Power Device Technologies for Sustainable Growth of Power Conversion Applications

Power devices have gone through a rapid technological evolution, along with the advancements in power electronics during the last few decades. More recently, the enormous advancement made by MOS-gated power device technologies such as IGBTs, power MOSFETs, and power modules have tremendously helped fast proliferation of power electronics application in industrial, commercial, residential, transportation, utility, aerospace and other emerging fields that include newer power generation systems. The second part of this keynote given at PCIM China deals with new areas of power module advancement including prospects of SiC power devices for future application needs. **Gourab Majumdar, Mitsubishi Electric Corporation, Fukuoka, Japan**

As the trend in almost all power electronics applications based on inverter control continued to be towards higher efficiency, more ruggedness against abnormalities, steadier performance, higher noise immunity, higher frequency operation, down-sizing etc., the initial IGBT modules needed new dimensions towards higher functionality and better performance.

Integration technology IPM

In order to overcome the IGBT's inherent parasitic limitations and maximize its performance, fulfilling the ever-increasing application systems' needs, a concept integrating dedicated drive and protection circuits with the IGBT in an appropriate packaging was introduced by Mitsubishi Electric, based on a new invention in the late 1980s [10]. The resulting module was named 'Intelligent Power Module' or IPM because of its self-drive and self-protection capabilities (Figure 10).

An integrated sensing and protection circuit scheme detects any over-current situation of an internal IGBT power switch almost instantaneously, and turns off the switching current safely at a subdued shutdown speed to suppress destructive surge voltage. The scheme, thus, effectively enlarges the SOA of the internal IGBT. Secondly, by virtue of a smart integration concept, only positive biasing is required for gate driving and protection circuitry of each integral IGBT of an IPM. With a proper layout design, a low impedance circuit is created across the gate-emitter of each IGBT at its turn-off switching operation and during its turned-off state.

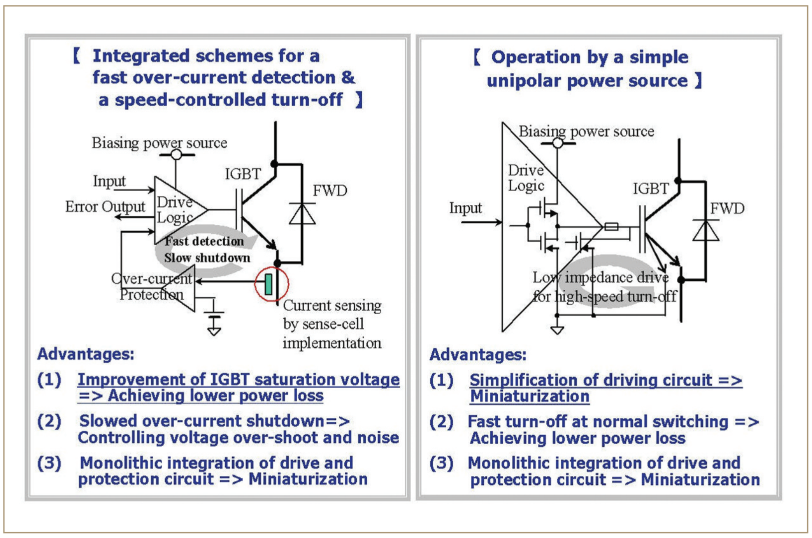

Figure 10: Fundamental concept of IPMs

Thus, the conventional need for a negative gate biasing for IGBT's turning-off and off-state operations is eliminated. This feature contributes to downsizing of application system by simplifying IGBT drive circuitry. Also, a fast turn-off type internal gate control scheme reduces switching losses of the IPM and, thereby, it effectively solves the other trade-off issue between on-state loss and turn-off switching loss of a conventional IGBT by making suppression of both losses possible.

Furthermore, simple monolithic integration of IGBT's drive and protection circuitry for IPM use has been made possible and has created many future scopes for higher functionality. Thus, large-scale-integration (LSI) process technologies were utilised to produce dedicated low-voltage ASICs (LVIC), which were later paired with high-voltage ASICs (HVIC) for further functionality enhancements, together with optimised packaging techniques and circuit layout designs. Figure.11 is the basic block diagram of an IPM that also highlights its main advantages. Each IGBT chip integrated in an IPM typically contains an on-chip current sensor, which feeds back collector current information to an internal ASIC for processing and performing over-current and short-circuit protection functions on a real-time basis.

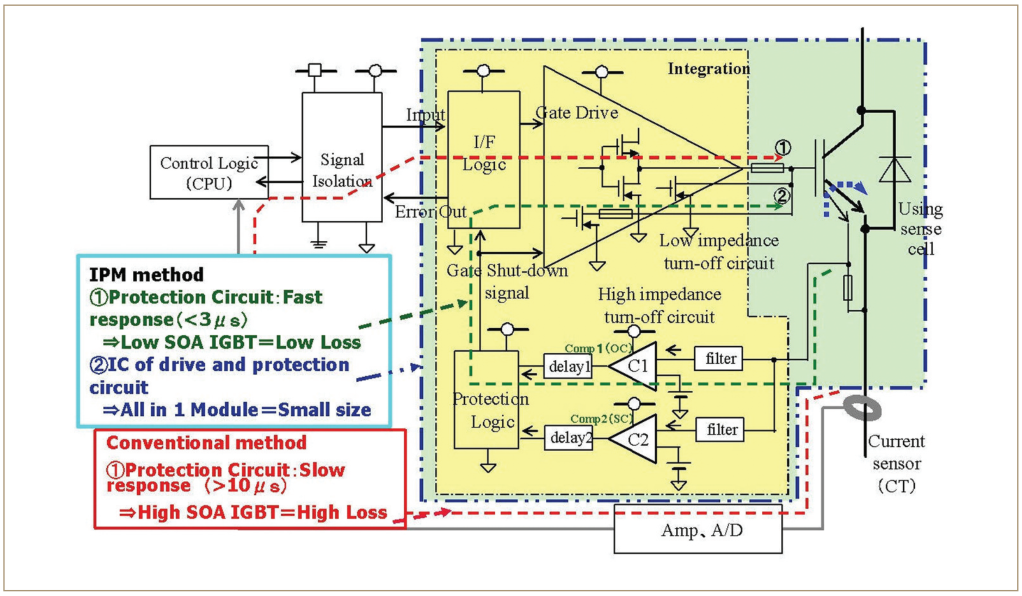

Figure 11: Feature of IGBT drive and protection

The IGBT elements for IPM applications can be designed to have a very low forward voltage drop characteristic close to the ideal level acheivable by the device's theory, without being hindered by the internal parasitic thyristor's latch-up issue.

To protect internal IGBTs more efficiently against over-temperature an on-chip temperature scheme has lately been developed. Figure 10 schematically explains this protection scheme and shows an actual chip architecture depicting the location of such integrated sensing elements (a string of series connected small-signal type poly-silicon diodes) on the chip surface. All IPMs from 5th generation level are featured with this scheme.

Another example of IPM advancement by its intelligent function is a low noise radiation feature achieved by a unique gate control scheme. The main cause of noise radiated from the power module is fast switching operation performed by the internal IGBT power elements. Fast switching characteristics is desirable for reducing switching losses in power conversion applications. However, noise level increases with the dv/dt generated due to speed of switching transients and thus, the trade-off relationship between noise generation and switching losses has been a difficult design issue in the power conversion system applications.

The new feature in the latest 5th generation IPM series solves this issue adequately by changing the gate switching speed at a preset value of switched collector current level, typically 50% of the rated I_C- based on information available from on-chip current sensor's feedback as shown in Figure 13. In actual applications, the IPMs from this new series have demonstrated an 8dB average noise reduction without increasing their total power losses.

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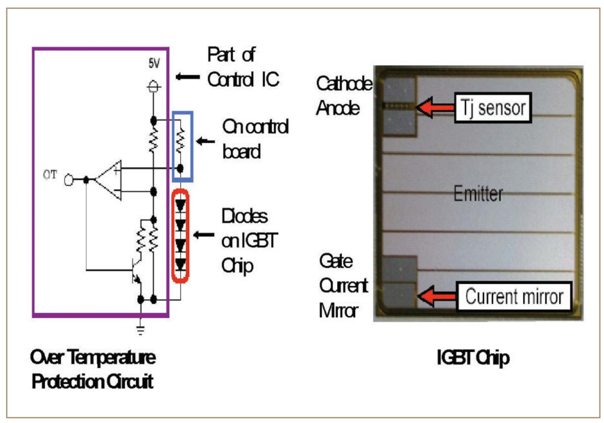

Figure 12: For improving over-temperature protection performance, a new 'on-power chip' diode-sensor scheme is used in the latest 5th generation IPM series

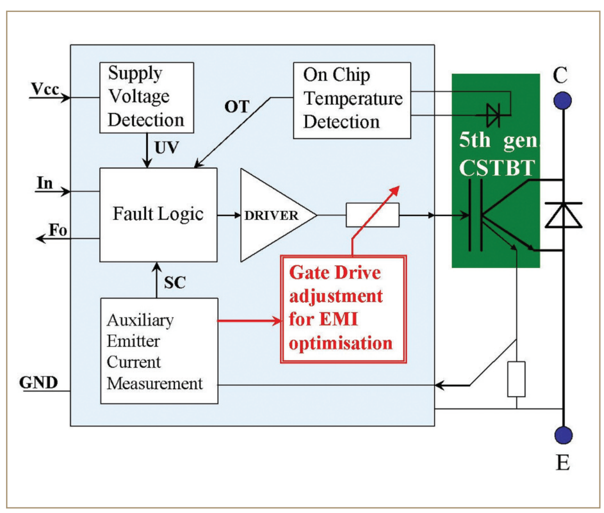

Figure 13: 5th generation IPM's internal block diagram depicting a new gate drive adjustment feature that effectively reduces radiated EMI noise

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Furthermore, a continuous demand for further compactness (hence lower system cost) and high quality performance led to the development of a super compact size IPM named the DIP-IPM (Dual-In-line-Package IPM) using transfer-mould packaging construction, targeted particularly at low power inverter applications for the household appliances (Figure 14).

In the following years, further miniaturised versions of this transfer-molded packaging concept, providing high-density silicon power solutions up to 1200V class through incorporation of 1200V HVIC technology and the latest in the power chip technologies, were successfully developed and commercialised. Thus, IPMs are largely contributing as key components to achieve the energy saving goals of various application systems such as industrial motor drives, high voltage inverters for railway systems, automotive and inverter systems for home appliances, covering fractional horse power to mega-watts applications. The expansion has led to a substantial market share for this smart integrated solution and brought in demand for higher performance, higher power density and more built-in functionality [7, 8, 9, 10].

New power semiconductor material

With achievements made by several generations of IGBT and IPM devices, the Si-Power is considered to be approaching limits in terms of performance improvement. For this reason, extensive research works are being carried out globally to implement a new candidate for material that can replace silicon in this field.

Among several wide-band-gap materials, which are tipped for power semiconductor

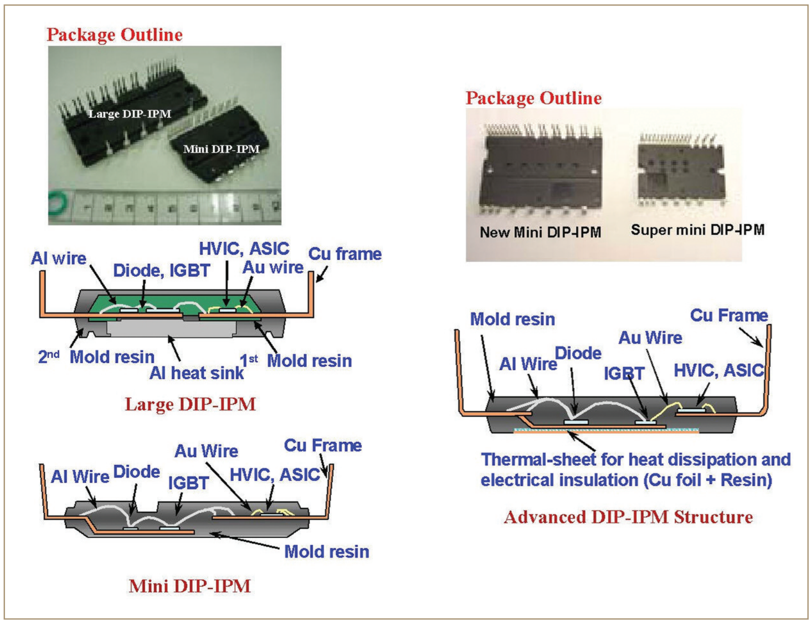
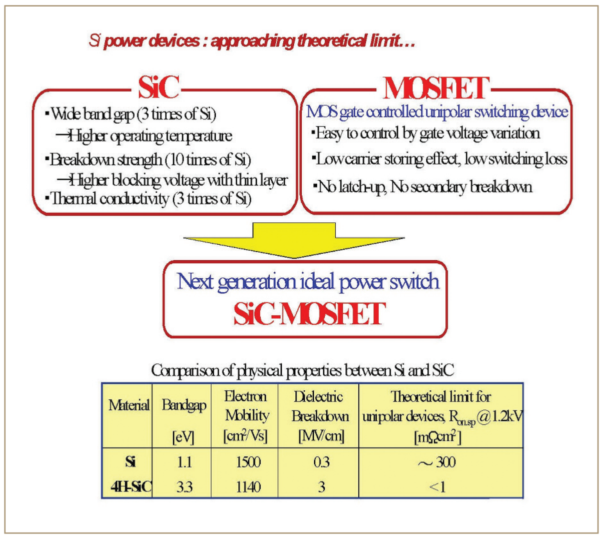


Figure 14: **Transfer-mould DIP-IPM package structure**

Figure 15: **Features of SiC material and SiC-MOSFET for power device application**



Material	Bandgap [eV]	Electron Mobility [cm^2/Vs]	Dielectric Breakdown [MV/cm]	Theoretical limit for unipolar devices, $R_{on.sp}$ @1.2kV [$m\Omega cm^2$]
Si	1.1	1500	0.3	~300
4H-SiC	3.3	1140	3	<1

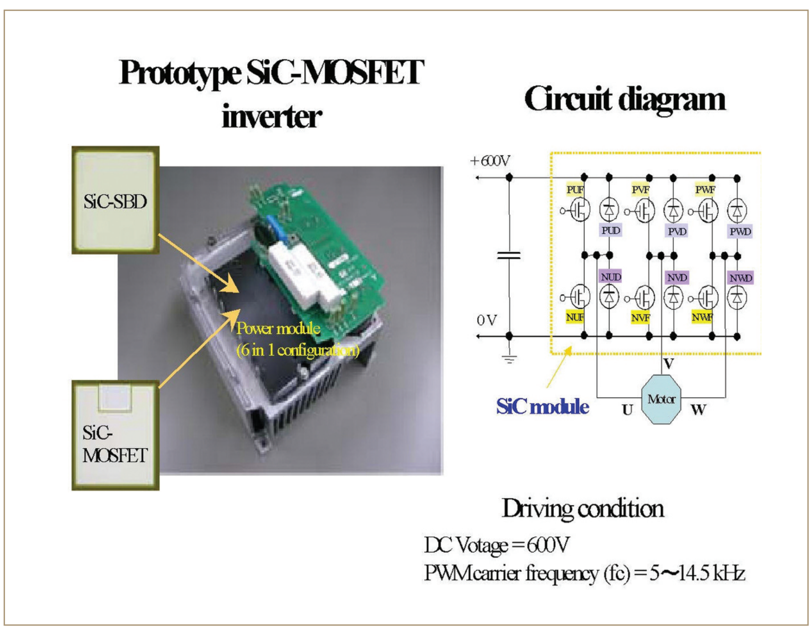


Figure 16: **A prototype 3-phase high frequency inverter using an experimental 1.2kV SiC module**

applications, 4H-SiC is today considered to be the most suitable one for its overall superiority, not only in terms of physical properties, but also in terms of feasibility of manufacturing both base material and devices from it with minimum complexities. Out of many arguments and analyses to define an optimum power device solution using SiC, the unipolar MOSFET structure has proven to be the best choice for device implementation for future applications up to at least 1200V class.

Figure 15 explains this view in a brief form. To evaluate this prediction quantitatively, a prototype three-phase inverter system was built by fabricating an experimental six-pack SiC module using 1200V class 4H-SiC based MOSFET and SBD chips. Each arm of the three-phase configuration in the module used a MOSFET chip of active area 7.8mm² and an SBD chip of active area 4mm².

In the inverter experiment, a 10A/1200V 5th generation silicon IGBT/FWD based module was also used for comparison purposes. Figures 16 and 17 show a prototype full-SiC module and a test-bench fabricated for evaluating SiC device on an actual inverter system environment. A three-phase/400V/3.7kW rated induction motor drive system was created for this purpose. Figure 17 also presents test waveforms depicting full-load output currents of the SiC module and comparison of its power losses with an equivalent silicon IGBT module of 5th generation level.

Comparing total operation losses in the high power three-phase inverter system, the SiC device based solution avails a large loss-saving advantage over the silicon IGBT based solution, which can be 54% or larger if a carrier frequency of 14.5kHz or higher is used. It has also been found that the SiC based MOSFET and SBD combination can remarkably reduce power losses in actual system applications of switching frequency higher than 20kHz. Thus, SiC unipolar devices have a significant potential to replace bipolar IGBT devices in various application fields, including industrial and consumer motor drives, power supplies, automotive power electronics and very high voltage systems in the near future. However, several critical issues still remain to be overcome to bring SiC devices in full-fledged commercial use. Some of these are improving wafer size and quality, solving device processing hurdles, and reducing wafer and device processing costs.

Among these items, the most critical one is the availability of viable quality low-cost SiC wafers from various sources in the global market [11]. For medium power-ranges, the power devices are expected to grow continuously primarily depending on silicon based chip and module technologies for several more years and SiC is expected to become a material choice for power semiconductors in the future. Figure 18 is a projection of major technological trends that are expected in the future.

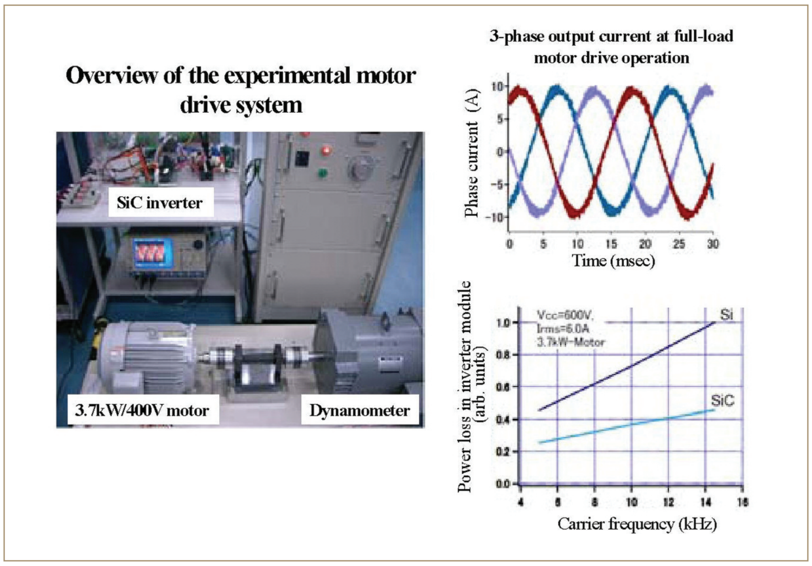


Figure 17: Test-bench for evaluating SiC MOSFET inverter and a 5th generation silicon IGBT inverter using a three-phase/400V/4.7kW motor drive set-up and test results

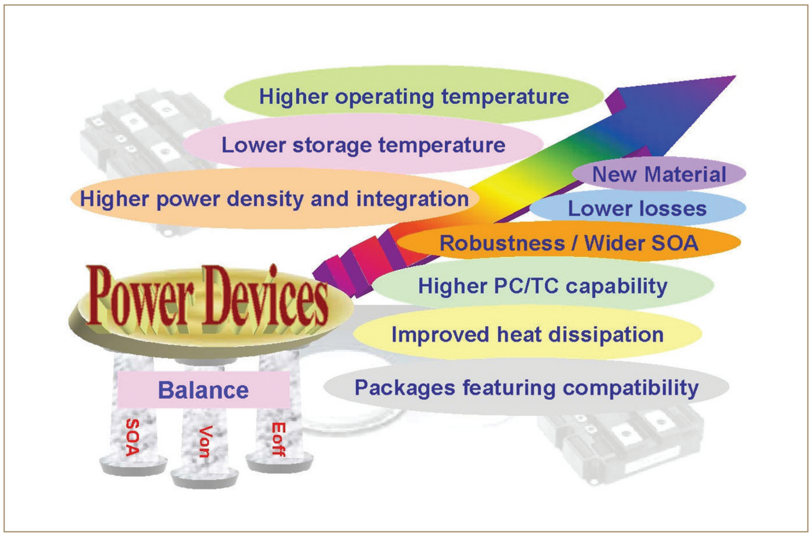


Figure 18: Projection of technological trends for future power devices and modules

Conclusion

In this article, the importance of power modules for various power conversion applications and new technologies related to power chips and power module packaging concept have been reviewed. Also, practical demonstration of SiC device performance has been made and analysed. The ever-increasing global energy demand and environmental issues will continue to drive power devices for greater advancement of power electronics in this century. Thus, a sustainable growth in this field is expected to follow.

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