SiC Power Devices for Industrial Inverters

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1. Introduction

Energy saving as well as efficient energy management is seen as one of the key issues to retard the warming of the global climate system which is very likely due to the observed increase in anthropogenic greenhouse gas concentrations [1]. Today 40% of all energy consumption is electrical energy, with increasing tendency in future. Therefore power electronics plays an important and growing role in order to control the energy flow between source, load and temporary storage. For example by using power electronics there is a tremendous potential to save energy in motor drives which today share 50-60% of all electrical energy consumption in the developed world [2]. Above all power devices high voltage switching transistors and diodes are the most important semiconductors in the field of power electronics. Consequently, R&D efforts should focus on next generations of semiconductors and device concepts. As will be shown, converters with SiC devices are significantly more compact and are attractive looking at the system costs although SiC devices are and will be much more expensive than silicon devices. This paper intends to show the relevance of SiC power devices with focus on industrial applications.

2. Requirements and Context in Industrial Applications

Unipolar silicon carbide power devices are able to substitute bipolar silicon devices in the voltage classes from 600V to 3300 V. Because of the absence of minority charge carriers which would need time for generation and recombination unipolar working devices can switch between on-state and off-state with much less dynamic energy loss per switching cycle than bipolar devices do. Thus the switching frequency can drastically be increased. The system benefit is the fact that the size of passive components can be reduced by nearly the same factor the switching frequency is increased. Alternatively, the feature of very low switching losses can directly be transferred into energy savings which is a key issue for efficiency dominated applications.

For motor control in industrial applications, Si-IGBTs are commonly used as active power devices in the converter since their turn-on and turn-off is well controllable by the gate driver and on-state losses are low. The reverse current during freewheeling is carried by a paralleled fast recovering Si PIN diode. The switching power ranges from 5 kVA to 1 MVA needing blocking capabilities of 600 V, 1200 V, 1700 V, 3.3 kV and 6.5 kV, respectively. Energy saving aspects require the converter to be operable in both directions, from source to load and vice versa. For the majority of motor drives there is no need to enhance the switching frequency since motor and converter are directly connected. Hence there is little need for LC filter elements in order to suppress harmonic content. However, SiC devices open up novel applications if higher switching frequencies are required or are at least advantageous (>> 4 kHz for standard drives, >> 400 Hz for large drives), for example:

- Sinusoidal output or input is required and place for bulky LC filters is unwanted.
- High rotation speed e.g. for machine tool drives (≥ 30,000 rpm, torque ≥ 200 Nm)
- High dynamic servo drives with high positioning accuracy
- Distributed inverters, located at the motor and remote from control unit
- Improved motor life time by damping the harmonic content at the output of the inverter which degrades bearings and motor insulation
- Noise sensitive applications
- Uninterruptible power supplies (UPS) for (3 phase, power range 10 - 100 kW)

In addition to the advantage of low switching losses, SiC devices can be operated at higher junction temperatures supposed the packaging is enabled to stand it. In particular, DC-DC conversion for automotive applications will benefit from SiC by the reduction of size and weight of LC components. The heat sink temperature can be extended to 120°C and an additional cooling circuit for the power electronics can be skipped. Therefore, new concepts for the packaging technology are necessary to enter this interesting market with SiC. The big challenge for the packaging technology is to connect lots of SiC chips having very low on-resistance, high current ratings under extended junction temperature conditions (-40 … 250°C) and heavy fluctuations in temperature in a reliable way.

3. SiC Power Devices

3.1 Schottky Barrier Diodes (SBD)

The penetration of silicon carbide into the power device market began with 600 V Schottky barrier diodes (SBD) in high-end PFC power supplies and continues in industrial motor drives for a power range up to 100 kW. In May 2006 Siemens announced the first frequency inverter for 690V supplies [3]. It uses power modules equipped with 1700V Si IGBT and 1700V SiC SBD. The inverter has line-commutated regenerative feedback and covers the power range from 7.5 to 55 kW. Due to the switching frequency of 16 kHz it is working quiet, extremely efficient and energy saving. A small sinusoidal filter is integrated in order to be used in combination with unshielded motor cables having a length up to 300 m. So it is ideal suited e.g. for modernization of plants in the chemical industry since it avoids the installation of new cables. Details of the circuit concept as well as details of the power module will be demonstrated in the paper.

3.2 Junction Field Effect Transistors (JFET)

Among all available SiC power switching prototypes the SiC JFET is the most reliable one and has the lowest on-resistance, closest to the theoretical limit. New technologies with an optimized utilization of the drift zone are shown which further improve the on-resistance as well as the saturation current [4]. SiC JFETs are used in those industrial applications where a very high switching frequency leeds to energy efficient and compact system solutions. Mainly above 1000 V the SiC JFET can outperform the Si MOSFET due to its lower specific on-resistance and the Si IGBT due to its switching behavior. A high current rating related to a small chip size leads to an excellent dynamic performance since both the input capacitance and the Miller capacity are very small. However, the device is normally on and implies an alternative gate control and safety precautions. Due to the low reverse recovery charge of the body diode the JFET can also be used in diode free converters [5].

3.3 Metal Oxide Field Effect Transistors (MOSFET)

The SiC MOSFET has the same application field as the JFET. The acceptance is better since the device is normally off and matches standard gate driver circuitry. But up to now the SiC MOSFET suffers from low inversion channel mobility due to carbon related interface states. In addition, the long time stability of the MOS system might cause concerns due to the high field stress in the oxide. However, new reliability tests show encouraging results regarding the so called intrinsic stability of the gate oxide. Progress in decreasing extrinsic defects can be stated as well. In order to decrease the channel resistance the ratio of channel width to channel length w/L remains the key design parameter. It can be optimized for example by self aligning techniques. This paper will show a MOSFET Demonstrator for 10 A current rating, a blocking capability of 1700 V and a specific on-resistance of 20 mΩcm^2 at 150°C. The device will be the basis for first prototypes of full-SiC inverters for motor control planned for 2008.

3.4 Bipolar Diodes

For voltages from 3 kV to 10 kV the switching losses in inverters are even more dominated by the freewheeling diode than for lower voltages. This makes SiC pin diodes interesting not only because the forward voltage drop is similar or even smaller than in Si pin diodes. As will be shown they exhibit a reverse recovery charge orders of magnitude smaller than that of equivalent Si pin diodes due to the short n type base and due to short lifetime of minorities. Only with SiC pin diodes today's 6.5 kV Si IGBT exploits its full dynamic potential. As will be demonstrated the quality of SiC diodes is not only a question of substrate defect density but also a question of epitaxy and an appropriate (thick enough) emitter and base design [6]. With optimized design rules the forward voltage drift can drastically be minimized which has been seen as a severe problem. Paralleling of SiC pin diodes seems now to be reliable and the first prototypes of inverters are running.

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[4] P. Friedrichs, R. Elpelt, "Layout considerations for improving the on-state performance of vertical SiC switching devices", submitted to PESC'07, 17-21 June - Orlando, Florida, USA.

[5] C. Rebbereh, H. Schierling, M. Braun, "First inverter using silicon carbide power switches only", Proc. of EPE 2003, 2-4 Sept. 2003, Toulouse, F, ISBN 90-75815-07-7.

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