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A new generation of 600V GaAs Schottky diodes for high power density PFC applications

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Abstract

A new 600V GaAs Power Schottky diode is compared with Si and SiC diodes in a 200W CCM-PFC system. With both, GaAs and SiC, the PFC system losses were reduced up to 25%. Higher on-state losses of GaAs vs. SiC are compensated by lower MOSFET losses due to the GaAs diode's lower capacitance. Given the cost advantage and ruggedness of GaAs compared to SiC technology, this new GaAs diode is a very promising device for high frequency and high power density applications.

1 Introduction

Increase of power density is one of the main tasks for power electronics today: system sizes shall be reduced although in general the power output of the user applications increases. There are two ways to meet this challenge: 1. reduction of losses by more efficient power electronic devices; 2. reduction of active and passive components' number, weight and size, generally by increasing switching frequencies.

An important example is the optimisation of Power Factor Correction systems (PFC). Boost converters with PFC can mainly be operating in Continuous Current Mode (CCM) or Discontinuous Current Mode (DCM). In DCM, however, most of the circuit components have to be oversized due to high current peaks, which in turn mandates complex EMI filtering. Moreover, the system tends to be unstable at light load [4]. CCM operation does not have these drawbacks. In many cases the system can be realised with fewer and smaller components. Though, because of the hard switching, it requires boost diodes with extremely low switching losses. Even more important than the losses in the diode itself are the additional losses induced in the MOSFET that has to conduct the diode's reverse recovery current. Without diode reverse recovery, the MOSFET size can be reduced and costs can be saved.

Unfortunately, Silicon (Si) bipolar diodes always show significant switching losses due to their reverse recovery behaviour, especially at elevated temperatures as occurs in operation. Unipolar ("pure Schottky") diodes on Si can only be made for voltages up to about 100V. To overcome this silicon limit, high band gap semiconductors have come into focus during the last few years. Gallium Arsenide (GaAs) and Silicon Carbide (SiC) Schottky diodes have been made with breakdown voltages up to 600V and even several thousands of Volts respectively without (or more precisely with extremely small) reverse recovery. These devices are available for several years now, and their advantages have been shown in numerous applications and publications [1-5].

2 Technology

2.1 Gallium Arsenide and Silicon Carbide

Considering the general physical parameters of Si, SiC and GaAs, SiC seems to be the material of choice for high frequency power devices. It can withstand the highest electric field leading to diodes with very high breakdown voltages and low forward voltage drop. Moreover, it has the lowest thermal resistance allowing a high on-state current density.

Nevertheless GaAs has some advantages which have to be taken into account:

- The non repetitive peak current in SiC diodes is limited due to the significant positive temperature coefficient of the forward voltage drop [5]. Therefore the device size has to be chosen large enough to avoid over-current destruction. GaAs devices can offer more than two times higher surge currents for the same average current rating (shown in fig. 2).
- The junction capacitance of GaAs devices is much smaller compared to SiC (more than 5 times), even though SiC diodes can operate at higher current densities.
- Avalanche capability is higher in GaAs. In SiC bipolar current flow can lead to defect growth and finally to the destruction of the device.
- GaAs does not suffer from general material problems like SiC still does. Therefore GaAs offers larger wafer size, larger die sizes (with current ratings up to 100A, actually), higher yield, no need for high temperature processing, and higher growth rates – finally resulting in significantly lower costs.

2.2 GaAs injection mode Schottky diodes

Like for Silicon, GaAs Schottky diodes can be divided into low barrier devices (“pure” Schottky diodes, which we also named “1^{st} Generation”) and high barrier devices, so called “Injection Mode Schottky Diodes” or “2^{nd} Generation”. These 2^{nd} Generation Schottky diodes are designed to use the phenomenon of minority carrier injection under forward conduction [1, 2]. When the Schottky barrier is chosen to be higher than half the semiconductor's band gap, the region close to the metal becomes p-type because electrons from the semiconductor enter the metal until the Fermi level is flat. Under forward bias, the holes from this p-type layer are injected into the neutral n- region and so carry a part of the current. Furthermore at high current densities, additional electrons are entering the n-region to maintain charge neutrality. This leads to a conductivity modulation of the n- layer [8]. As a consequence the diodes show decreasing differential resistance with increasing current flow and temperature, leading to lower VF, higher surge current capability and higher current rating. Fig.1 shows the forward characteristics for 300V diodes in comparison.

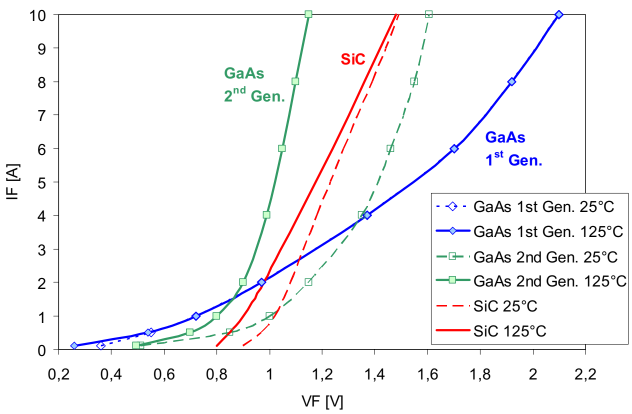

Fig.1: Typical forward characteristics of 1^{st} Gen. and 2^{nd} Gen. GaAs and SiC Schottky diodes, 300V/10A types

It can be seen, that the 1^{st} Generation GaAs devices (pure Schottky diodes) show almost no temperature dependency, but have the highest VF at high currents. The 2^{nd} Generation GaAs devices (injection mode Schottky diodes) have a much lower VF at high current, and at elevated temperature they even outperform typical SiC Schottky diodes.

This minority carrier injection effect is well known for Si power Schottky diodes, too. But while in Si it leads to a drastic increase of reverse recovery, in GaAs, due to the very short minority carrier lifetime, the resulting reverse recovery still is extremely low.

Furthermore, the leakage current is much lower for the larger barrier height, which makes the diodes capable for high temperature application (typically I_R=1mA at T=250°C for a 10A diode).

2.3 The new 600V GaAs device

To create 600V GaAs devices, two 2nd Generation 300V Schottky diodes are series connected in a backside isolated ISOPLUS220™ package. By this, the resulting capacitance is reduced not only by the series connection of the two junction capacitances, but also the ISOPLUS™ package offers a much lower parasitic capacitance than a comparable standard TO220 package (15pF compared to 124pF [3]).

In the following measurements we considered the 10A version, called DGSS10-06CC. Due to the 2nd Generation characteristics its surge current capability is 80A, which is much higher than comparable 10A SiC devices can handle (fig. 2).

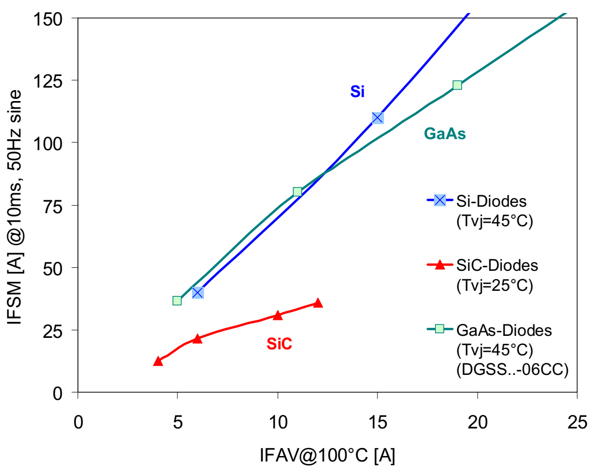

Fig. 2: Surge current capability IFSM (data sheet values) for typical 600V GaAs-, SiC- and ultrafast Si-devices

Further versions are designed for 6A up to 100A current rating, so that for most applications targeted here no parallel connection of diodes should be necessary.

3 Measurement

3.1 PFC test set up

To give an application example, different diodes (10A/600V) were tested in a typical 200W PFC circuit. This boost converter was running in continuous current mode (CCM). Input voltage varied from 90V to 260V, switching frequency from 110kHz to 250kHz. Measurements were done at 20°C and 70°C environment temperature. The PFC transistor was an 11N60S5 MOSFET by Infineon. The temperatures of the diode and the transistor were measured to characterise the losses. The schematic of such a PFC board is shown in fig. 3.

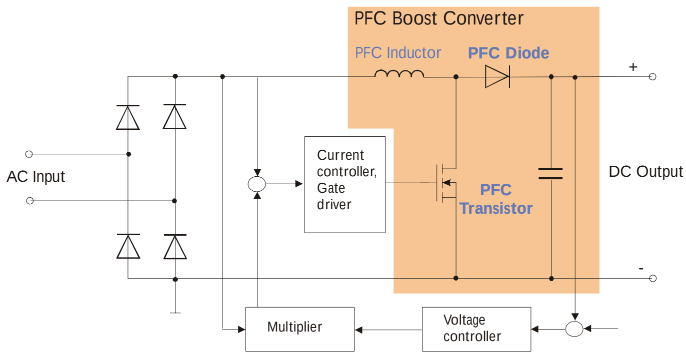

Fig. 3: Simplified Power Factor Correction Circuit

3.2 Results

Fig. 4 shows a typical measurement result of system efficiency vs. input voltage. It can be seen, that the usage of GaAs and SiC Schottky diodes leads to significantly higher efficiencies compared to the ultrafast Si diodes as expected from their superior properties.

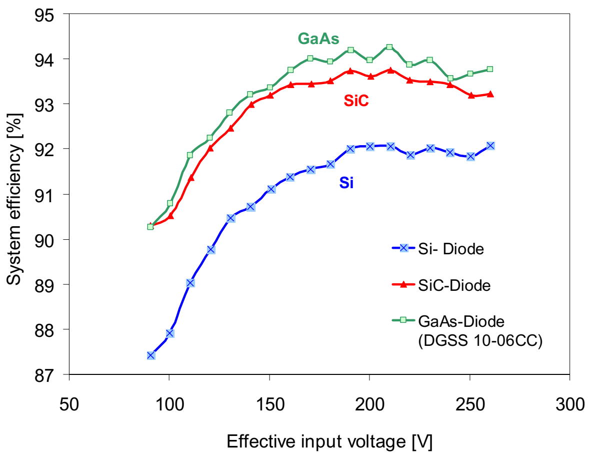

Fig. 4: Typical measurement result of PFC efficiency for GaAs-, SiC and Si-Diodes in 200W PFC system (CCM) at 200kHz, 70°C.

Fig. 5 summarizes the results for an input voltage of 220V for all tested frequencies. Obviously, the system losses with the GaAs device are almost temperature independent, while the Si diode leads to increased losses at higher temperature, especially at higher frequencies.

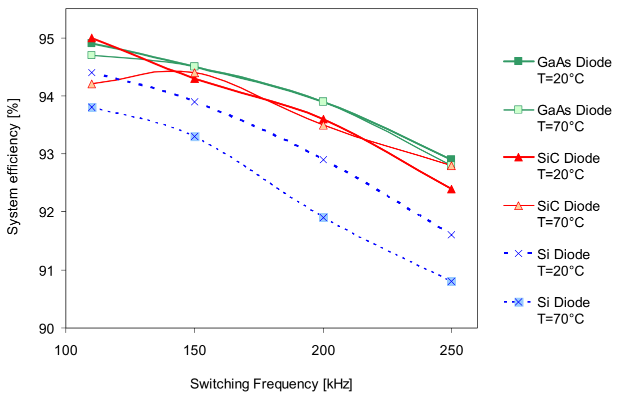

Fig.5: PFC efficiency for different diode types and temperatures vs. switching frequency at 220V input voltage

In Fig. 6, the corresponding losses are shown relatively to the losses of the Si diode. At 110kHz the GaAs diode already leads to about 15% less total losses compared to Si. This increases with switching frequency up to 25%.

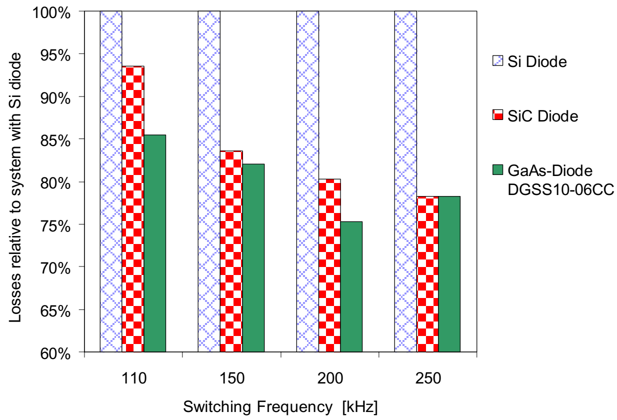

Fig. 6: Relative PFC system losses for GaAs- and SiC- compared to Si-Diodes vs. switching frequency. (220V input voltage, P_{PFC}=200W, T=70°C)

The SiC diode shows similar results, but in this experiment under no condition did they lead to higher efficiencies than the GaAs devices (see fig. 5).

This can be explained by analyzing the losses in the diode and transistor as indicated by their temperature (see tab.1). In operation, the GaAs diode itself gets warmer than the SiC diode due to the higher on-state losses. But the transistor gets warmer with the SiC diode. As it shows no reverse recovery, the additional losses must be due to the SiC diode's higher capacitance that has to be charged when the MOSFET turns on. Consequently, for GaAs and SiC the losses in the diodes and transistors add up to the same amount and so lead to the same total efficiency.

PFC diode technology	Si	SiC	GaAs
Temperature of diode [°C]	31,8	29,3	34,2
Temperature of transistor [°C]	77,9	71,0	67,3
Temperature of environment [°C]	19,0	19,4	19,0
⇒ Calculated losses [W]	9,6	8,1	8,2

Tab.1: Typical temperatures of transistor and diode, and calculated losses on PFC test board (230V input voltage, P_{PFC}=200W, switching frequency = 110kHz)

Furthermore, with increasing temperature the GaAs on-state diode losses decrease while the SiC diode losses increase. With increasing frequency, the losses due to the diode's capacitance increase less for the GaAs diode than for the SiC. Therefore, the evaluated cases (low temperature, moderate frequency) are the worst cases for GaAs.

The Si diode, finally, shows moderate losses itself, but leads to the highest losses in the transistor due to its reverse recovery behaviour. Therefore the calculated total losses are higher than for GaAs or SiC.

3.3 Conclusion

Of course, the whole PFC circuit would have to be optimised in a real application. A PFC board design has to find an optimal trade off between shrinking of passive components (by increasing frequency), increasing system efficiency, and the right choice of MOSFET and diode type and size to get the maximum value of the system within the requirements of the application. Nevertheless it was shown, that not in every case SiC diodes automatically give the best results. The system losses have to be analysed carefully, and especially the diodes capacitances – not only their reverse recovery – have to be taken into account.
The new DGSS GaAs device family is a viable alternative, which might be the best choice for many applications.

4 Outlook

We think that in future power applications both, GaAs and SiC devices will find more and more use. The increase of power density - and therefore system value - easily pays for the higher costs for the GaAs or SiC devices compared to Si diodes.

It depends on the specific design of the application which technology is optimal. Generally, up to 600V GaAs is preferable, while for voltages much higher than 600V SiC will be the semiconductor material of choice. In a transition region at about 600V, the circuit conditions have to be analysed carefully. In the example of a PFC system that has been shown here, the GaAs devices turned out to result in at least as good system efficiencies as the SiC diodes, and GaAs will be the more cost effective solution.

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