Market and Technology Trends in WBG Power Module Packaging
2014 Power Electronics Market Status
POWER ELECTRONICS AND 21\textsuperscript{ST} CENTURY CHALLENGES

World Evolution lead to new challenges for power electronics

- Population Growth
- Mega Cities
- Energy Production
- Transportation needs
- Renewable Energy
- Efficiency Improvement
- Limited Resources
- \( \text{CO}_2 \) Emission Reduction
After two tough years, the 2014 is the recovery year with a market of 11.5 B$.

Power device market evolution between 2006 and 2020

2006-2020 power device market size > 400 V

Market size (M$)

<table>
<thead>
<tr>
<th>Year</th>
<th>Power IC</th>
<th>Power Modules (M$)</th>
<th>Discretes (M$)</th>
<th>Growth rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>$2,458M</td>
<td>$1,280M</td>
<td>$4,804M</td>
<td>1.6%</td>
</tr>
<tr>
<td>2007</td>
<td>$2,335M</td>
<td>$1,409M</td>
<td>$4,851M</td>
<td>3.0%</td>
</tr>
<tr>
<td>2008</td>
<td>$2,218M</td>
<td>$1,709M</td>
<td>$5,011M</td>
<td>-22.1%</td>
</tr>
<tr>
<td>2009</td>
<td>$1,708M</td>
<td>$1,286M</td>
<td>$3,971M</td>
<td>45.7%</td>
</tr>
<tr>
<td>2010</td>
<td>$2,562M</td>
<td>$2,181M</td>
<td>$5,466M</td>
<td>24.2%</td>
</tr>
<tr>
<td>2011</td>
<td>$3,587M</td>
<td>$3,290M</td>
<td>$5,719M</td>
<td>-15.8%</td>
</tr>
<tr>
<td>2012</td>
<td>$2,690M</td>
<td>$2,820M</td>
<td>$5,098M</td>
<td>0.3%</td>
</tr>
<tr>
<td>2013</td>
<td>$2,744M</td>
<td>$2,730M</td>
<td>$5,169M</td>
<td>8.4%</td>
</tr>
<tr>
<td>2014</td>
<td>$3,007M</td>
<td>$3,173M</td>
<td>$5,352M</td>
<td>11.6%</td>
</tr>
<tr>
<td>2015</td>
<td>$3,278M</td>
<td>$3,805M</td>
<td>$5,787M</td>
<td>8.3%</td>
</tr>
<tr>
<td>2016</td>
<td>$3,573M</td>
<td>$4,262M</td>
<td>$6,101M</td>
<td>-1.5%</td>
</tr>
<tr>
<td>2017</td>
<td>$3,287M</td>
<td>$4,458M</td>
<td>$5,979M</td>
<td>7.9%</td>
</tr>
<tr>
<td>2018</td>
<td>$3,583M</td>
<td>$4,845M</td>
<td>$6,374M</td>
<td>7.9%</td>
</tr>
<tr>
<td>2019</td>
<td>$3,905M</td>
<td>$5,267M</td>
<td>$6,798M</td>
<td>7.7%</td>
</tr>
<tr>
<td>2020</td>
<td>$4,257M</td>
<td>$5,714M</td>
<td>$7,229M</td>
<td>7.7%</td>
</tr>
</tbody>
</table>
What evolution for power devices between 2014 and 2020? Split by voltage

Medium voltage devices will have the highest growth by 2020.

Low Voltage
400 -> 900V

Medium Voltage
1.2kV -> 1.7kV

High Voltage
2kV -> 3.3 kV

Very High Voltage
> 3.3kV

Power Electronics, by voltage. Comparison 2014 - 2020

<table>
<thead>
<tr>
<th>Voltage</th>
<th>2014</th>
<th>2020</th>
<th>Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Voltage</td>
<td>$8.430M</td>
<td>$11.881M</td>
<td>+41%</td>
</tr>
<tr>
<td>Medium Voltage</td>
<td>$2.021M</td>
<td>$3.541M</td>
<td>+74%</td>
</tr>
<tr>
<td>High Voltage</td>
<td>$748M</td>
<td>$1.208M</td>
<td>+61%</td>
</tr>
<tr>
<td>Very High Voltage</td>
<td>$327M</td>
<td>$552M</td>
<td>+69%</td>
</tr>
</tbody>
</table>
Geographical split

- **Asia is still the destination** of more than 75% of power products. Most of the integrators are located in China, Japan or Korea.
  - The biggest integrators' production lines are concentrated in China, with almost 40% of devices delivered to this country.
  - Asia's share is increasing as European integrators open new manufacturing lines in these “low-cost” manufacturing countries.
  - Asia's dominance over power device sales has grown from 65% in 2011.
- **Europe** is very dynamic as well with top players in traction, grid, PV inverters and motor control.
- **The big names of the power electronics industry are historically from Japan.** Their industry is very much vertically integrated, with a considerable part of devices sold in the local market in Japan.
Semiconductor Devices plenty of opportunities for WBG
SEMICONDUCTOR DEVICES: PLENTY OF OPPORTUNITIES FOR WIDE BANDGAP

Life–Cycle of Power Device Technologies

A new generation every ~20 years…

Bipolar

Unipolar

Field Effect Transistors

1970

1990

2015

2020

Diode

Thyristor

GTO

IGCT

IGBT

MOSFET

BJT

SiC BJT

Gen. 2
Max. 600V

Gen. 6
Max. 6500V

SJ MOSFET

SiC JFET

SiC MOSFET

SiC diode

GaN HEMT

Thyristor & MOSFET era

Si IGBT era

WBG era??

Silicon
SiC
GaN

A new generation every ~20 years…
SiC will stay the preferred choice for high $T^\circ$ application.

GaN could possibly reach high-voltage values but thus will require bulk-GaN as the substrate.

Silicon cannot compete at the high-frequency range.
High electron mobility and high junction temperature are the key characteristics.

- **Intrinsic properties**
- **Impact on operation**
- **Impact on power module**
- **Impact on power system**

**High Junction T°**
- No recovery time during switching
- Low losses: less energy to dissipate
- Fewer cooling needs

**High electron mobility**
- High switching frequency
- Smaller filters and passives

**System size and weight reduction**
SEMICONDUCTOR DEVICES: PLENTY OF OPPORTUNITIES FOR WIDE BANDGAP

Power device technology positioning

- Historically, silicon had the complete monopoly of the semiconductors industry in Integrated Circuits (IC), in Microchips and in Power Electronics.
- New raw materials for semiconductors such as Wide Bandgap materials Silicon Carbide (SiC) and Gallium Nitride (GaN) have been developed since some decades now.

WBG devices are primarily positioned in high-end applications.
Example on SiC
IMPLEMENTATION OF SiC IN POWER ELECTRONIC MARKET

Relative device market shares 2013 vs 2020

Currently, PFC and PV represent the largest applications for SiC devices.

- Rail
- PFC
- EV/HEV
  - Inverter
  - Wind
- Grid
- PV inverter
- Motor control
- UPS
- Others, MilAero

2013

$96 M

2020

$362 M

Source: SiC report 2014, Yole Développement
MAIN PLAYERS – ORIGIN OF SiC INVOLVEMENT

Large amount of companies in SiC Playground

From SiC material to SiC device
- Infineon
- Fraunhofer IISB

From Si to SiC device technology
- ROHM
- Panasonic
- Raytheon
- Renesas
- Microsemi
- STMicroelectronics

From others III-V to SiC device technology
- SanRex
- DENSO
- Mitsubishi Electric
- Fairchild Semiconductor
- Toshiba
- Bosch
- Hitachi
- JRC

New entrant SiC pure-player
- Global Power Technologies Group
- GeneSiC
- USCi
- ascatron
- Northrop Grumman
- Monolith Semiconductor Inc.
Before 2009, the market was dominated by Cree and Infineon.

COMMERCIAL SIC DIODE PRODUCTS (1/2)

Date introduced to the marketplace

- **600V/10A SBD**
  - Jan 2002
- **First 600V SBD**
  - June 2001
- **600V/20A SBD**
  - Aug. 2002
- **First 1.2kV SBD**
  - Feb. 2003
- **2nd gen. SBD**
  - May 2005
- **1.2kV SBD**
  - Feb. 2007
- **1.2kV SBD**
  - Feb. 2003
- **600V JBS**
  - July 2009
- **600V SBD**
  - Feb 09
- **3rd gen. SBD**
  - Feb 09
- **First 600V SBD**
  - June 2001
- **600V/10A SBD**
  - Jan 2002
- **600V SBD**
  - July 2009
- **1st gen. SBD**
  - 2001
- **2nd gen. SBD**
  - May 2005
- **3rd gen. SBD**
  - Feb 09
- **600V SBD**
  - Feb 09

(Next slide)
COMMERCIAL SIC DIODE PRODUCTS (2/2)

Date introduced to the marketplace

More players have come into the playgrounds.
More and More SiC transistors availables.
POWER ELECTRONICS SIC DEVICE MANUFACTURING

Status of SiC device makers as of Q2 2015

Time to mass-production

Year

0 1 2 3 4 5 6 7

Prototyping

Qualification

Ramp-up

Mass-production

New Japan Radio
NEEDS ON POWER PACKAGING DEVELOPMENT

• Even if wide bang gap semiconductors comes to a sufficient TRL level, Power packaging is becoming one of the bottleneck for wide adoption.

• It is important to notice that market shares are not directly linked to when will the component be available but rather when integrators be able to get benefits from these component is their systems.

• Designing a totally new product with these new semiconductors will induced R&D expenses that has to be compensated by the added value at the system level (cost, size, operating condition, etc..) compare to regular Silicon solutions.

• To grab this added value, an integrator has to get full benefits from wide band gap devices with:
  • An increased operating frequency
  • An increased operating temperature

• Latest developments in power packaging that enable low stray inductance package and reliability at high temperature fully impact future trends in the compound semiconductor.
Power packaging innovations: Key developments for large WBG devices adoption
POWER PACKAGING MARKET AND TRENDS

How is a standard power module designed?

- Power module with baseplate is the standard design (70 to 80% of available power modules).
- DBC (Direct Bond Copper) packaging is the most widespread packaging. These modules are complex and expensive.
- Common failure in a power module is caused by thermal cycling. Mismatching CTE (Coefficient of thermal expansion) can make layers detach from one another. Some gel filling also cannot handle high temperatures.

A standard power module is a complex assembly of different materials including active devices.
Many innovations are taking place in power module packaging.

**COMPETITIVE PACKAGING TECHNOLOGY**

Improvement aspects in packaging, with examples…

**All applicable to Si and SiC**

- **Die interconnection**
  - Ge power overlay
  - Delphi Viper
  - aPSi3D module

- **Die attach**
  - Includes cooling

- **DBC + baseplate**
  - Includes cooling

Improvements in packaging can be made in 3 different aspects:

- **Die interconnection**, which is searching for innovative wire bonding or no-wires connection for better lifetime and reliability
- **Die attach**, which uses new materials for better lifetime
- **DBC+baseplate**, which uses new materials and suppress layers for improved cooling and smaller size
Both materials and design are evolving in the power module.

**POWER PACKAGING MARKET AND TRENDS**

Which evolution for each part of modules?

<table>
<thead>
<tr>
<th>Interconnections</th>
<th>Encapsulation</th>
<th>Die attach</th>
<th>Substrate</th>
<th>TIM</th>
<th>Baseplate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al wire bonding</td>
<td>Silicon gel</td>
<td>Sn soldering</td>
<td>DBC</td>
<td>Thermal grease</td>
<td>Standard baseplate</td>
</tr>
<tr>
<td>Ribbon bonding</td>
<td>Epoxy resin</td>
<td>TLPS</td>
<td>AMB</td>
<td>PCM</td>
<td>Double side cooling</td>
</tr>
<tr>
<td>Cu wire bonding</td>
<td>Silicon gel/epoxy resin high temperature</td>
<td>Silver (paste/film) sintering</td>
<td>Leadframe</td>
<td>Single/double layer</td>
<td></td>
</tr>
<tr>
<td>“Top side” bonding</td>
<td>New materials such as parylene</td>
<td>AuSn/AuGe Brazing</td>
<td>No substrate?</td>
<td>Which evolution for TIM? Removal?</td>
<td></td>
</tr>
<tr>
<td>Ball bonding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2015 | 2018 | 2020 | 2025...
In the future, power modules will have been entirely reshaped, with the changes depending on the power targeted.

**Bosch example**
- Molded package
- Double side soldering
- Low inductance

**Mitsubishi example**
- Six Pack IGBT/Diode Package
- Cooling fin
- Thick copper layer for thermal spreading
- Direct substrate cooling
- Encapsulation with parylene
- Ribbon bonding
- Silver (Ag) sintering for die attach
- Pin-fin baseplate

**Mid-power modules**
- Die on heatsink
- Ceramic heatsink?
- Ball bonding?

**High-power modules**
- Wide use of leadframe
- Over-molded package
- Top interconnections
- Ag sintering for die attach
- Encapsulation with parylene
- Ribbon bonding
- Silver (Ag) sintering for die attach
- Pin-fin baseplate
Low inductance and high temperature packaging are key issues for WBG module packaging.

As courtesy of ABB

Linpak has a very low-inductive internal module design and the massive DC-connection enables both, a very low-inductive busbar design and a high current carrying capability. LinPak is becoming the latest standard for IGBT and could be used for future SiC solutions.

APEI HT-3000 WBG power module: 1200V, +400A, 200°C, industry standard footprint;

Parasitic inductance comparison between the HT-3000 and other power module types.
• WBG material provide additional possibilities compare to regular Silicon. Such performances can have benefits all over the value chain, from the device to the converters and systems.

• After many years of developments, WBG devices exist now on the marketplace. Their performances in term of voltage and current rage are compliant with most of designers needs.

• However, these devices have not spread over the market and reach a large volume. Packaging is one of the factors slows down the market adoption.

• Low inductance and high temperature packaging are key issues for WBG module packaging. Despite some intial tentatives, more efforts are needed to develop suitable packaging for WBG modules to bring WBG devices to a larger market.
Any questions?
Hong LIN

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