Power Packaging for Automotive Semiconductors – Now and Future

Dr. Ajay Sattu
Sr. Manager, Automotive Strategic Marketing
Amkor Technology, Inc.
2045 East Innovation Circle
Tempe, Arizona, 85284, USA

SUMMARY

There is little doubt that the automotive industry is going through an electronics revolution. With this impending growth, there are several opportunities for stakeholders to increase their revenues while adding functional and economic value to end users. Whether its autonomous driving, infotainment systems or electrification applications in a car, performance, reliability and cost aspects shape each player's differentiation strategy. As a result, there is tremendous innovation from both integrated device manufacturers (IDM) and outsourced assembly and test (OSAT) suppliers. This paper will provide a brief overview on value creation in the electrification segment, specifically for power semiconductor packaging.

TABLE OF CONTENTS

1 MARKET TRENDS

A number of environmental, economic and social factors are influencing future vehicle designs and powertrain choices. Considering carbon dioxide (CO_2) emission regulations, tax incentives and charging infrastructure [1], powertrain strategies will see a significant evolution in both the short and long term. Power semiconductors are the key components in the powertrain systems of electric vehicles (EVs), hybrid electric vehicles (HEVs) and plug-in hybrid vehicles (PHEVs). Several publications note that compared to the average semiconductor content of $330 in gasoline cars, EVs may have more than $750 in semiconductor content per car [2] with majority of the value share taken by power devices used in the main inverter, on-board charger and DC-DC converter. As the number of electric and electrified vehicles (HEV and PHEV) increases, demand for sophisticated power electronics solutions reducing electrical losses, system weight and total cost of ownership will increase.

The current workhorse – silicon (Si) technology – based power devices such as MOSFETs and IGBTs play a major role due to their technology maturity, manufacturability and established supply chain. Generally, MOSFETs cover the low voltage (<200V) space while IGBTs contribute in the high voltage (>600V) applications. On the package side, power discrete packages such as transistor outline (TO), small outline transistor (SOT), Power Quad Flat No-Lead (PQFN) and TO-Leadless (TOLL) packages are well established for automotive sector in the low power (< 5kW) applications [3]. However, for high power (> 50kW) sub-systems, molded or frame-based power modules are needed [3]. The product portfolio of several power device suppliers includes discrete, molded and frame modules with configurations such as single switch, half-bridge, full-bridge and three-phase designs as shown in Figure 1.

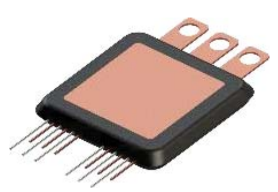
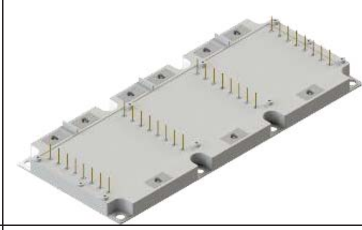
Single Switch	Half-bridge	Full-bridge
		
Power Discrete	Molded Module	Frame Module

Figure 1: Power Solutions for xEV

As electric and electrified vehicle (xEV) solutions increase, so do the requirements on cost ($/kW) and power density (kW/Kg or kW/l) of the power electronics. Currently, cost targets are roughly 5 $/kW, whereas power density is around 12 kW/l. These targets are expected to reach 3 $/kW and 60 kW/l by 2035 [4]. These future roadmap targets cannot be achieved with existing semiconductor device technologies, packaging technologies and system level architectures. The trend may diverge into two paths: fully integrated solutions in which electric motor and power electronics are co-designed or to a single power management converter to manage power across the entire vehicle [4].

2 Technology Paradigm Shift – Si to SiC & GaN

To cope up with the requirements from vehicle and system manufacturers, semiconductor suppliers need to offer superior solutions in a multitude of areas. From the semiconductor technology aspect, Silicon power devices will continue to play a critical role as more performance is eked out. However, new wide bandgap materials such as silicon carbide (SiC) and gallium nitride (GaN) are expected to play a much bigger role in the next decades, especially in the high-power traction inverter and mid-power converter applications [5]. As shown in Table 1, these new materials offer improved thermal and electrical performance over traditional silicon devices but have challenges around their manufacturability, integration and cost. To maximize the potential benefits of wide-bandgap materials, advanced components, converter topologies and integration will need to be co-developed.

Property	Si	GaAs	GaN	SiC
Energy Gap (eV)	1.11	1.43	3.4	3.2
Critical Electric Field (MV/cm)	0.6	0.5	3.5	3.0
Charge Density (x 1013 /cm3)	0.3	0.3	1	0.4
Thermal Conductivity (W/cm/K)	1.5	0.5	1.5	4.9
Electron Mobility (cm2/V/s)	1300	6000	1500	600
Saturation Velocity (x 107 cm/s)	1	1.3	2.7	2

Table 1: Comparison of Properties of Key Semiconductor Materials

At the packaging level, high-temperature performance, integration and reliability are the three main trends that are expected to drive innovation. For high-temperature performance of power discretes and modules, key design requirements include better thermal interface materials (TIMs), novel substrate concepts and improved encapsulation technologies [4]. Further, innovation is required for new materials to provide better mechanical stability and robustness, as well as improved bonding mechanisms to better withstand extended power and temperature cycling. With the increased acceptance and proliferation of SiC and GaN devices, current packaging solutions need to be optimized since they cannot be drop-in replacements of their silicon counterparts. For example, with the introduction of wide-bandgap materials, significant space savings are expected with reduced number of passive components, enabling package-level integrated solutions with gate drivers and filters.

Finally, current inverter and converter architectures will see improvements in efficiency due to incremental improvements from the incumbent silicon devices. To offer further functionality, hybridization strategies, such as integration with SiC rectifiers or GaN transistors, and efficient designs, such as distributed architectures, are expected to meet the market demands. In the future, to unlock the full potential of wide-bandgap devices, further innovation in circuit designs to incorporate high-frequency switching, soft-switching and resonant switching will offer more efficient and increased power density solutions. The market trend to integrate electric motor and power converters will bring several challenging package requirements, principally in the areas of mechanical, thermal and electrical performance when juxtaposed with extended temperature ranges. For SiC and GaN devices, current package technologies may limit performance via stray inductances causing switching losses and parasitic capacitances causing common-mode currents.

3 Value Chain Analysis

Historically, the semiconductor industry has gone through several cycles from a packaging technology perspective. For example, shorter life cycle products as those in mobile communications see a sharp increase in technology consolidation and volumes once a packaging platform is qualified. Such a package may see a drastic replacement while newer disruptive technologies are brought forth. In contrast, automotive product life cycles have typically been longer. Automotive products, in general, have been built on robust Si nodes and stable packages. However, automotive power packaging technologies may start to follow the semiconductor maturity model in the future as shorter development cycles are expected to drive automotive suppliers' go to market strategy. IDMs generally keep low volume and high margin products for in-house production. Over the years, as technologies mature and production volumes increase, businesses have been strategically shifted to OSATs. This approach aligned well with the business models of OSATs – providing appealing economics and responsiveness to customers' needs. However, due to rapid advancements in sectors such as automotive, OSATs are expected to keep pace with the innovation, offering sophisticated and technologically differentiated solutions.

The successful value creation by OSATs will primarily depend on capital investment and productivity, appealing cost structures and pricing models. Technological differentiation is necessary to address certain specialized application spaces such as the power modules for inverter and converters in automotive segment. Given the non-standardization in the current offering of power module solutions, there is reason to believe car and system manufacturers will demand some level of standardization, allowing for multi-sourcing and price pressure on the suppliers. IDMs, who generally invest significant capital investments in front-end rather than back-end, may look to OSATs to fulfill some of the power module manufacturing. Collaboration among IDMs, OSATs and system manufacturers will be very critical for the power packaging ecosystem.

4 Power Packaging

Considering the wide array of requirements – high temperature materials, higher switching frequencies, higher reliability and more power dense solutions – packaging technologies need to scale up to meet the stringent demands of automotive sector. Although its well understood that advanced power packaging technology requires material set development, structural optimization and process innovation, computer-aided design (CAD) tools and modelling methodologies are equally required to achieve the desired results [6]. The evolution within power packaging is understood to go through three phases as explained below.

4.1 Short Term (0-2 Years) – Standardization

The semiconductor packaging industry, including both IDMs and OSATs, is quite fragmented resulting in severe non-standardization among interface materials, mold compounds and bonding mechanisms. In the short term, some development can occur to standardize latest packaging technologies allowing multi-sourcing of manufacturers. Further, integration of active components with passive components to provide low-cost, double-sided cooling solutions will drive the efficiency improvements of power discretes and modules in traction inverter applications. Developments in embedded chip and planar interconnects to reduce parasitic inductance will enable high frequency switching and thus meeting higher efficiency metrics. Finally, the materials and assembly process are expected to evolve, meeting the wide range of temperature and power cycling required per the application profiles [7].

4.2 Medium Term (3-5 Years) – Integration

As a natural progression, next set of improvements are expected in the integration of gate drivers, filters, controllers and sensors into a single package. Integrating power and control components will offer a differentiation strategy for the suppliers in the supply chain. Obviously, the higher level of integration to achieve a converter-in-package (CIP) will require significant research in materials capable of handling temperatures in excess of 250^{o}C [4]. Especially with the adoption of high-density converters, CIP integration will be positioned well to achieve the long-term targets of 60 kW/l. However, underlying material sets capable of high-temperature operation and suppression of electromagnetic interference (EMI) due to high-frequency switching will be paramount.

4.3 Long Term (6-10 Years) – Design for Cost Reduction

As power packaging becomes more standardized, the trend moves more towards easy to manufacture power modules with modularity and pre-packaged chips. As such, the manufacturing volumes will also move to high-volume and low-cost production lines, offering best performance to price metrics. Similarly, low-cost substrates and laminate materials with low (<16 ppm) coefficient of thermal expansion (CTE) and high (>20W/mK) thermal conductivity become standard offerings while maintaining wide temperature and power cycling requirements. Functional integration schemes, such as three-dimensional (3D) integrated heterogenous assemblies, will further enable optimized vehicle level thermal management and ease the requirements on dedicated power electronics cooling.

5 Amkor's Power Packaging Program

As a leading automotive OSAT supplier, Amkor has a strong presence in the value chain. Of the 40 different package families that Amkor offers, at least 26 of them are automotive qualified. Amkor's strong position stems from a global presence, partnerships with top automotive suppliers and over 40 years engagement in this sector. Amkor's power packaging is supported from two different factory locations – Amkor Malaysia (ATM) and Amkor Japan Fukui (JFI). Broadly, Amkor offers several value-creating features and technology differentiators such as advanced lead frame technology (XDLF), copper (Cu) clip interconnects, aluminum (Al) wedge bonding and space-saving surface-mount, flat lead designs. From a packaging perspective, Amkor's power packaging program has evolved from traditional through hole and gull-wing packages to flat lead, exposed pad, dual side cool and low-profile alternates. As a result, its product portfolio involves packages offering very high (approximately 100A) drive currents and body sizes greater than 300 mm^2 as shown in Figure 2.

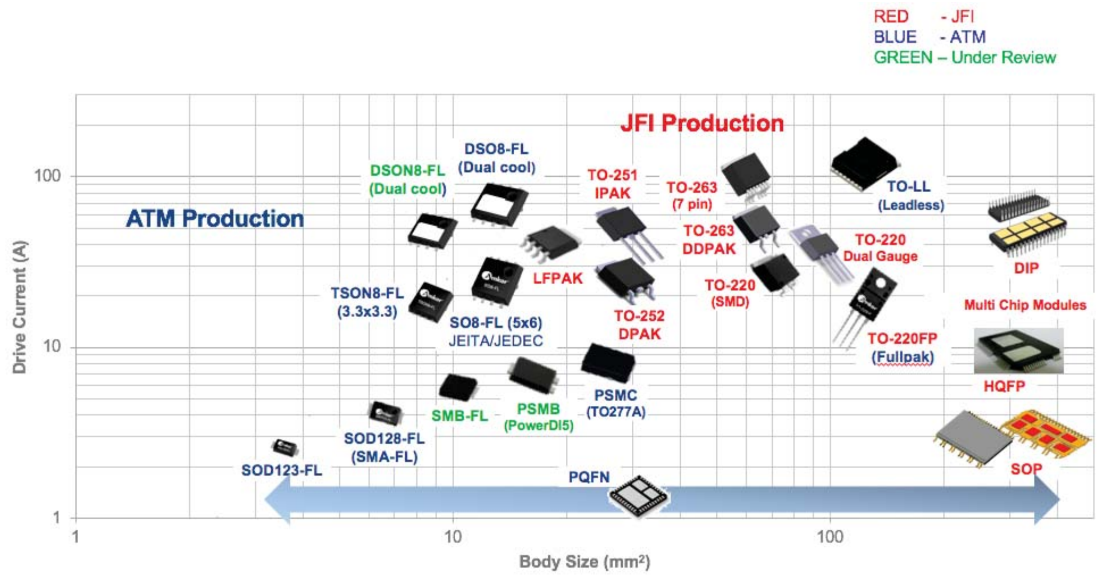


Figure 2: Amkor's Power Packaging Lineup

For example, the TOLL (Figure 3) package is a highly efficient space-saving package featuring extremely low parasitic resistance and strong thermal performance, making it well suited for high-current and high-voltage applications. It meets the existing JEDEC package outline and is 30% smaller and 50% thinner than a D2PAK (TO263) package that Amkor currently offers. TOLL package leads are designed with wettable flanks making it a great fit for the automotive market. The TOLL package has been a main stay package for IDMs in the automotive applications. As the demand for multi-sourcing and standardization increased, Amkor was able to bring this package to market. Additionally, LFPAK56 (5 x 6 mm) as shown in Figure 4, is yet other new product offering from Amkor that is suitable for DC-DC conversion, body electronics and automotive safety applications. From a design perspective, the LFPAK utilizes a beam lead structure that eliminates the junction between a Cu clip and the outer leads resulting in lower resistance and improved reliability. From an intelligent package and lead frame design, the LFPAK not only offers the best reliability performance but also efficiency improvements in switching applications. Amkor's latest power package portfolio covers the short-term standardization trend discussed previously.

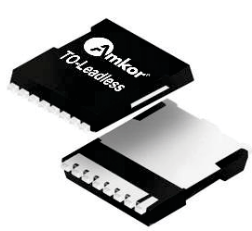


Figure 3: Amkor's TO-Leadless (TOLL) Package

Figure 4: Amkor's LFPAK56 Package

One of the recent developments in Amkor's Power Packaging Platform is a Dual Side Cooled (DSC) molded power module (Figure 5) for high-power traction inverter applications. Of the two types of high-power modules, frame based or molded, that are prevalent in the market today, molded modules provide superior thermal and electrical performance. Due to package structure – dual side cooling – heat generated during power switching can be extracted rather effectively. Also, with this molded power module design, parasitic inductances of the collector (drain) and emitter (source) connections in an IGBT (MOSFET) are reduced significantly. Though, gate connections are still realized with wire bonds in exiting solutions, clip type connections can be used as well.

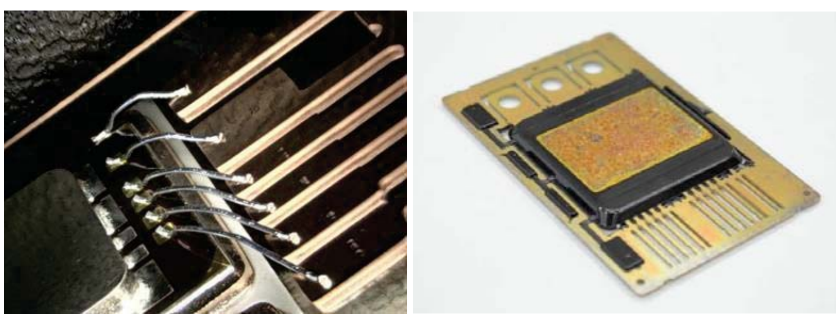


Figure 5: Amkor's DSC Molded Module Package

Wide-bandgap devices may help relax the demands for the large and heavy heat sinks currently used in frame modules. With either established or advanced semiconductor technologies, the molded modules are an excellent fit in helping manage the thermal burden in electric motors. The value proposition of molded modules goes beyond thermal and electrical performance – these modules can be integrated with advanced the electric motor architectures used in xEV applications. For higher wattage considerations, more packages can be inserted into the existing slots to increase high-power performance. This package has passed Amkor's internal development phase and the Automotive Electronics Council's AEC Q101 qualification requirements. From a power package trend, this package favors both short-term and medium-term requirements. In the future, this package may evolve to include the integration of other active devices such as controllers, sensors and filters.

6 SUMMARY

The power semiconductor segment is an essential factor in several high-growth automotive electronics areas, driven by the macro trend of electrification. Though power discrete packaging is a mature market, there is further room for innovation to accommodate emerging wide-bandgap devices. Customized power module designs present compelling business opportunities for OSATs such as Amkor that can rely on its strong technology know how, supplier management and driving efficiencies. Apart from a broad product portfolio, an OSAT supplier must also focus on quality, automotive process controls and automotive certified personnel. Amkor not only can offer these requirements but also has the financial and technical strength to make significant investments in equipment and facilities and provide long-term support for its automotive customers.

6.1 REFERENCES

[1]. S. Rokadiya and Z. Yang, “Overview of global zero-emission vehicle mandate programs,” International Council on Clean Transportation (ICCT), Apr 24, 2019.

[2]. Infineon Company Presentation – IFX Day 2018, June 2018.

[3]. Infineon Automotive Power Selection Guide 2018.

[4]. Automotive Council UK, “The Roadmap Report | Towards 2040: A Guide to Automotive Propulsion Technologies,” 2018.

[5]. Chen et al., “A Review of SiC Power Module Packaging: Layout, Material System, and Integration,” China Power Supply Society’s CPSS Transactions on Power Electronics and Applications, Vol. 2, Issue 3, Sep 2017.

[6]. R. Dey and A. Sardar, “Trends in Power Electronics Packaging technologies for xEV,” Power Electronics Technology Foresight, Vol. 3, Issue 8, Aug 2014.

[7]. Nirmaier et al., “Mission Profile Aware Robustness Assessment of Automotive Power Devices,” Design, Automation, and Test in Europe Conference & Exhibition 2014.