New Matched IGBT and Diode for Motor Drive Systems

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I. INTRODUCTION

In electrical energy transfer electronic devices are generally required to operate in “switch mode”. That is they should have ideal switch like characteristics; appear like a short circuit passing current with minimal voltage drop across it when on and block the flow of current by supporting full supply voltage across it appearing like an open circuit in the off state. They operate in a different mode from power amplifying devices which allow power transfer according to a linear relationship with an input signal, such as in audio amplification. In switch mode operation an electronic control signal is applied to turn the switch on and removed to turn the device off. In present day MOS controlled devices the control signal is typically in the 5V - 15V range while the power supply voltage can be in the 50 - 6500V range.

Power electronics represent a strategically important prerequisite for innovations and competitiveness in transport engineering, industry and consumer electronics, data processing and communication. The pressure for rational use of energy, for miniaturization of electrical systems, and for intelligent energy management, has been the motor for the revolutionary development of semiconductors over the last 2 years, and will continue to be so in future.

The major system integration challenge for the new generation of power electronic transducers is to raise the power density, with the objective of miniaturizing the electronic systems. Raising the system efficiency across the entire load range, improving the electrical system parameters such as the accuracy of control of the load variables, the dynamics of disturbance variable control etc., and the reliability, which to a large extent determine the failure rate of modern electronic products, represent further difficult requirements for future power electronic actuators. In addition, the current industrial standard takes for granted a high level of operational security, such as overload and short-circuit protection, overvoltage protection, undervoltage shutdown, overtemperature protection, raised ambient temperatures, etc.

In the second half of the 70s, the most critical development step resulted in a new generation of power MOSFET components, and about 10 years later their planned further development into the IGBT. A completely new milestone was set down in the second half of the 90s with the introduction of the CoolMOS, the FS NPT, IGBT and the HE-EMCON diode. In parallel with the device developments, which were making the main headlines, IC manufacturing technology was steadily developed to optimize it as necessary for power semiconductor components. One step which was absolutely critical for the new generation of components was the development of thin wafer technology, with the ability to produce even large wafers at high yields. The focus in every subsequent development and new generation of power semiconductor components has been on reducing the fractional losses – static and dynamic losses – while at the same time raising the switching frequencies, improving the thermal resistance R_{thjc} and increasing the robustness. All these parameters are to some extent affected by the cell geometry, but quite critically by the wafer technology.

Infineon is the world leader in the processing of ultrathin semiconductor wafers, and hence the leader in the optimization of the electrical characteristics of MOSFETs, IGBTs and fast-switching diodes. With such comprehensive technological leadership in the processing of ultrathin wafers, Infineon Technologies is thus in possession of technical know-how which is quite critical for future component concepts in the voltage range from just a few tens of Volts up to 6.5kV. Apart from the use of this new technology in MOS-controlled switches, this approach offers quite decisive advantages with fast-switching diodes. The new semiconductor concepts for discrete components in the low-power range, and module technologies in the medium- and high-power ranges, offer completely new perspectives on cost-saving solutions for future power electronics systems. They thus open up future markets in domestic appliances, such as washing machines, refrigerators etc., in industry and in automotive engineering. The key to achieving these cost objectives lies in comprehensive system optimization and system integration.

Today IGBTs, with diodes matched to their particular switching behavior, cover the entire power spectrum for electrical drive engineering, from fractional power up into the Megawatt region. The current and voltage ranges (1A/3600A; 600V/6500V) are classified into fine steps, matched to the application fields.

The NPT-IGBT technology in particular is notable for its robustness; for example its temperature stability, latch-up free, high short circuit capability parallel switches etc., but certain operating conditions, which depend on the voltage range, must nevertheless be observed in applications. While the switching rate is virtually unlimited for the lower voltage classes such as 600V/1200V, in the upper voltage classes, such 3.5kV, 6.5kV, certain limiting values must be observed.

II. THE NEW IGBT CONCEPT

The IGBT has a MOS gate control structure identical to that of a power MOSFET. The only difference is the n^+ drain contact of the power MOSFET is replaced by a p^+ minority carrier injector in the IGBT, see Figure 1.

Using this simple and elegant adaptation a whole new class of hybrid MOS-bipolar solid state device which was particularly aimed at power switching, was demonstrated in the early eighties. When the MOS channel is turned on, the p^+-n diode at the high voltage terminal (anode) is turned on, and minority carriers (holes) are injected into the n^- drift region. This minority carrier concentration soon exceeds the electron concentration in the low doped n-region, and electrons entering the n-drift region from the channel are “stored” within it together with the injected holes to preserve charge neutrality. The net effect is that there is a much larger concentration of electrons and holes in the n-drift region, compared to that in a power MOSFET where the electron concentration is limited to that of the low doping in the drift region.

This is the classical conductivity modulation effect which can be achieved in a semiconductor by having charge carriers of two polarities carrying the current flow. Hence the on state resistance in the IGBT drift region is much lower than that in a MOSFET. The IGBT can be viewed as a MOS turn on diode in parallel with a p-n-p bipolar transistor. The collector of the transistor is formed by the p-body region with the n-drift region acting as a wide base.

In principle, the IGBT has all the advantages afforded by voltage control inherent in a MOSFET together with the low on state voltage enabled by bipolar conduction. However, the large stored charge in the n-drift (wide-base) while allowing low on resistance also severely reduces its high frequency and hard switching capability. Removal of the excess stored charge on removal of the inversion channel has to occur through holes being extracted through the expanding p-collector (body)/n-base (drift) depletion region to the p-body contact, while electrons have to be extracted through the anode. This process takes time, and results in the current through the IGBT remaining high while the voltage rises, thus drastically increasing its switching losses compared to the MOSFET.

Over the last decade a major effort has been directed at optimising the trade off between low on resistance and high turn off losses in the IGBT through minority carrier life time control in the n-base (by employing electron and α particle irradiation), thin wafer technology for non-punch through type design with optimum n-base doping and length for a given blocking voltage, and detailed design of the source region to prevent latch up of the parasitic thyristor. These efforts have led to the point that the IGBT is the device of choice for all power control applications at voltages above 600V. A range of IGBTs are available for different applications based on the trade off between on state resistance and switching losses. They are robust and capable of hard switching applications. Their voltage rating has steadily increased to the point where IGBTs rated at 6,5kV are available for traction and power system applications. Parallelised IGBT chips in module configurations with current ratings as high as 3,5kA are also available. The IGBT is a fully controllable solid state power switch which is now suitable for utility power system applications. It will allow the new fine grain distributed power generation system to evolve through seamless integration of small dynamic clean energy generating units into the existing distribution network.

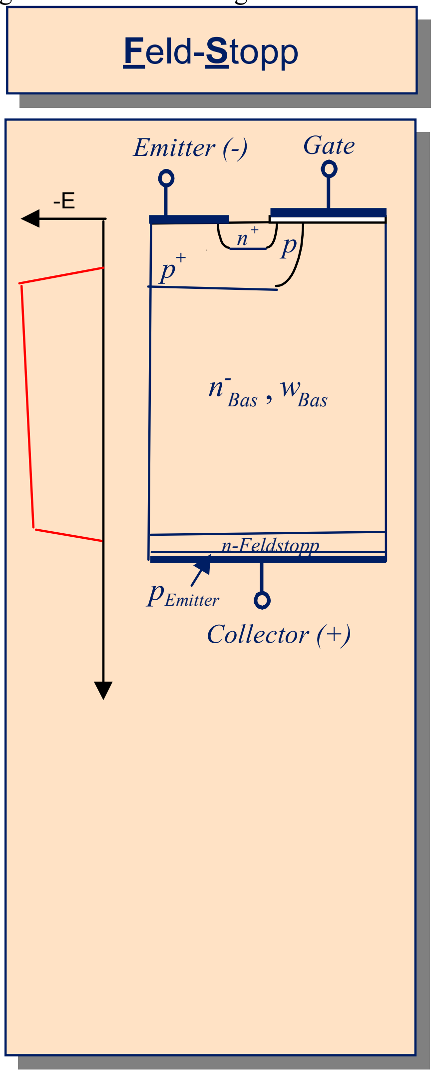

Fig. 1: Cell structure of a new FS-NPT-IGBT

The on state voltage drop in an IGBT can be further reduced by the use of the trench gate structure. The planar MOS control gate in the DMOS IGBT is replaced by a vertical gate formed on the sidewall of the trench etched into the Si surface, see Figure 2.

This structure allows for some increase in current density through better utilization of Si area, but more importantly allows reduction of on resistance through the establishment of a more efficient stored carrier distribution through the drift region. This allows the TIGBT to have an enhanced PIN diode-like carrier distribution compared the p-n-p bipolar transistor-like carrier distribution in the DMOS IGBT. Its switching speed is the same as that of a DMOS IGBT.

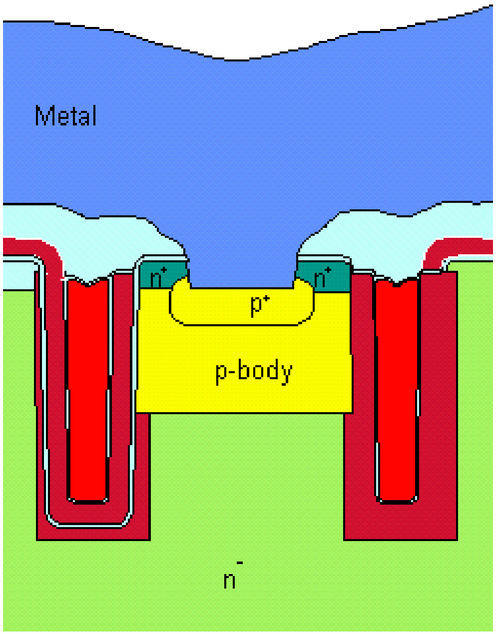

Fig. 2: Trench cell structure of FS-NPT-IGBT concept

The TIGBT is particularly suitable at voltage ratings above 1,2kV. By incorporating other design features such as thin wafer technology and the Field Stops (FS) concept the on resistance of 1,2kV IGBTs, the most important rating for 3-phase industrial motor drives, is predicted to change as shown in Figure 3.

FS IGBTs capable of switching more than 1kA into 6,5kV supply are available. The FS IGBT is likely to become the most suitable device for high voltage traction drives and power system interfaces.

Besides the reduced on state voltage of the Field Stop IGBT due to the reduced wafer thickness there are also significant influences on the switching behaviour: As long as inductive turn off occurs at low collector-emitter voltage there is the well known turn off behaviour of the NPT IGBT with a very low, but rather long tail current. But if the collector-emitter voltage changes to values where the electrical field reaches the field stop layer, the tail current endurance is reduced, at very high collector-emitter voltages nearly no tail current is left (Fig. 4).

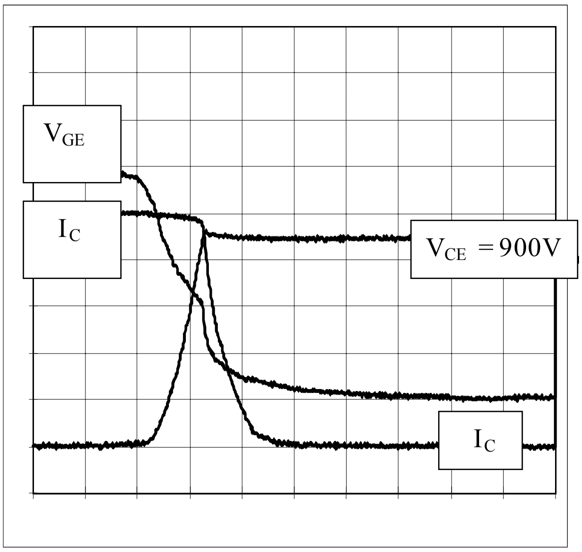

Fig. 4: Turn off behaviour of FS IGBT at different V_{CE} voltages ($t=0.2\mu s/div$, $V_{GE}=5V/div$, $I_C=5A/div$)

NEW OPTIMIZED IGBT FOR HIGH SWITCHING FREQUENCY

To achieve the best performance for each application there has to be a separate IGBT concept for applications with low switching frequency and for applications with high switching frequency. One of the application specific IGBT is Infineons latest IGBT development - the IGBT³. Compared to the IGBT-2 this IGBT shows a massive reduction in the conduction losses while the switching losses stay the same. On the other hand for the applications with high switching frequencies the IGBT is optimized in a way to reduce the switching losses.

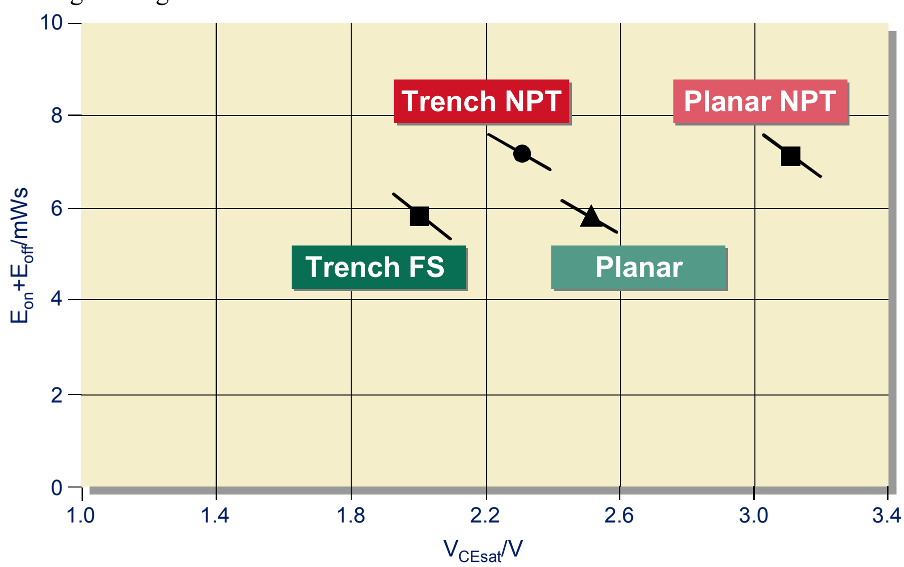

Fig. 3: The trade off between switching energy loss and on state voltage for new Trench FS-NPT-IGBT

In future Infineon will offer three Types of discrete IGBT's :

- The 600V High Speed IGBT is recommended for the high frequency power switching applications with switching frequencies between 40kHz and 100kHz. Possible applications are welding machine and switch mode power supply.
- The Fast IGBT in 600V and 1200V version is the best choice for general purpose Applications - with switching frequencies below 40kHz.
- The upcoming 1200V IGBT³ will be the ideal power switch for the motor-drive Applications – with switching frequencies below 30kHz.

For the 600V High Speed IGBT the Backside Emitter implantation is adjusted in a way that the on state carrier concentration inside the n^- layer is reduced and thus the switch off losses becomes less. Because of the lower carrier concentration the V_{Cesat} value for the High Speed IGBT is higher as for the Fast IGBT.

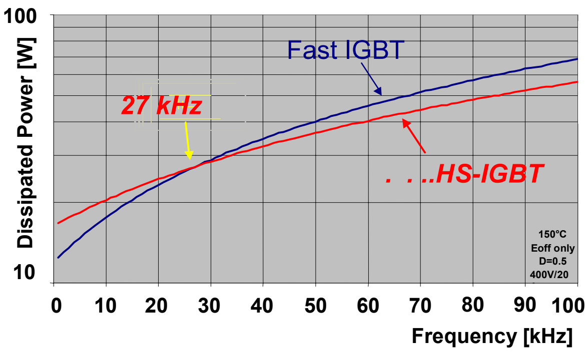

Fig. 5: Dissipated power versus the switching frequency for triangle shaped currents.

The Simulation result in Fig. 5 shows that for switching frequencies above 40 kHz the High Speed IGBT has lower overall losses compared to the Fast IGBT.

Because the High Speed IGBT depends on the Infineon IGBT-2 technology the advantages from the Fast IGBT Series are relevant for the High Speed IGBT. The positive temperature coefficient makes paralleling easier and is an essential feature for welding applications.

Electrical Performance of a 6500V FS-IGBT

The 6.5kV IGBT modules are designed for traction applications working at a voltage level of $3kV_{dc}$. Due to their high blocking voltage capability they ensure a large safety margin for inductive voltage overspikes during turn off. This allows an increase of the dc-link voltage of 30% up to 4.5kV caused by worst case voltage fluctuations and regeneration. At this worst case dc-link condition save turn off can be handled for di/dt=10kA/µs with a total stray inductance of 200mH.

The blocking voltage is rated at 6.5kV at room temperature which guarantees a blocking capability of 6kV at –40°C. The planar cell structure is a stripe cell. The plasma enhancement at the emitter side is optimized by the cell pitch an width. The field stop is realized by an ion implantation process with a very low dose not influencing the low dose p emitter but high enough to stop the electrical field under blocking conditions. The vertical optimization concept allows the adjustment of the on state voltage of the IGBT over a wide range. By virtue of the field stop layer, the switching losses are low due to the reduced length of the tail current during switch off. This effect is more significant for higher collector-emitter voltages resulting in a slightly increase of the turn-off losses. In Fig. 6 the typical turn off waveforms of the 6.5kV module (T=125°C) for a dV/dt=3.4kV/µs at a dc-link voltage of 3.6kV (E_{off}= 3.7J) is seen.

The FS concept does not demand any additional charge carrier lifetime killing processes. Therefore positive temperature coefficient of V_{CEsat} has been achieved. This eases the paralleling of chips inside a module as well as paralleling modules in the inverter. The new 6.5kV-Emcon-diode used, shows a low reverse recovery current peak and has also a neutral temperature coefficient.

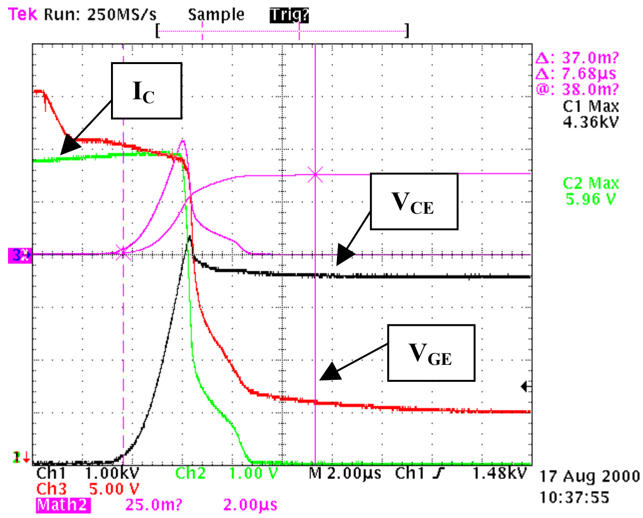

Fig. 6: Turn off behaviour of the 600A/6.5kV IGBT-module at 600A, dc-link voltage 3.6kV/125°C (Roff=22 Ohm, t=2µs/div, V_{CE}=1kV/s, V_{GE}=5V/div I_C=100A/div)

Due to the outstanding ruggedness of the NPT-structure even the 6.5kV shows a high short circuit capability. During the short the current is limited at 6 times of the nominal current rating.

The New Diode Concept

In parallel to the new IGBT concept an optimized fast switching soft recovery diode with low forward voltage drop and low reverse charge has been developed. Equally to the IGBT idea the carrier distribution in the diode is adjusted from the cathode and anode side. The electric field is controlled via a field stop layer. The basic idea of this high efficient diode is shown in Figure 7.

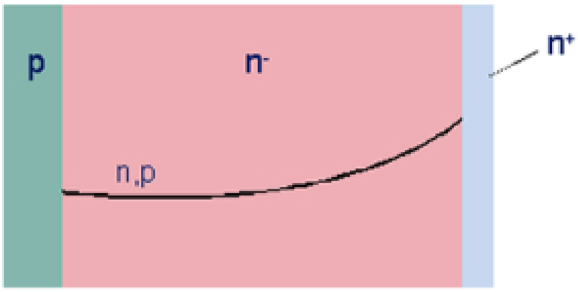

Fig. 7: New EMCON diode concept, carrier distribution

The new EMCON High Efficiency (EMCON HE) free wheeling diode is the next development step of the EMCON concept. The technical improvements are mainly based on two reasons.

First, it was possible to further reduce the efficiency of the anode emitter by means of an optimised ion implantation process. This 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.

Second, similar to the FS IGBT the EMCON HE diode also makes use of the improved Infineon field stop structure leading to a vertically optimised device with soft recovery behaviour (see Figure 8).

This field stop effect in combination with a controlled implanted cathode emitter in the back of the chip are only possible by means of ultrathin wafer technology. During manufacturing the wafers are brought to their final thickness of 120 µm by grinding. Then there follow several ion implantations, high temperature and lithography process steps with these thin wafers.

This facts enable a further reduction of the already weak carrier lifetime killing of the EMCON diode thus leading to reduced forward voltage and smaller temperature coefficients of the electrical parameters.

Of course the free wheeling diode has a strong influence on the dynamic behaviour of the whole IGBT module. Thus beside the diode forward voltage also the dynamic characteristics of the diode must be considered in detail. Especially the maximum reverse recovery current of the diode during commutation determines the turn on losses of the corresponding IGBT to a great extend. Therefore a major goal for the development of the new EMCON HE diode was not only a reduction of the forward voltage. Compared to the current EMCON diodes used in low loss IGBT2 modules there is an improvement of 20 % for the maximum reverse recovery current and almost 30 % for the reverse recovery charge (see Figure 9).

	EMCON HE	EMCON
V_F @ 25°C, 150A	1,65V	1,90V
I_{rrm}	120A	150A
Q_{rr}	25µC	35µC

Fig. 9: Typical values for diodes with rated current 150A, commutation at 125° from forward current 150A with 2000A/µs with DC link 600V

Dynamic Behaviour of IGBT and Diode

While for the 600V/1200V and 1700V NPT-IGBT there is basically no gate resistor needed for the 3.5kV and 6.5kV a minimized gate resistor is required. The low voltage IGBTs are having a full rectangulator SOA-Diagram. In the case a fast recovery "soft behaviour" freewheeling diode –like a HE-EMCON-Diode– is used the turn on switching behaviour is unlimited. The turn off behaviour is given by circuit layout –low leakage inductance is required– and not by the IGBT chip technology.

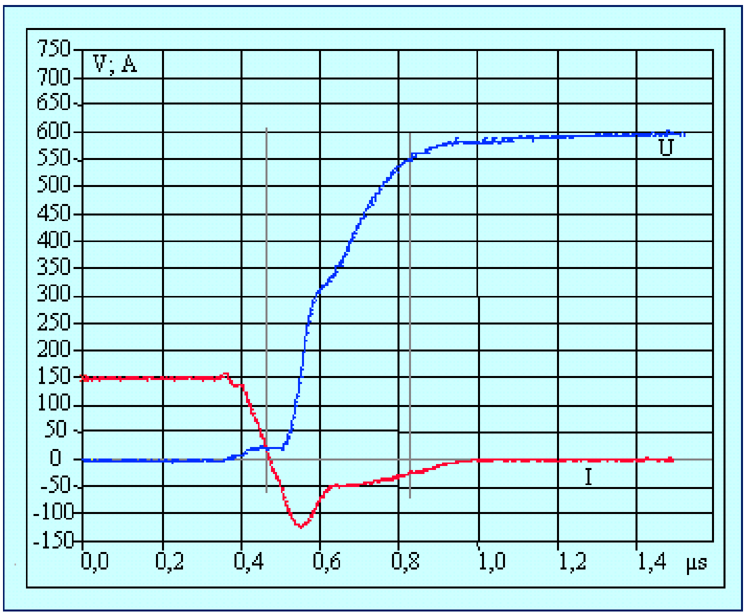

Fig. 8: Commutation of an EMCON HE diode at 125°. Rated current and operating current 150A, DC link 600V, t = 0,2 µs/div

In case of high voltage IGBT it must be considered that during the dynamic intervals there are extremely high current densities occur. For this reason the turn on behaviour is limited –by a certain gate resistor– due to the dynamic electrical field distribution in the freewheeling diode and during the turn off there are high dynamic electrical field distribution in the IGBT itself. For this reason there is a certain gate resistor required, for example $R_G \approx 22\Omega$ as shown in figure 4.

PERFORMANCE CHARACTERISTICS OF IGBT TECHNOLOGY

The outstanding advantages of IGBT technology over GTO technology are that the power semiconductor elements (IGBT) are easy to control and that in principle it is possible to operate the components without snubber circuits, although a certain reduction in power has to be accepted. Especially the first characteristic creates a good basis for achieving high levels of system reliability because, as a result of this feature, the complexity of the converters can be reduced substantially.

Another advantage is the easy scalability of the components in terms of their current-carrying capacity. The semiconductor devices are made of individual silicon chips connected in parallel (multi-chip design). It is simple to connect the devices in parallel if the reduction factors are dully taken into account. Consequently, the converters can be easily adapted to different power requirements.

CONCLUSION

IGBT along with optimized diode technologies are available from 1A up to 3600A, 600V up to 6500V. In the low voltage applications $V_{Br} < 2000V$ there is almost no limitation of these components in the switching behaviour in the high voltage area $V_{Br} \geq 2500V$ a certain gate resistor is recommended not to destroy the IGBT during turn off and the diode during turn on due to the "dynamic" electrical field stress.

In recent years IGBT technology has established itself the entire field of motor drive systems up to traction systems including HVDC systems and will completely supplant GTO thyristors in new converter designs. High line voltages or extremely high performance requirements do not place any limitations on its area of application – be it for reasons of cost or for technical reasons.

The customer thus receives a cost-effective system at extremely reliability performance.

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characteristics	IGBT module	GTO-thyristor	improvement
driving circuit	voltage controlled: U_{GE} = +/- 15V	current controlled: I_{Gon} = 10A I_{Goff} = 0,3 ... 1,0 I_{load}	IGBT: cost, reliability
short circuit protection	short circuit failures can be controlled in several cases by the device itself	no short circuit protection by the device itself	no substantial difference
current-carrying capacity	single chips in parallel, scalable	Si-disk: ∅ 85 mm (Silicon)	IGBT: easily adaptable to different power requirements
insulation	internal	external	IGBT-module: simple housing, simple assembly
snubber circuit	not required	required	assembly, costs
current density	low	high	

Fig. 10: Comparison of the characteristics of GTO-thyristor and IGBT