Power semiconductors

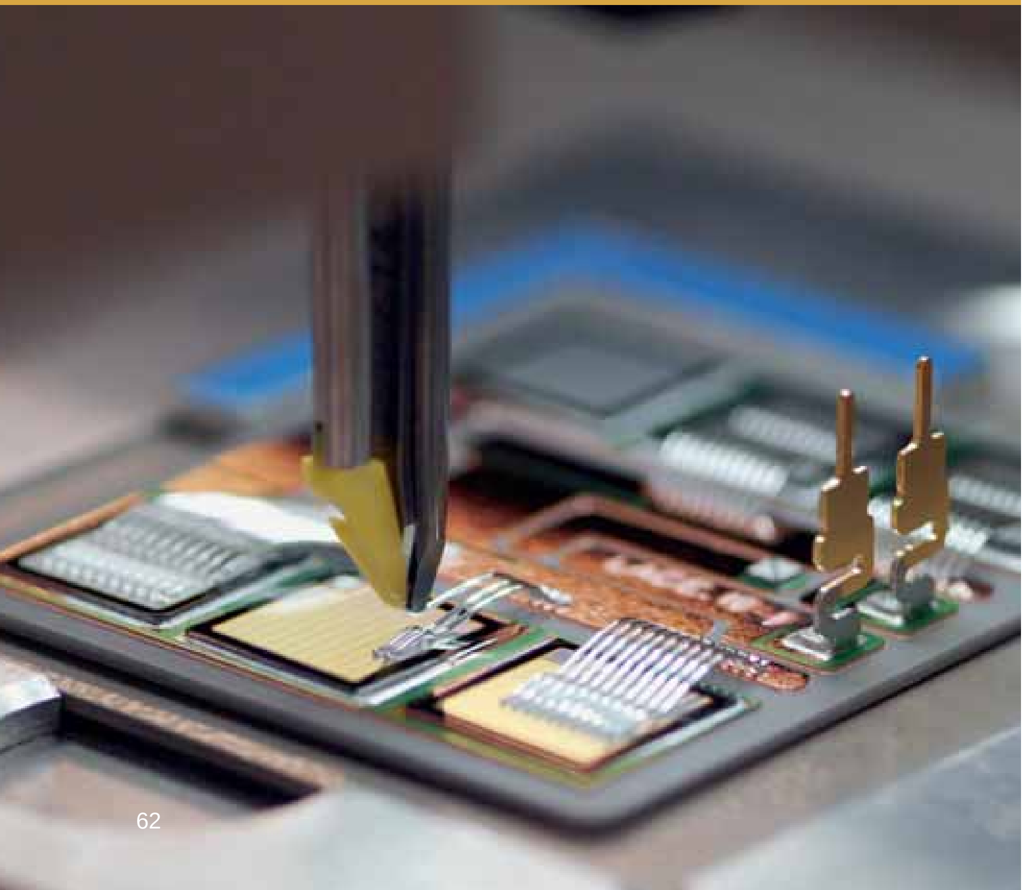
Part two: Housing technology and future developments

Stefan Linder

Power semiconductors have, over recent decades, become ubiquitous in a broad range of applications. This was a consequence of the continuous and rapid development of power semiconductor technology, resulting in very powerful, effective, and easy to use devices. In the first part of this article, published in the previous edition of ABB Review[1], aspects of chip design and optimization were discussed, as were considerations of the application of different classes of devices, notably of IGBTs and IGCTs.

The continuous optimization of silicon has brought performances closer and closer to the physical and technological limits. The result is that, short of radically new breakthroughs, the potential for further improvement in this aspect of the design is diminishing. Semiconductor device housings, however, still have considerable potential for leveraging performance. This article therefore looks further into this aspect.

Today, virtually all commercial power semiconductors are entirely silicon-based. Looking into the future, this article further discusses the potential of so-called "wide-bandgap" materials, such as silicon carbide, gallium nitride, and diamond.



Whereas, until about a decade ago, power semiconductor housings were not much more than containers for the devices, they are now more and more becoming the limiting element in power electronic systems. The attention of developers is, therefore, increasingly focusing on aspects of housing design to tackle its limitations.

Housing forms

Two conceptually different housing forms have become established in the high-power range: the insulated housing and the pressure-contact module 1. The main difference between them is that the electrical circuit in the insulated module is galvanically isolated from the heat sink by a ceramic insulator, whereas in the pressure-contact design, the current flows vertically through the entire module, ie, also through the heat sink.

Both housing forms are fundamentally suitable for IGBTs and IGCTs. In practice, however, IGCTs are currently only offered in pressure-contact housings, whereas IGBTs are manufactured in both variants. The insulated housing currently dominates in systems with low output powers (mostly below one MW), as the circuit can be implemented with a lower mechanical outlay (and hence at lower cost). The pressure-contact housing, on the other hand, is preferred for several reasons for output powers greater than approximately 10 MW. The two most important of these are discussed here:

Footnote

[1] Stefan Linder, Power semiconductors – Part one: Basics and applications, ABB Review 4/2006, pp 34–39.

- In systems with very high power outputs, semiconductors must be connected in parallel and/or in series. For the latter, pressure-contact housings present a considerable advantage, as the modules can be arranged in a stack, only separated by heat-sinks. One example of this is in HVDC (High voltage DC) power transmission installations, in which up to 200 modules are connected in series.
- A pressure-contact housing must be used if the application requires a guaranteed uninterruptible current flow (eg, a current-source inverter, but also all systems that must respond to a semiconductor or control fault by discharging the DC link energy by means of turning on all semiconductors). In a pressure-contact housing, the metallic pole pieces fuse if a semiconductor fails, thereby ensuring a low-impedance current path. In the insulated housing, on the other hand, the current flows through bonding wires, which evaporate upon a high current pulse during a fault, hence leaving an open circuit.

Requirements for housing technology

The challenge in creating a housing design consists of two main factors:

- Modern power semiconductors are operated at a continuous power dissipation of 100–200 W/cm² of silicon. This power density is (per surface area) approximately one magnitude greater than a kitchen stove hotplate operated at maximum power. This poses extreme demands on the housing technology and the materials used.
- The coefficient of thermal expansion (CTE) of silicon is approximately five to ten times smaller than that of most metals (Cu, Al) suitable for electrical and thermal coupling. This means that critical components in the housing (bonding wire contacts, solder joints) are subject to considerable thermomechanical stress during load changes. This considerably limits their service life.

As a result of these requirements, there is no alternative to using expensive and highly sophisticated materials.

Potential for improvements in the housing technology

Increased junction temperatures

The useful output power P_{useful} of power semiconductor devices is scaled in accordance with the law:

$$P_{useful} \propto \frac{T_{j,max} - T_{ambient}}{R_{th}} \qquad (1)$$

$T_{j,max}$ is the maximum junction temperature, $T_{ambient}$ is the temperature of the heat sink (the ambient), and R_{th} is the thermal resistance between the semiconductor junction and the ambient.

> Increasing the maximum junction temperature would enable the inverter to be operated at a higher switching frequency, resulting in reduced harmonics and so permitting filters to be smaller in size.

It is immediately apparent from this formula that the increase in the maximum junction temperature of high-voltage devices (above 1700 V) from 125 °C (today's standard) to 150 °C, results in an increase in performance of 25 to 30 percent (assuming an ambient temperature of approximately 20–40 °C). An alternative to using this performance increase for achieving a higher output power, is to "invest" the better cooling capability in larger losses at a given power. The latter would enable the inverter to be operated at a higher switching frequency, resulting in reduced harmonics and so permitting filters to be smaller in size.

In practice, a series of important preconditions must complied be with, to permit this potential to be fully utilized:

1) Properties of silicon

- The power semiconductors must still be able to safely turn off the larger rated current at the higher junction temperature.
- In voltage inverters, the freewheeling diodes must be able to safely withstand the increased surge current in case of a fault.
- IGBT devices must still have an adequate short-circuit withstand time.
- The silicon components must exhibit stable behavior at 150 °C, ie, they may not permit any temperature-induced accelerating current redistribution.

2) Properties of the housing and interconnection technology

- The interconnection technology must have an adequate thermo-mechanical fatigue resistance caused by alternating loads.
- The materials used must tolerate the temperatures that arise.

The surge capability of freewheeling diodes usually represents a major obstacle in optimizing a semiconductor's application – in fact, it is often the limiting element, already at 125 °C. An increase in output power, however, usually goes along with an increased demand in terms of surge current. This requires larger diodes, which reduces the remaining space for switching devices (IGBT or IGCT), and generally also results in an increase in turn-on losses. Hence, without innovative approaches, the latitude for an increase in performance through an increase in the semiconductor junction temperature appears restricted. The potential is definitely significantly lower than the purely thermal consideration of the formula (1) suggests.

The thermomechanical fatigue resistance to alternating loads is the primary limiting factor in the interconnection technology. 2 shows the capability of modern insulated high-power modules in the case of a maximum junction temperature of 125 °C, and the approximate corresponding curve for the same module construction if $T_{j,max}$ is increased to 150 °C. The figure also shows the curve that would be required to provide the system with the life expectancy at 150 °C as it has at 125 °C. It can be seen that demands increase markedly at a higher maximum junction temperature, especially at large temperature excursions. This is because significant changes in the load conditions (eg, full load/zero load cycles) cause a higher temperature excursion (by up to additional 25 °C). The demands do not increase

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to such a great extent at a small ΔT, since the temperature of the junction is influenced to a lower degree by small fluctuations in power output. For example, if the power output drops from 100 to 90 percent at an ambient temperature of 30 °C, the junction temperature decreases by 9.5 °C at $T_{j,max}$ = 125 °C and by 12 °C at $T_{j,max}$ = 150 °C.

Considering the fact that the load cycling capability of modern products only barely meets the requirements in many applications (particularly in traction), it can be inferred that an increase in the capability of the modules by at least a factor of five is required to increase the junction temperature to 150°C. This may only be possible through the development of new technologies. In particular, large-area solder joints will probably have to be replaced by improved connection technologies. Perhaps the most promising candidate is the so-called low-temperature bonding (LTB) technique, which connects two parts by a spongy silver flake-based sinter layer. In addition to increased resilience to load cycling, low-temperature bonds also exhibit lower thermal resistances.

Reduction in thermal resistance

As an alternative to increasing the maximum junction temperature, an increase in the output power can also be achieved through a decrease in the thermal resistance R_{th} (see formula 1). The typical distribution of the R_{th} in an assembly with an insulated high-power IGBT module containing a total IGBT surface area of 45 cm² is approximately as follows:

IGBT junction to the AlSiC (Aluminum Silicon Carbide) base plate	7 K/kW
AlSiC base plate to the heat sink (dry contact)	6 K/kW
Heat sink to the ambient	10–35 K/kW*

* This value is strongly dependent on the cooling method (low for liquid cooling, higher for forced air convection cooling)

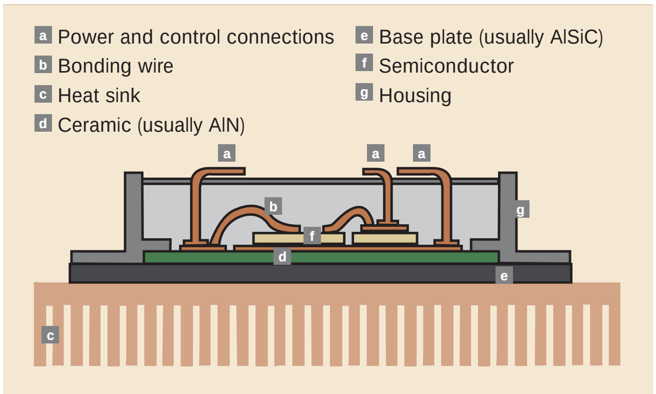
What stands out is that the dry contact of the module to the heat sink has approximately the same thermal resistance as the module itself, and that 40 to 70 percent of the entire R_{th} is located between the heat sink and the ambient. Hence, addressing the module-external R_{th} promises to yield greater returns than exclusively concentrating on that within the module. The motivation to work on the module-external R_{th} is further fueled by the large performance margins of modern devices (as explained in ABB Review 4/2006), and by the fact that new materials are beginning to emerge that are capable of reducing the internal thermal resistance of the modules by 30 to 50 percent. Such materials include advanced MMCs (Metal-Matrix Composites) which have both a favorable CTE adaptation and an extremely high thermal conductivity. Diamond MMCs, whose thermal conductivities of 400-700 W/mK even surpass copper, are an example of this. On account of its high CTE difference from silicon, copper is only used in combination with other materials that have an adapted CTE (eg, molybdenum 1i).

The surge capability of freewheeling diodes usually represents a major obstacle in optimizing a semiconductor's application – in fact, it is often the limiting element, already at 125 °C. An increase in output power, however, usually goes along with an increased demand in terms of surge current.

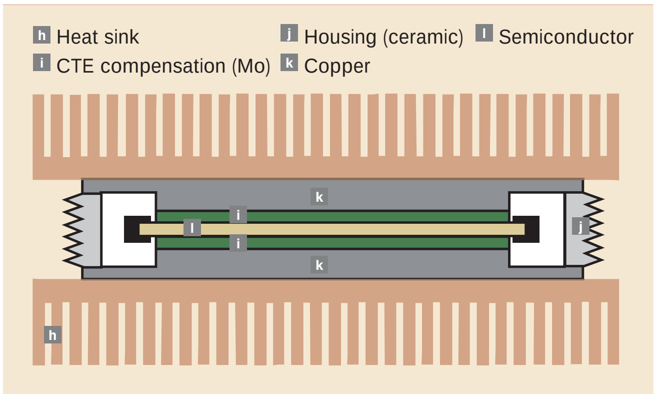
In addition to improvements in the heat sink, the dry (non bonded) contact to the module deserves special attention. Its thermal resistance is not only high, but also notoriously susceptible to variations, since a homo-

1 Common housing forms for high-power semiconductors:
An insulated module (left) and a pressure-contact module (right, a typical IGCT is shown here).

In insulated **housing modules**, the semiconductor f is galvanically isolated from the heat sink c. Electrical contacts within the module are provided by bonding wires. In case of a device failure, these wires tend to evaporate and the module ceases to conduct.



In **pressure contact** modules, the load current enters through one surface k and leaves through the opposing surface. Low electrical and thermal resitances of the contacts are assured through high mechanical pressure on those surfaces. In the event of a failure, the metallic pole pieces i fuse and current can continue to flow through the module.



geneous contact pressure and a good contact of the surfaces are difficult to ensure. The use of thermal greases and silicone oils only slightly alleviates the problems, since the thermal conductivity of these substances is at least a factor 100 lower than those of the metals of the base plate of the module and the heat sink. A very promising approach to the solution of this problem lies in the use of special metallic interlayers with high thermal conductivity, whose properties are designed so that they turn very soft or even fluid under operating conditions. Hence, they form a connection between the heat sink and the module that exhibits an R_{th} similar that of a bonded joint. As an alternative to this, it is also conceivable that modules with an integrated heat sink will experience a revival, since the dry contact has been completely eliminated in this concept. Such products have not been able to establish themselves on a wider market so far, for reasons of cost and complexity.

New semiconductor generations

Silicon devices

Especially in the 90s, a large number of novel component ideas were examined, of which the MCT (MOS-Controlled Thyristor), the FCTh (Field-Controlled Thyristor) and the EST (Emitter-Switched Thyristor) are the best known. The common objective of these device concepts consisted in combining thyristor-like properties[2] with lower driver power. Since all these components had conceptual deficiencies and because the plasma distribution in modern IGBTs has already closely approached the thyristor ideal, innovation with regard to new types of structures has markedly decreased in the meantime. Today, the probability of the IGBT and the IGCT being replaced by a fundamentally different silicon component seems remoter than ever.

"Wide bandgap" materials

Components based on so-called "wide bandgap" semiconductor materials represent an alternative direction of development. The advantage of these materials, the most well-known of which are silicon carbide (SiC), gallium nitride (GaN) and diamond (C), consists in their distinctly higher breakdown field strength in comparison to silicon. This enables significantly lower component thicknesses and higher dopings of the mid-section[3] than in silicon, which, for reasons discussed in part one[4], leads to considerably lower losses in the semiconductor.

A fundamental problem of SiC components with conductivity modulation is attributable to the fact that SiC pn-junctions only begin to conduct at approx. 2.8 V (in contrast to silicon, which only requires a voltage of approx. 0.7 V).

Only SiC can presently be considered a serious candidate in the high-power range. SiC is so far the only material that enables vertical components, ie, components, in which the current flows vertically through the semiconductor body and not along the surface. Only such vertical construction permits an adequately large cross-section to be provided for the required currents, while maintaining an acceptable component size.

Preferred SiC component concepts

Similarly to silicon, SiC permits the manufacture of both unipolar and conductivity-modulated ("bipolar") semiconductors. On account of the larger permitted drift zone doping, however, the economic use of unipolar SiC components is viable up to significantly higher blocking voltages than with silicon, specifically up to about 2–4 kV. However, bipolar SiC components are clearly in the focus of interest for use in the high-voltage and high-power range.

- In the case of unipolar components, Schottky diodes with nominal currents of up to 20 A and voltages up to 1200 V are already commercially available today. They are mainly used in switching power supplies and in solar cell inverters. Furthermore, unipolar SiC switches (MOSFETs and JFETs) have already been successfully manufactured, albeit only on a laboratory scale. A serious problem consists in the fact that SiC MOSFETs and SiC JFETs with attractive electrical characteristics have so far always been naturally conductive („normally-on"). Components with such characteristics have never been accepted by the market, even so the associated challenges appear to be technically solvable.
- In addition to diodes, bipolar components such as IGBTs, bipolar transistors (BJT) and thyristors for voltages up to 10 kV have already been successfully manufactured. In the case of the BJT, it should be noted that although it is a bipolar component, usually no conductivity modulation occurs in the conductive state (unless it is operated at a very low gain). The BJT must, therefore, be classified as a unipolar component on account of its loss characteristics.

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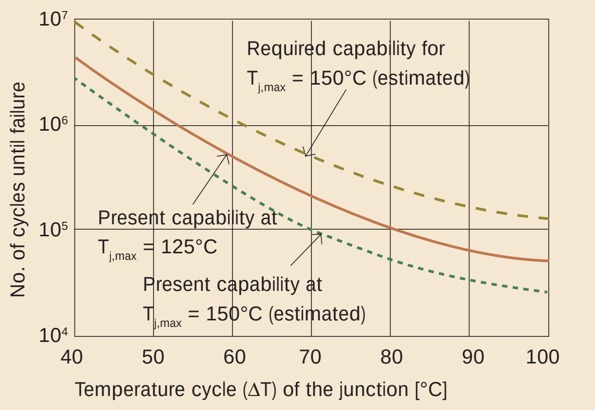
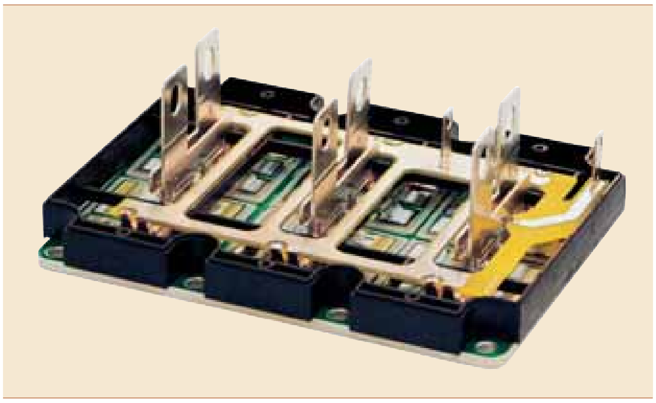
2 Fatigue life expectancy as a function of thermal excursions of modern insulated high-power IGBT modules with AlSiC base plates (eg, ABB HiPak or Infineon IHM)



Ease of use

Assembly of a HiPak power semiconductor module

Inside a HiPak module (see also page 64, 1 left)



conductivity-modulated components have at least one pn-junction in the current path, they have high conduction losses. This makes them unattractive below a breakdown voltage of approx. 4–6 kV. In addition, the current onset voltage (“built-in voltage”) of SiC pn-junctions has a very negative temperature coefficient. This can lead to a risk of inhomogenous current distribution in large components.

Material quality of SiC

SiC still remains a material which is very difficult to produce in a quality comparable to that of silicon. The frequently discussed “micropipes“ are only one of a series of harmful crystal defects, some of which can have a negative effect on the device’s long-term stability, especially in the case of bipolar components. The industrial production of large-area SiC components is, therefore, not yet possible. Another negative point lies in the fact that the incentive to improve the quality of SiC is rather low. This is because most SiC is not used for the production of power semiconductors, but as a carrier material for the manufacture of LEDs (light-emitting diodes). A different type of SiC is used for LEDs (6H instead of 4H), and a much lower material quality is adequate for economic production, on account of the minimal size of the LED.

SiC housing technology

It is undisputed that SiC components will, even in the long term, remain considerably more expensive than silicon components of the same size. The prospect of commercial success in the high-power range is based on the fact that the components are able to operate at a significantly higher current density than silicon components due to their lower losses, and on the higher permitted junction temperature (in excess of 400 °C). Unfortunately, there are two serious obstacles standing in the way of this objective:

- For the reasons mentioned in the subsection “Increased junction temperatures”, it is difficult to establish a housing technology which permits significantly higher junction temperatures than is usual in silicon. It can therefore be assumed that the losses per unit are of large-area SiC devices must remain within the same limits like those of silicon components, provided that reliability requirements remain unchanged.
- In addition, there is the problem that SiC devices have shorter switching times (ie, higher di/dt) than silicon. Because of this, the permitted stray inductances in housings are lower than for silicon components. However, the fact that stray inductances are mainly determined by insulation clearances and conductor cross-sections makes it difficult to achieve the required values in housings for high output powers.

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Unfortunately, the combination of SiC material quality problems, high costs, and technological difficulties both in the components and in the housing technology, reduces the prospects of SiC breakthrough in the high-power range within the foreseeable future.

Summary

IGBTs and IGCTs have established themselves as the two most successful semiconductor switches in the highest power range in recent years. Both concepts are developing in parallel, and it can be observed that the development objectives are increasingly converging. At the present stage, both components can be considered mature, ie, quantum leaps seem unlikely, and future progress is likely to take the form of evolution rather than revolution. However, this does not apply to housing and interconnection technologies, which may permit to exploit the so far unused potential of silicon. The motivation to innovate in this area is high, as the large scale introduction of “wide bandgap” materials to the high-power range is still a long way ahead. At present, SiC appears to be the only one of these materials to have a realistic chance.

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Footnotes

[2] See also the sub-section “Optimization of forward-power losses and turn-off losses by adjustment of the plasma distribution” on page 36 of part one of this article (ABB Review 4/2006).

[3] The so-called drift zone – see figure 4 on page 37 of part one of this article.

[4] See “Design objectives of the IGBT and the IGCT” on page 35 of part one of this article.