Present and future of IGBT module technology

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Today power conversion without IGBT modules can hardly be imagined. The success of IGBT's has lead to a great variety of different modules. At the low power end (10A/600V) modules like the EasyPIM with their high level of functional integration are common, while at the high power end single switches up to a power rating of 600A / 6500V set the benchmark. As different as the applications of these modules are the technologies used to build them. This paper will give an overview of today's chip and packaging technologies.

What's to be considered in the design of IGBT modules

In the highest degree of simplification an IGBT module can be seen as an insulated switch. In this function its features should be low losses and no ringing in operation, easy to drive and rugged under all conditions. The losses are determined by switching- and conduction losses. For the conduction losses the resistance of the power semiconductors and the power leads have to be reduced. To reduce the switching losses the overlap of current and voltage in the power devices during switching must be minimised. This can be accomplished by faster switching, by having less charge in the devices that needs to be moved or by optimisation of the switching waveforms. At the same time that switching times would like to be increased for reduced switching losses, it must be limited not to cause ringing or exceeding the dV/dt - dI/dt limits of connected circuitry. To avoid ringing the stray inductances and stray capacities which can not be avoided in a module have to be optimised. For the design of a rugged switch it is important to identify the mechanisms of destruction in a power semiconductor. A significant limit is over temperature. To reduce the risk of an over-heating either the losses can be reduced or the thermal resistance can be improved. When paralleling semiconductor devices an homogenous temperature distribution is advantageous. High temperatures as well as temperature cycling not only result in spontaneous destruction but also reduced life time. To improve long term reliability not only power losses and thermal resistance can be improved, but also the mechanical design of power modules in terms of combination of materials has a significant influence. Another possible failure mechanism is over voltage. To avoid over voltage not only static voltage needs to be controlled but also voltage peaks due to transient currents at stray inductances must be considered. For the design of IGBT modules this means, that the internal stray inductance, the switching speed and the voltage rating must be considered. Over current is not a failure mechanism for IGBTs in the first place, although switching off an IGBT module is only allowed up to a current of twice the nominal current or under short circuit conditions. To survive short circuit for at least 10µs without over heating the IGBT needs to limit the current during short circuit. Driving an IGBT module should be easy to limit the complexity of the gate drive unit. The design of the front cell of the IGBT and considering the layout of the auxiliary connections helps here. To design the best possible device in respect to these considerations various technologies not only for the semiconductor itself but for the whole system have been developed. An overview of these technologies will be given in the following chapters.

IGBT Technology

The first IGBTs developed in mid 80s were fabricated on relatively thick p^+ doped silicon wafers on which in an epitaxial process a n^+ buffer layer and a n^- drift zone was grown. To structure the gate well known planar MOS cells were implemented on top of the n^- drift zone. For minimisation of carrier lifetime heavy metal diffusion or highly energetic radiation is necessary to create recombination centres. Although it is not quite accurate IGBTs of this type are called **P**unch **T**hrough- or **PT** IGBTs (the name is deduced from the fact, that the electrical field punches from the n^- zone into the n^+ layer in the case of blocking conditions). Only when the technology to handle thinner wafers had been developed it was possible to use n^- doped homogeneous float zone wafers. Into the back of these wafers a p-emitter is diffused. While having seen a different process to structure the back side of the IGBT, these so called **N**on **P**unch **T**rough- or **NPT** IGBTs still were build with the same planar cell (in this case the name NPT is used because the electrical field ends within the n^- layer) [1]. In a next development step focus was laid on design of the MOS cell. The main idea for an improvement was to turn the planar cell with formerly horizontal n-channel to a trench geometry. To accomplish this the trench cell IGBT was developed. As the front cell geometry is almost independent of the base material trench IGBTs are made in both types PT- or NPT IGBTs. The latest in IGBT technology has been the introduction of **F**ield **S**top- or **FS** IGBTs**,** some kind of mixture between vertical PT and NPT concept combining the advantages of both by adding an additional medium doped n layer inside the NPT structure [2]. Again this new vertical concept is nearly independent of cell design, therefore six different types of IGBTs can be found on the market today (Figure 1).

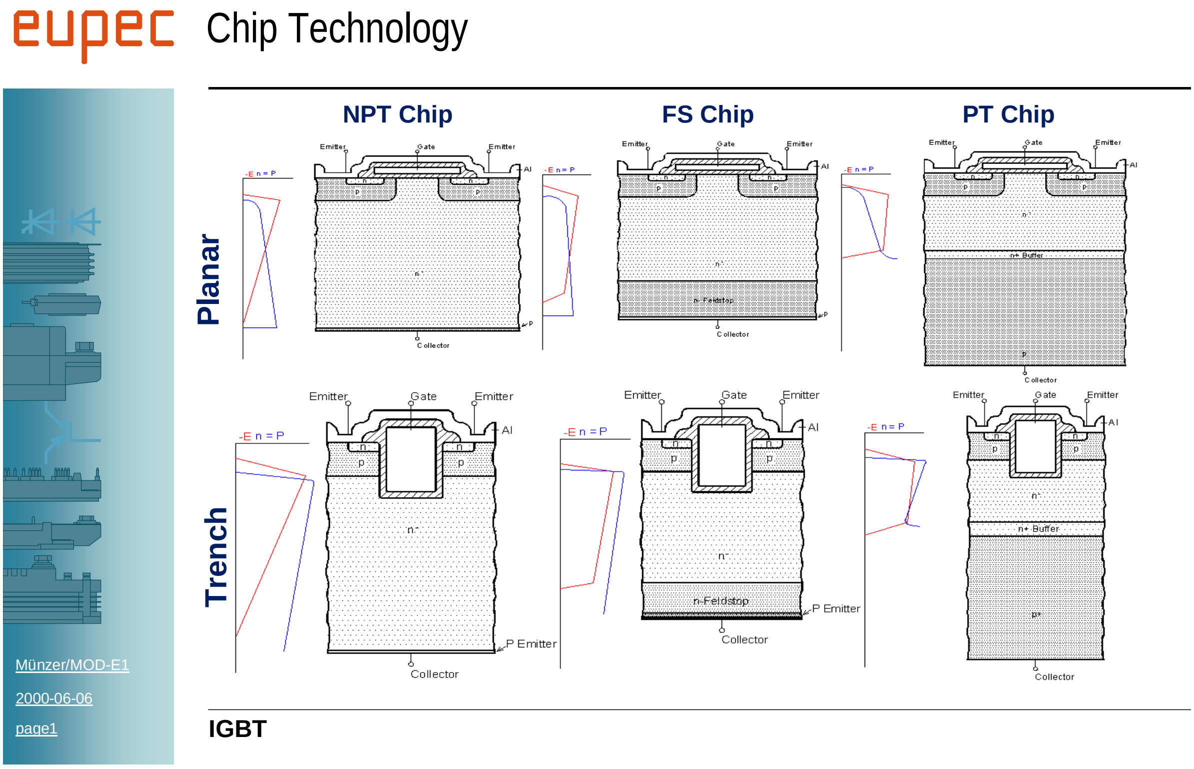

Fig. 1: Cross section of different IGBT technologies

Advantages and disadvantages of different IGBTs

The aim of IGBT development has always been to reduce switching- and on state losses. Still the device was to remain rugged and easily controllable. PT IGBTs already had the desired voltage-controlled MOS input and due to the carrier overflow in the centre region low on state losses compared to MOSFETs of the same blocking voltage. At turn off a PT IGBT would have a high and long tail current. Due to life time killing in PT IGBTs at least the duration of tail currents and with this switching losses during turn off are reduced to an acceptable value. But the life time killing that is needed to reach acceptable switching losses causes a wide parameter spread as well as the special ratio between n^+ buffer layer thickness/doping and substrate doping. This in connection with the negative temperature coefficient in V_{CEsat} of PT IGBTs makes it difficult to parallel these chips. As switching times and switching losses are also very temperature dependent an optimised control of PT IGBTs is not as easy to implement as for NPT IGBTs. Further disadvantages of PT IGBTs are very high $^{dV}/_{dt}$ during voltage rise and some higher production costs. The NPT IGBT got rid of most disadvantages of PT IGBTs. It does not have life time killing and the back emitter efficiency is well adjusted by the implanted emitter dose and therefore parameter spread is much lower. The NPT IGBT is less temperature dependent and has a positive temperature coefficient in V_{CEsat}. For hard switching applications the NPT IGBT has very low switching losses, however in resonant applications switching characteristics of PT IGBTs tend to be better as tail current of NPT chip is longer though at lower level. Due to a more advantageous ratio between electron and hole current NPT IGBTs are more rugged than PT IGBTs under short circuit and overload current conditions. While NPT IGBTs have a triangular field distribution when blocking the field in a PT IGBT is trapezoidal. As a trapezoidal field leads to thinner base region for a given blocking voltage, it is desirable to implement an additional n layer for stopping the electrical field in a NPT IGBT. Field stop IGBTs have implemented this n layer by a special diffusion process and therefore combine the advantages of NPT and PT IGBTs. For each technology there is a trade off between turn off losses and conduction losses. Depending on the emitter efficiency and/or carrier lifetime all these IGBT versions can be either tuned for fast switching or for low on state losses. So far only the vertical concept of different IGBTs have been evaluated in this chapter. All of these can either be combined with a planar or a trench cell. While planar cells are easier to build, they are rather space consuming. To produce trench IGBTs at a decent yield production facilities of higher standard are needed. Due to the trench cell geometry an increased carrier concentration is achieved especially near the transistor cells and so it is possible to reduce the on state losses of an IGBT with a trench cell significantly. But special care has to be taken that with trench cell concept the short circuit current still is low enough to remain controllable. This current can either be limited by a well adjusted cell design by means of cell size and pitch or via an external real time control chip. Secondary naturally is a cost intensive solution, which also is subject to reliability problems due to the additional parts. Although there are fields of application for each cell -vertical combination the trench cell field stop IGBTs like Infineon´s so called IGBT^3 combine the most advanced chip technologies.

Diode technology

Being necessary for almost every application the free wheeling diode is the other type of semiconductor in an IGBT module. In the beginning of the development of IGBT modules the influence of these free wheeling diodes on the module were often underestimated. With switching times getting faster the recovery behaviour of the diode got more critical. To develop a good free wheeling diode is a difficult task not only because there is always a trade off between low on state losses and low reverse recovery charge to be made, but with only two connections it does not have many options to influence the behaviour. In terms of development steps the diode moved in parallel with the IGBT. First free wheeling diodes were based on epitaxial technology. These **EPI** diodes are build by growing a n^- layer on top of a relatively thick n^+ silicon wafer afterwards the p layer is diffused. Due to the thickness of the base material such diodes are easy to handle in production. The switching speed of EPI diodes gets adjusted by recombination centres. Diodes of this type still can be found in modules with voltage ratings below 1200V. A first improvement was the introduction of **C**ontrolled **A**xial **L**ifetime diodes. With the development of an implantation process for He^{++} ions it was possible to change the local distribution of the recombination centres [3]. For an optimised profile of the charge carrier life time of these diodes an elevated concentration of recombination centres close to the pn junction is implemented. The recent approach the **Em**itter **Con**trolled concept could only be realised with improvements in the semiconductor technology [4]. The basic idea of this diode type is that the static and dynamic behaviour of the device is determined to a big extend by the emitter efficiency of the anode and cathode of the diode. The base material for EmCon diodes is a homogeneous n^- wafer. The p zone at the anode and the n+ zone at the cathode are brought into the chip in a diffusion process. Just recently an improved Emcon diode called **Emcon H**igh **E**fficiency (Emcon HE) has entered the market. The two improvements are a further reduction of the efficiency of the anode by means of an optimised ion implantation process and the introduction of the field stop to the diode. The reduced efficiency of the anode emitter leads to a reduction of the charge stored just underneath the anode during on-state and consequently to a reduced maximum reverse recovery current. Because of the optimised structure of the anode the ruggedness of the device was even improved compared to standard Emcon free wheeling diodes. Similar to the FS IGBT the Emcon HE diode makes use of the improved Infineon field stop structure leading to a vertically optimised device with soft recovery behaviour especially during extreme commutation. This field stop effect in combination with a controlled implanted cathode emitter in the back of the chip is only possible by means of ultra thin wafer technology [5]. Improvements in wafer handling and processing enabled the use of several high temperature steps, ion implantation and lithography with wafers at a final thickness of no more than 120µm for the 1200V Emcon HE diode. For devices with lower blocking voltage the final thickness is even less (e. g. 70µm for a 600V Emcon diode) but there is no big difference in the fragility of the wafers. Both technical improvements mentioned above enable a further reduction of the already low carrier lifetime killing of the Emcon diode. This leads to reduced forward voltage and smaller temperature coefficients of the electrical parameters as discussed below. Figure 2 shows a cross section of the Emcon HE diode.

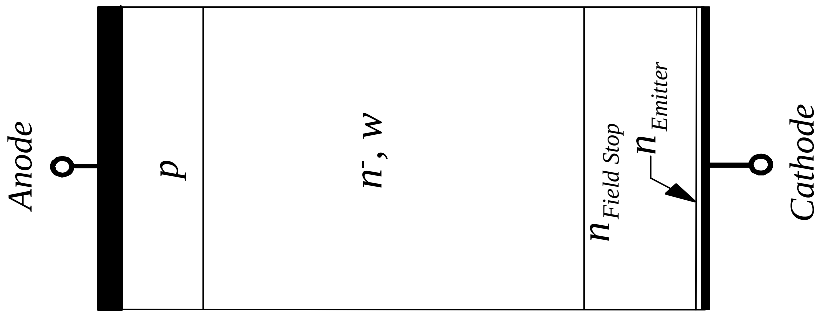

Fig. 2: Cross section of an Emcon HE diode.

Assembly technology

With power density and switching speed of semiconductors improving over the last decades assembling technology had to adapt not only to these demands but also to the customers needs for higher power ratings, more functionality, lower costs and improved reliability. Pressure contact devices used to be standard for power semiconductors, but with the introduction of the first semiconductor module a development was started that lead to a market which is dominated by IGBT modules of various kinds (figure 3).

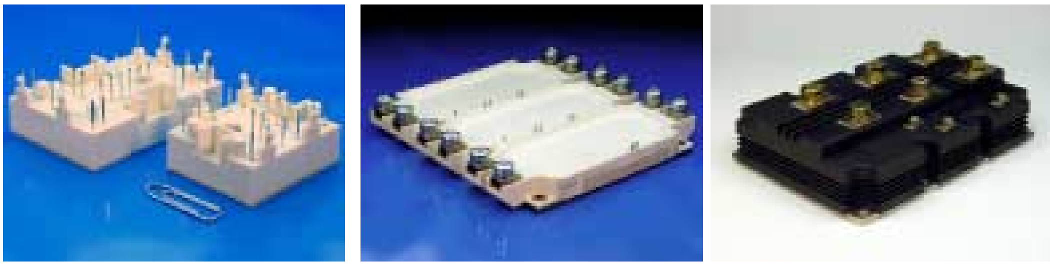

Fig. 3: Typical housings for low, medium and high power IGBT modules

The features that define a power semiconductor module are connection of one or more semiconductors in a single housing with insulated base. While for internal connections of first power electronic module only solder joints were used the development of bond wire connections marked the biggest single development step towards modern IGBT modules. Today all series IGBT modules consist of structured copper laminated ceramic substrates (DCB;AMB) on which the dies are soldered. The top of the chip is connected via bond wires either directly to the terminals, to other chips or to copper areas on the substrate. The internal circuitry of the power module is realised by variation of layout in bond and substrate layout. As stray inductances and stray capacities are determined by the layout of the copper structures as well as the bonds, it is important to optimise them against ringing for each module separately. The advantage of using bond-wires for the interconnections is their flexibility, high reliability and the good yield in production. But they contribute to the stray inductance in a module and as current density in the chips rise the thermal layout of bond wires starts getting critical. For calculation of maximum current rating of a bond wire the temperature rise in the middle of the wire is the limiting factor, because the bond wire dissipates its losses mainly along the wire via the bond into the surface of chip or substrate. Understanding the mechanism of bond wire limitation, it is easy to conclude that the maximum current rating is proportional to the diameter of wire and anti-proportional to its length. The temperature profile along a bond wire can be seen in figure 4.

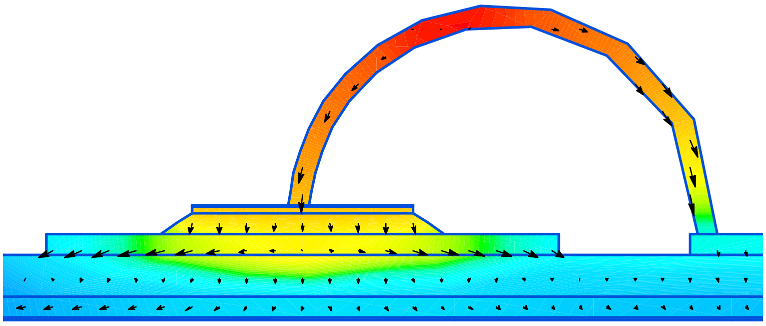

Fig. 4: Temperature profile of a bond wire.

A plastic housing and a isolating gel to cover the chips are also part of all series IGBT modules [6]. A distinctive mark for different modules is the material of the ceramic. For standard modules substrates made from Al_2O_3 are state of the art. Although the thermal behaviour of AlN substrates is significantly better, they are only used in applications where the gain of higher power density can pay for the difference in price. For small modules with high levels of functional integration it is possible to build modules without base plates. To make good thermal contact to the heat sink a thermal grease is applied to the substrate which then needs to be pressed onto the heat sink via the housing [7]. For higher power levels copper or AlSiC base plates are used. When using a base plate the substrates are soldered to the base plate. To mount the module onto the heat sink a thermal grease is laid on the base plate which then gets screwed to the heat sink. Advantage of a base plate is not only due to the mechanical stability it offers, but also because of its high thermal capacity and conductivity. A module with a base plate always has a better transient thermal impedance and due to a better temperature distribution before the thermal grease layer the overall thermal resistance is not higher than in a module without base plate although the base plate contributes to the thermal resistance (Figure 5).

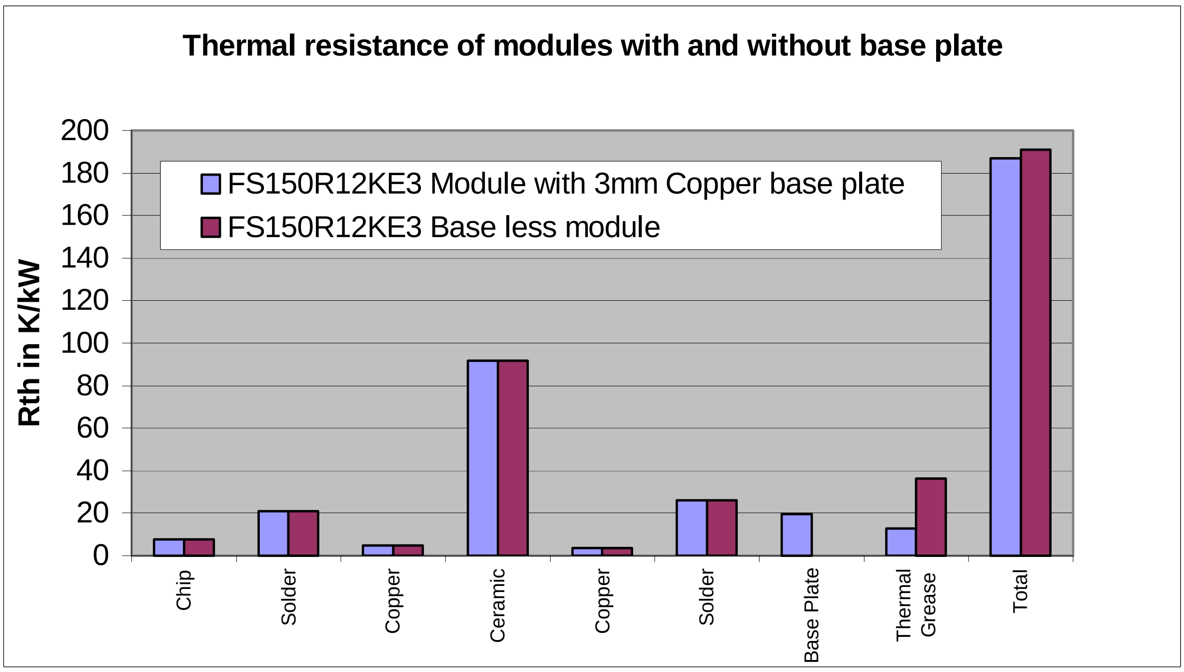

Fig. 4: Thermal behaviour junction to heat sink

Interconnection Technologies.

One issue of power packages is the variety of interconnection technologies. Today modules with screws, plugs, solder pins, press pins and springs can be found in the market. For high power applications nut and bolts are the only reliable solution to connect power terminals. For the medium power range (2 – 50 kW) modules with solder pin connection are state of the art. With introduction of solder pins (EconoPACK modules) it was possible to integrate the assembly of IGBT modules into a fully automated production line. For high volume drive production all components can be fitted on one PCB, which then can be handled in a wave solder process. Only for low currents as they occur in the auxiliary terminals and the power terminals of low power IGBT modules the pros and cons of various connection systems are not as easy to distinguish. The impact of the connection technology on the design of the power electronic system is quiet severe. Today also here solder connections are most common. They can conduct sufficient currents, they are reliable and cheap. The necessary solder processes are part of most electronic production lines and the module can be de-mounted if needed. While a plug is easy to connect, the current that can be conducted is very limited. Plug solutions are always rather expensive as the customer needs to buy the counterpart of the plug. Press pin connections show good results in first prototypes. The main disadvantage is that it needs extra tooling to press the module into place. Also servicing of a drive with a press connection is not possible. A concept that would not need extra tooling is the spring connection. For low currents spring connections might be applicable however the main concern about spring connections is the reliability of such a connection [8].

Conclusion

In the first section of this paper an overview of various IGBT technologies was given. It was shown that all six commercially available IGBT types are a combination of two front cell and three back side designs. In the next chapter the evolution of free wheeling diodes was described. How these semiconductors are assembled to build a power module was shown after that. As interconnection is an important issue for the success of a power module a separate chapter takes care of this matter.

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