technology could grab up to 15% of market shares in this field in 2020.

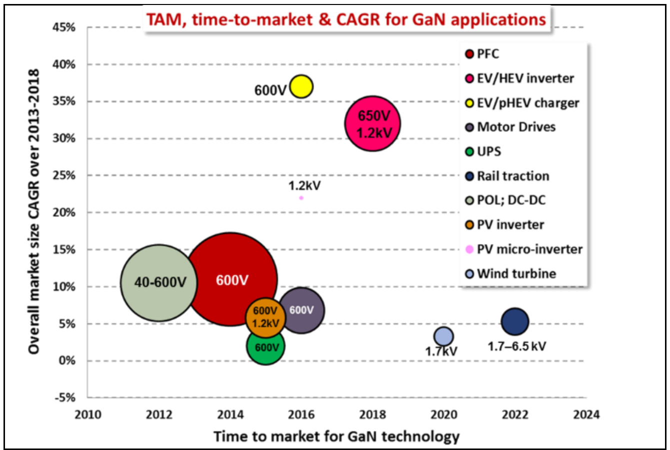



Figure 3: Estimated accessible markets, growth rate, and time to market of main GaN applications

Room for extra cost in motor drive applications is very unlikely. Therefore, the incentives to implement new technologies such as GaN have to be serious and strong. Considering the possible improvement on the conversion efficiency augmented by a predictable price parity with Si solution by 2018, we do expect GaN to start being implemented in motor control by 2015-2016, at quite a slow rate, and reach about \$45m revenues by 2020 (Figure 3).

PV inverters has already adopted SiC technology and products are now commercially available. GaN could possibly partially displace SiC, playing with a better price positioning. However now that SiC is in place, the qualification of GaN may be more challenging.

2) Recent announcements shows the GaN industry is shaping along mergers, acquisitions and license agreements. Latest Transphorm-Fujitsu agreement in addition to Furukawa IP portfolio exclusive licensing are very positive signs that GaN technology is spreading over all the value

chain, reinforcing market position of leaders but also probably leaving weakest players by the wayside of the road. Reasonably speaking, we are forecasting 2014 will only generate $10m to $12m device sales. Such a moderate business will only let the strongest survive and will probably kill several early-birds who will see their cash-flow quickly melting.

We think that real power GaN business will only decently start by 2016, exceeding the psychological threshold of $50m revenues. The key question is now: how to survive another 1.5 to 2 years? Far from being overly-pessimistic, we are afraid some entities won't cross the chiasm and will be acquired or will go bankrupt.

Today power GaN business is mainly centered on low voltage DC-DC converter (typically Point-of-Loads POL) using available 200V-rated devices. However this business only generates a few million $ revenues. Thanks to 600V device introduction this year, GaN will certainly grow quite fast in power-supply and PFC applications where technical added-value and economics are obvious.

We have simulated several case-studies and came to the conclusion that even though today market price for GaN devices exceeds Silicon ones, the improvement on efficiency and savings on the electricity bill can compensate this extra cost in less than 1 year for a 300W 24/7 operation power supply (data server type). Projected in 2018, the same power supply could even be cheaper than the silicon counterpart simply thanks to the reduction on passives (capacitor, self induction) cost, along with switching frequency increase.
Therefore, we envision a preliminary take-off of the PFC segment by 2015 along with an 80% CAGR over 2016-2020.

Other applications such as the PV inverter and, to a lesser extent, in motor control, we see GaN starting to capture market share by 2015-2016.

The next big thing, will unquestionably be EV and HEV segments where GaN could definitely play a role in power systems such as low-voltage (14V -> 200-400V) DC-DC converters and later on for battery chargers (on-board 3.6 & 7.2 kW first then off-board 50kW+). However, we do not see any chance for GaN to enter in the power-train inverter (60kW+) before 2019-2020, due to the lack of current capability and projected price of high-current devices.

3) 600V-rated GaN devices have been announced and promoted more than 2 years ago. However, only a few preferred customers have had access to it for qualification purposes. The majority of the power electronics community is unable to source such devices. That has probably affected the GaN technology credibility and let room for main competing technology, SiC, to keep on expanding its presence over the industry.

Similarly Noff (e-mode) availability has also been over promoted and real devices with stable and reliable specs took time to be diffused from off-the-shelf. It seems that now the main players have caught-up with their original roadmap and devices are now available on the market place.

2014 was a game changing year as many players announced the availability off the shelf of 600V+ GaN-on-Si devices (Figure 4).

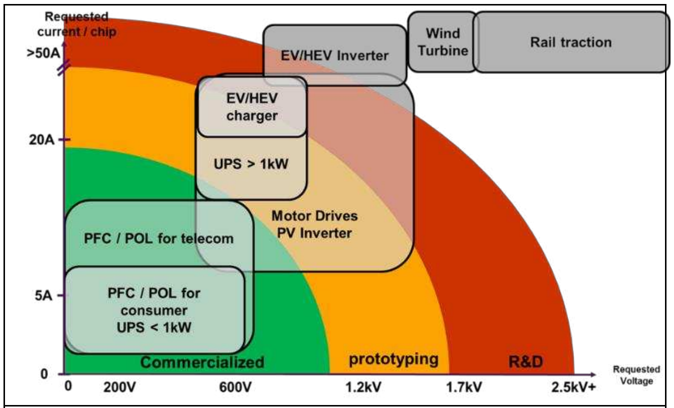



Figure 4: 2015 projection GaN device state-of-the-art (V & Amp) vs. application requests

SIC IN POWER ELECTRONICS

1) In 2013, SiC chip business has almost reached $100m thanks to already well-established PFC applications that still drives large volumes of diodes as well as PV systems that, despite a depressed market, was the landing field for newly SiC-powered inverter or micro-inverter line-ups. Surprisingly, train traction has adopted SiC sooner than expected thanks to the availability of 1.7kV full or hybrid modules that have been demonstrated and installed by Mitsubishi Electric in Japan.

Rail application could dynamically expand exhibiting a >80% CAGR over 2015-2020 since we expect other rolling-stock manufacturers will quickly adopt SiC in the metro first then in the high-speed trains. We also forecast PV inverters to keep on implementing SiC at almost 12% annual growth rate.

Adoption of SiC in train applications is a significant point showing how SiC could play an important role in the high and very high voltage ranges (>1.7kV). We stay convinced that these voltage (and related power) ranges is exactly the place where SiC can bring added-value despite a price positioning that won't play in the same playground than silicon. Here the savings are made at system level when passives and other cooling can be dramatically reduced when moving to SiC.

On the other hand, PFC will probably face more and more incoming GaN competition that is now claiming being able to compete on the 600V segment. Therefore we remain quite conservative regarding this application that may switch to Nitrides in the coming years.

2) It has always been said that SiC could play a major role in the EV/HEV power electronics. Most of the car makers do agree on a value of 10% fuel savings when moving from silicon to SiC in hybrid vehicles. For a pure electric car this metric will be translated into less battery needs or extended range for a given battery pack. It is now obvious that EV/HEV could easily capture the biggest portion of the SiC business cake.

However, even though all technical indicators are green, car industry is reluctant to implement SiC right now claiming that economics are not yet fully compatible with their expectations. Such conservatism is heavily impacting our previous predictions as, according to key industrial voices (Toyota, Denso, Honda, Nissan…), SiC will only be on the short list by 2018 for the most optimistic or 2020 for some others. By adding GaN 600V Noff devices now in the starting blocks, we are landing to the most conservative scenario we developed in the past years exhibiting a SiC device business in 2020 that will exceed $400m.

For the n-type substrates, 4” wafers are the main stream product on the market. The introduction of 6” n-type substrates in the power electronics devices are slower than expected. The quality of 6” wafers seems to still be an issue and the price is highly dependent on the quality, varying from 1300$ to 2000$. What is more, 6” wafers are still in constrained supply (Figure 5).

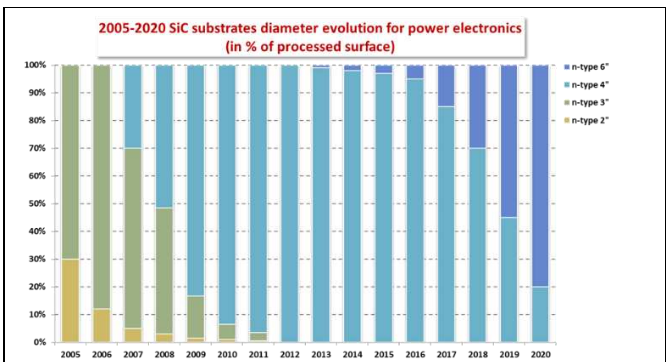



Figure 5: 2005-2020 SiC substrates diameter evolution for power electronics (in % of processed surface)

The ratio between the price of 6” and 4 n-type substrates is about 2.5X, which is still too high and does not make 6” wafers appealing for the device makers, despite their intention to transition to 6” to reduce device cost.

The price of 6” n-type wafer are expected to drop quickly in the two coming years and fall below the 1000$ threshold. The large scale transition to 6” is expected to take place in 2016-2017.

Concerning the players, Cree remains the market leader by far. II-VI, Dow Corning and SiCrystal are following. Asian players are gaining the market shares little by little but their volumes are still small compared to the leading players at the moment.

3) China is already a big player in the power electronic field with most of the integrators. At the device level, China has invested significant amounts in R&D and production of IGBTs in the recent years. Compared to US, Europe and Japan, China still has some way to go.

China is hoping to catch up with US, Europe and Japan in the power electronics field, with so called “third generation of semiconductors” (SiC & GaN). Consequently, Chinese government has put important funding in the SiC R&D and industrialization. Since 2006, several companies enter gradually in the SiC playground. Now, there are Chinese companies covering the entire value chain, from the material end to the device end (Figure 6).

In Asia, Japan is leading the SiC activities, China is catching up, and Korea is coming.


Figure 6: China Wide Band-gap Power Semiconductor Industry Alliance

## Conclusions

In conclusion we have successfully reviewed the power electronics trends from technologies to markets through the consideration of the device trends, their adoption rate and the materials considered.

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