ADVANCES IN POWER ELECTRONICS

Chris Bailey, Ph.D.
University of Greenwich
London, UK
c.bailey@gre.ac.uk

ABSTRACT

Power electronics is seeing significant growth due to electrification of transport, and carbon reduction using renewable energy. Innovations in devices (e.g. wide bandgap materials such as Silicon Carbide and Gallium Nitride) provide the opportunity to design smaller power electronic systems that are highly efficient. A key to realizing these benefits is innovations in packaging and design tools. Traditional materials and packaging architectures need to address the new environments that they will be subjected to higher temperatures, frequencies, and inductances, etc. New design and modelling approaches will be required to support innovations in packaging and reliability predictions. This paper details some of the recent advances in power electronics systems and details some of the challenges that need to be overcome.

Key words: Wide Bandgap, Power Electronics, Packaging, Design and Modelling.

INTRODUCTION

Power electronics refers to solid-state electronic devices that are used for the conversion and control of electrical power. Traditionally devices for this have been based on silicon such as MOSFETs (Metal-oxide Semiconducting Field-Effect Transistors) and IGBTs (Insulated-Gate Bipolar Transistor) which have been used in inverters (DC to AC), rectifiers (AC to DC), and converters (AC to AC, DC to DC). Silicon MOSFETS are used for applications with voltages below 600V but above 100V they can be subject to higher conduction losses. For voltages above 600V the use of the Silicon IGBT device is the preferred option. Given the need for operating power semiconductors at higher switching frequencies (to reduce losses), there has been significant interest in adopting wide bandgap devices such as Silicon Carbide and Gallium Nitride.

Key drivers for power electronics is the electrification of transport and reduction of carbon emissions through renewable energy. One of the highest growth areas for power electronics is in automotive where power electronics is used in automobile invertors (1). This paper details the latest advances in power electronics related to devices, packaging, and design.

DEVICES

Silicon based semiconductor device types such as BJT, MOSFET, and IGBT have a long history in power electronics modules. Wide band gap semiconductor materials (2) such as silicon carbide and gallium nitride provide the ability to operate a higher frequencies, power, and temperature compared to silicon. Hence there has been significant interest in adopting wide band gap devices for next generation power electronics systems. Figure 1 details material properties for these materials compared to silicon.

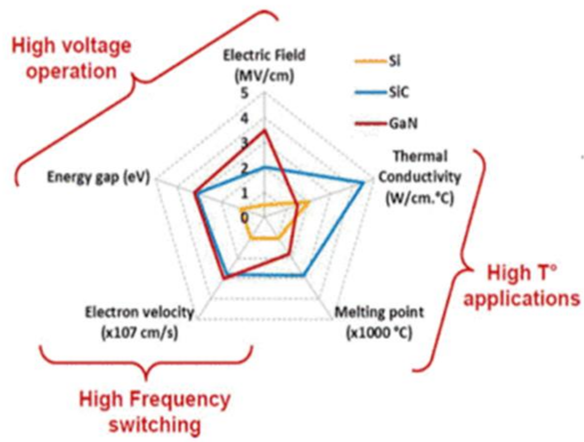

Figure 1: Comparison between Silicon, Silicon Carbide (SiC) and Gallium Nitride (GaN).

The properties of both SiC and GaN provide the opportunity to run at higher operating temperatures, frequencies and voltages compared to silicon. Each has advantages for different applications characterized by the required power and operating frequency as detailed in figure 2:

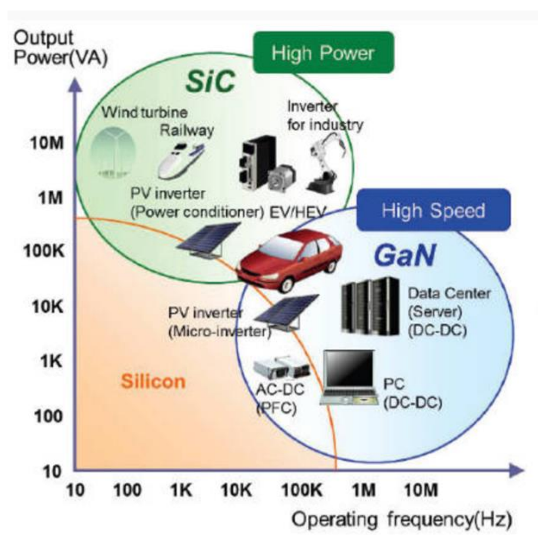

Figure 2: Applications for Silicon, Silicon Carbide and Gallium Nitride (Source CEA-LETI, France)

The faster switching frequencies will also result in lower power losses, and result in smaller and more efficient devices. Silicon carbide is particularly attractive for high power and high temperature operations due to is excellent thermal properties. Gallium Nitride is particularly suitable for mid-power but high frequency operations. The challenge for both devices is controlling parasitics (inductance, EMI) and thermo-mechanical behavior of associated packaging technologies. As detailed in the recent market report (2), the growth of Sic and GaN device market is expected to exceed $1Bn in 2020 and grow to $10Gn by 2028.

PACKAGING

Power semiconductors can be packaged as discrete or as modules which can combine both the power transistors with the diodes and other passive components into a single module. Figure 3 illustrates the conventional module for higher voltage applications (3) where the power module containing the power semiconductors and diodes is connection to the gate driver PCB through copper busbars.

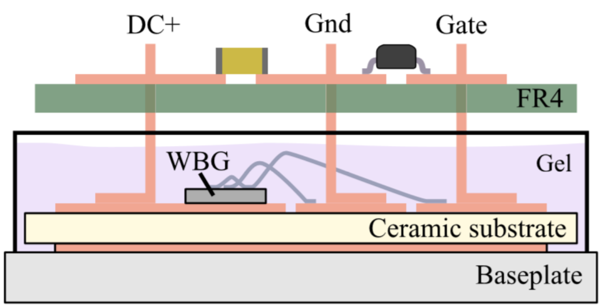

Figure 3: Conventional Power Module (3)

The challenge for this module architecture – particularly for high frequency devices is the high level of inductance and electro-magnetic interference that can be imposed on other devices on the PCB. Other packaging architectures can developed such as PCB embedding where the power semiconductor is embedded into the PCB, or DBC embedding where the PCB is removed and the passive components are packaged inside the power module, The fourth option is a combination of PCB and DBC embedding as illustrated in figure 4.

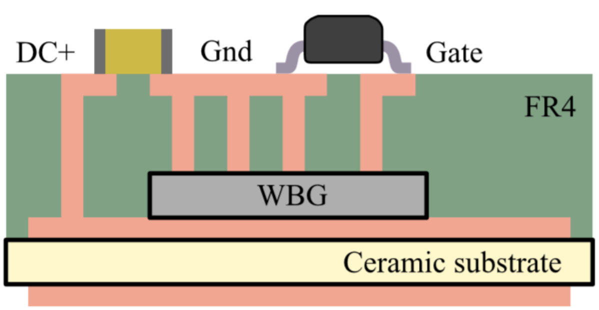

Figure 4: Alternative packaging architecture (3)

Each of these architectures have their advantages and disadvantages with regards inductance, thermal, electric fields, and manufacturability. This is illustrated in table 1.

Table 1: Advantages/Disadvantages for Power Module Architectures (3)

	Inductance	Thermal	E-field	Manufacture
(a) Conventional	− −	+ +	+ +	+ +
(b) PCB embedded	+ +	−	−	−
(c) DBC integrated	+	+ +	+ +	+
(d) PCB/DBC	+ +	+ +	+	− −

Figure 5 illustrates the metal interconnects that are required for electrical connections to the power semiconductor die. It also illustrates the potential failures that can occur at the die-attach and at the current connector on the die.

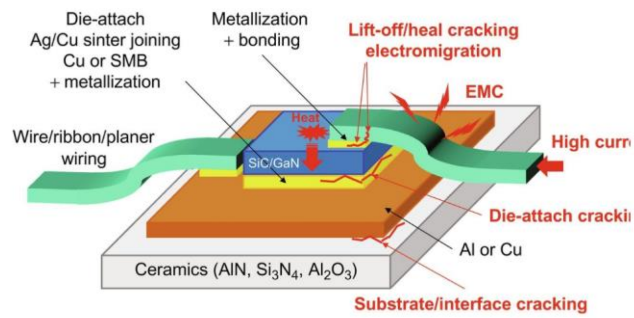

Figure 5: Metal interconnects for power devices (4).

Different die attach and electrical interconnects can be used. For die attach these can be:

- High temperature solders (MP 260 – 400C)
- Transient liquid phase bonding
- Sintered silver or copper

For the electrical connection to the power die options exist such as:

- Aluminum or Copper wiring
- Aluminum of Copper ribbon bonding
- Copper lead frame bonded to the die with solder or sintered

Each has their advantages and disadvantages in terms of their electrical and thermo-mechanical behavior (4). The use of ribbon bonds has been found to provide both thermal and mechanical benefits where one ribbon bond can replace three wire bonds and the structural behavior of this ribbon bond mitigates failures found with wire bonds (5).

The advantages of using silver as the bonding material is clear as its melting temperature is 960C, and hence its homologous temperature is in the range 0.19-0.4 compared to traditional solders with melting temperatures around 200C and homologous temperatures 0.5-0.9 related to the junction temperature of power semiconductor devices including wide band gap devices which can operate at much higher temperatures compared to silicon. Figure 6 details solver powder before and after sintering. Clearly the sintering process governs the microstructure and porosity of the final bond. Table 2 details the properties of both SnAg and sintered silver detailing its favorable properties.

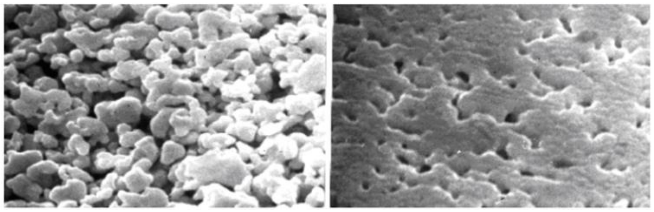

Figure 6: Silver powder and Sintered Silver structure (6)

Table 2; Properties for SnAg and Sintered Silver

Property		SnAg	Ag Sintered
Melting Point	C	221	962
Thermal Cond	W/mK	70	240
Electrical Cond.	MS/m	8	41
Layer Thickness	Um	90	20
CTE	Ppm/K	28	19

Another packaging technology used for power devices is the press-pack. This approach avoids the use of wirebonds and die attached where the power devices operate under pressure. A key requirement is the quality of the interfaces at the power die in terms of electrical and thermal resistance. Figure 6 illustrates this type of package.

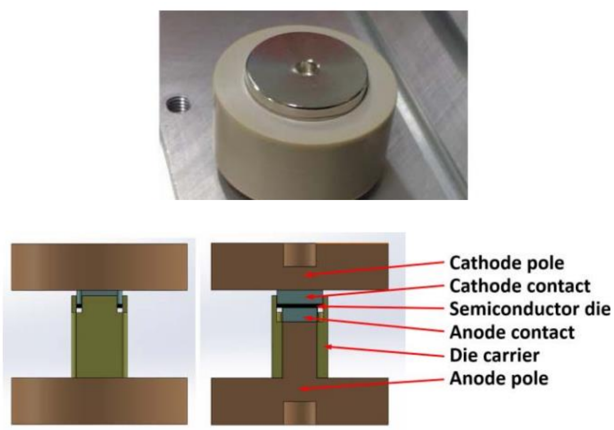

Figure7: Press Pack Architecture

Understanding the behavior of the contact pad materials and the semiconductor die under different clamping forces is a key requirement for the adoption of this type of package. Both Molybdenum and Aluminum Graphite are candidates for these contact pad materials, and both show good thermal behavior although greater stress is predicted with AlG pads (7).

DESIGN & MODELLING

For the power electronics packaging engineer key objectives for future power electronic systems are illustrated in figure 8.

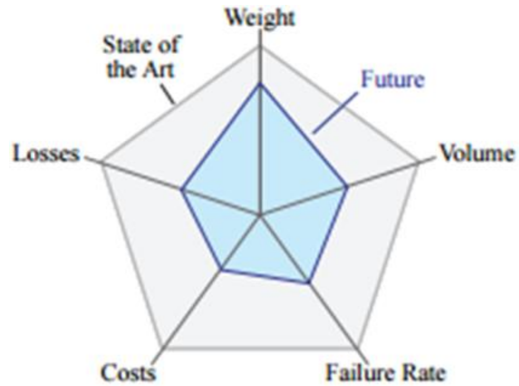

Figure 8: Key objectives for future power electronic systems

Expanding on the above we can state that future power electronic systems must have

- Reduced Volume and Weight
- Higher power density
- Higher efficiency
- Higher reliability
- Lower Parasitics (EMI, etc.)
- Lower costs

The adoption of wide band gap devices addresses a number of these objectives. Although in terms of packaging there is a requirement to address and predict parasitics, thermo-mechanical behavior, and reliability. Figure 8 details the current design workflow adopted by power electronics module designers:

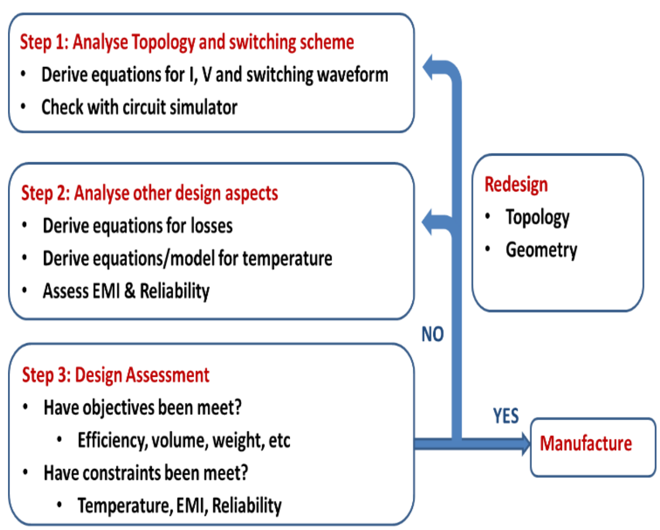

Figure 9: Traditional Design Flow

Much of these calculations are based on spreadsheets, previous knowledge, and single physics finite element modelling (electrical, thermal, mechanical). But for future power electronic systems – and those related to wide band gap devices – there is a need for multi-physics (multi-domain) design and modelling capabilities across the device, package, and system domains. Figure 9 illustrates this design flow within a multi-objective optimization framework.

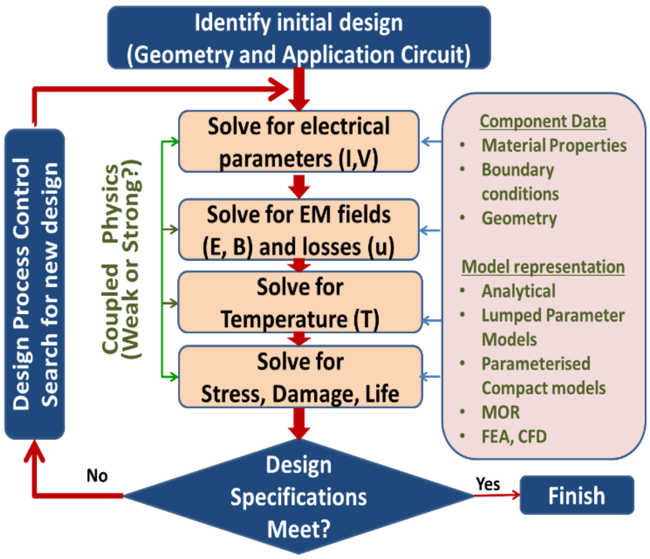

Figure 10: Design and Modelling Flow within Optimization Framework for Virtual Prototyping

Numerous tools are available for these types of analysis ranging from high fidelity finite element and computational fluid dynamics tools to behavioral models and spice circuit simulation models. The key requirement is the level of fidelity required at each stage of the analysis and how device, module, and system level models can be used collaboratively throughout the product development chain. In terms of reliability, a physics-of-failure approach is required, and this necessitates the need for accurate materials data and lifetime models for failure mechanisms and modes.

CONCLUSIONS

Power electronics is seeing significant growth due to drivers such as electrification of transport (e.g. electric cars) and carbon reduction using renewable energy (PV, wind, etc.). The use of silicon as the semiconductor material for devices is reaching its limits for many of these applications. Wide band gap devices with their ability to operate at higher frequencies, voltages and temperatures provide an opportunity to address these limits. But challenges need to be overcome such as:

- Wafer yield at 150mm is low compared to silicon.
- Innovations are required for gate drive designs, high dv/dt, and electromagnetic interference.
- Cost of SiC and GaN is still prohibitive to completely replace silicon
- Packaging and materials innovations are required to address EMI and thermo-mechanically induced stresses.
- Co-Design and Co-Simulation tools are required to optimize designs of future power electronics systems
- Innovations are required for magnetic materials to address core losses at high frequencies.

The power electronics community is growing bringing in engineers from different disciplines: electrical, mechanical, etc. Several organizations are documenting the current challenges for power electronics and posing potential solutions to these over a 5-15-year timescale through roadmaps such as:

- International Technology Roadmap for Wide Bandgap Devices (ITRW)
- Heterogeneous Integration Roadmap (HIR)
- Power America's Strategic Roadmap for Next Generation Wide Bandgap Power Electronics

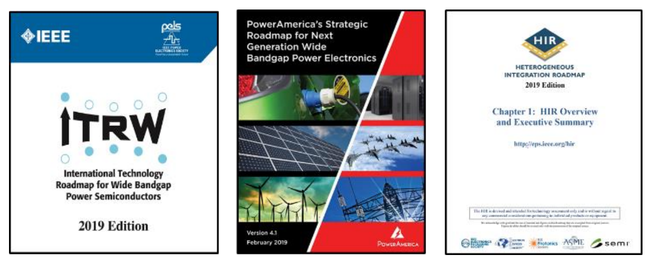

Figure 11: Power Electronics Roadmaps

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