A Silicon Carbide Inverter for a Hybrid Vehicle Application

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Abstract **– The recent progress made in the field of silicon carbide (SiC) transistors has made it possible to evaluate the benefits of using SiC transistors. This article will focus on how SiC bipolar junction transistors (BJT) can improve the power inverter in a hybrid car. More precise a BJT transistor named BitSiC 1206 from the TranSiC company will be evaluated.**

SiC semiconductors have several interesting advantages compared to Si based semiconductors:

- **SiC can withstand high temperatures, up to 600ºC.**
- **Higher thermal conductivity, lowering the junction to case thermal resistance.**
- **Positive temperature coefficient, easier to parallel.**
- **Faster and less reverse recovery, reducing switching losses**

1. Introduction

Today's power electronics in a hybrid car needs a cooling system separated from the main cooling system. A separated cooling system increases the cost. The properties of SiC might make it possible to use the standard internal combustion engine (ICE) water cooling system, The idea is to replace silicon (Si) transistors with SiC transistors which can withstand higher temperatures. The SiC BJT is provided from the company TranSiC that is developing a SiC transistor called BitSiC. To study a complete three phase inverter a PSpice model of a SiC BJT is built. The BitSiC PSpice model is used to simulate an inverter for a 5 kW electric machine (EM). The EM is intended for a BAS (Belt driven Alternator Starter) in a hybrid car of medium size.

Through simulation it shows that silicon carbide transistors can use the exiting cooling system in a car. Depending on the transistors capsule the SiC BJT can sustain a junction temperature up to 250 °C. With the SiC BJT low switching losses and low conduction voltage the efficiency reaches values of 98%.

2. BitSiC

In this project BJTs from the TranSiC company is evaluated. During the project two samples of the BitSiC is worked on, see figure 1. The SiC bipolar transistor (BitSiC) developed at TranSiC is made with epitaxial 4H-SiC wafers. TranSiC is aiming for the following transistor performance.

- Ic_max = 6 A
- Vce_max = 1200 V
- h_{fe} = 30...40
- Rise and fall time < 50 ns

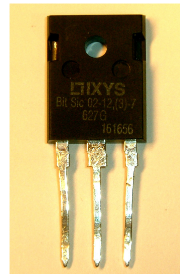

Figure 1. TranSiC's BitSiC transistor.

3. Test rig

To be able to test the BitSiC transistor and extract behaviour for the model a high quality laboratory test rig is needed. The idea for the test rig is to simulate a working environment for a transistor in a motor drive for a BAS. To do this it is necessary to be able to change the load, voltages and currents in a controlled matter. The test rig system is viewed in figure 2.

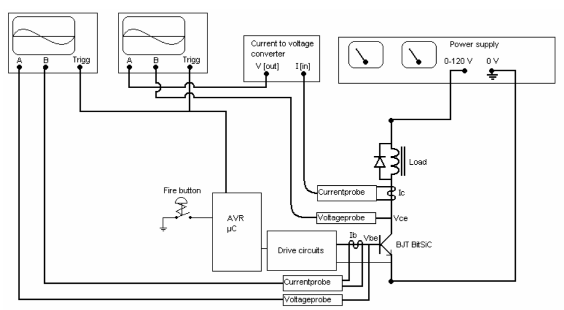

Figure 2. When the test rig makes a switch the transistor behaviour is captured and imported to PSpice.

4. Model

To model a BJT component in PSpice there are a set of equations with different parameters that have to be set. The idea is to take a transistor that has similar behaviour and "tweak" it to get the behaviour wanted. To model a BJT one first has to understand a simple diode and remember that simulation modelling is a curve fitting "game". Even if one has measured the BJT to calculate the different parameters, one still have to adjust the spice-parameters to get the right behaviour of the model.

PSpice BJT model is an enhanced Gummel-Poon model. The PSpice model consist of several levels, were the activation of higher levels increase the complexities of the model. By using the default parameters one gets the lowest level of the model and by changing the parameters one can access the higher levels of the model. Using default values the simplest Ebers-Moll DC model is simulated. With higher level of the model all of the junction capacitances follow. Right modelled it can give good AC and transient simulation result. Because both the Ebers-Moll and

Gummel-Poon models are symmetrical there are forward and reverse parameters, some of them associated with the base-emitter or the base-collector junction. Many of the parameters are of the same types, with the different that one changes the forward characteristic and the other changes the reverse characteristic.

To build a PSpice model of the BitSiC the behaviour from the test rig is imported into PSpice. When running a simulated version of the test rig one can see how the BitSiC model differs from the real BitSiC transistor. The model parameters are tweaked to fit the BitSiC behaviour. In this way a good model of the BitSiC is obtained that can simulate both the fast transients and the slow processes in the transistor. The Model performance can be viewed in figure 3.

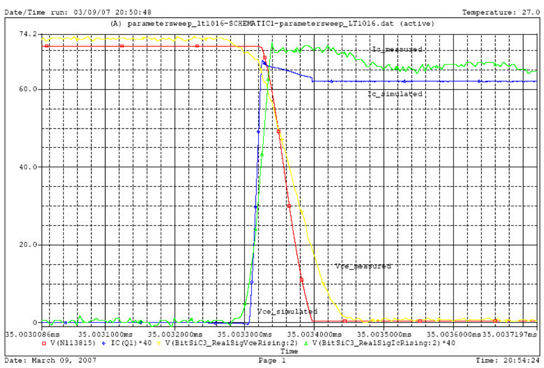

Figure 3. Simulated vs. measured performance of the BitSiC transistor.

5. Inverter

With the BitSiC PSpice model a complete three-phase inverter is built. The inverter has a maximum capacity of 5 kW and DC-link voltage of 112 V DC.

To be able to handle the current levels when simulating with the BitSiC, the transistors are placed in parallel. When normal Si BJT's is placed in parallel there might be stability problems due to the negative temperature coefficient, however SiC has positive temperature coefficient. This makes it easier to place the BitSiC BJTs in parallel, the only problem is that the driver has to handle the higher base current. The problem is that the driver has to be very fast with relative high current. There is not any single BJT fast enough that can handle enough current, the solution is to use a Darlington bridge with the BitSiC, see figure 5.1.

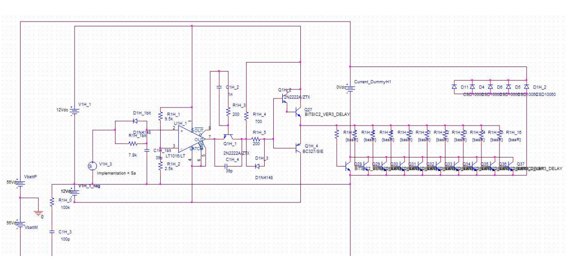

Figure 5.1 One sixth part of the three-phase driver circuit, highside.

6. Efficiency Results

With an Vce(sat) approximately at 1 - 1.4 V the inverter saves a lot of power if compared to a IGBT. This fact together with the fast and efficient switching resulted in a high efficiency for the inverter. With a PMW-frequency of 5 kHz the inverter got an efficiency of 98 % (not including the drivers), at 25 kHz the efficiency dropped a bit to 96 % (without the drivers). The efficiency for three different PWM-frequencies is seen in Table 6.1.

Table 6.1 Efficiency with and without diver for different PWM frequencies.

	5 kHz	25 kHz	100 kHz
efficiency with driver	0.94	0.94	0.91
efficiency without driver	0.98	0.96	0.92

7. Thermal calculation

The idea of using SiC transistor is that the same water cooling circuit as the Internal Combustion Engine (ICE) can be used. To show that this is the case the following calculation is done.

For the calculation the following is given:
Temperature for the ambient water: Ta = 130 °C
Heatsink thermal resistance: Rthha = 0.025 °C/W (ELFA)
Power dissipation for the transistors: Pbjt = 171.61 W
Thermal resistance for junction-case: Rthjc = 0.34 °C/W
Thermal resistance for case-heatink: Rthch = 0.6 °C/W

The maximum temperature of the heatsink can be calculated according to equation 7.1.

Equation 7.1.

$$Th = Rthha * Pbjt + Ta = 0.025 * 171.61 + 130 = 134.29\ °C$$

The junction temperature will be:

Equation 7.2.

$$Tj = Th + Pbjt * (Rthjct + Tthch) = 135.47 + 218.92 * (0.34 + 0.6) = 147.45\ °C$$

This means is that with the given data, a standard water heatsink will give the junction temperature at 147 °C for the SiC transistors. This is far from the maximum junction temperature for the SiC at 250 °C. Standard BJT or IGBT is rated up to 150 °C, there is one major problem with standard Si components. At degrees above 100 °C the performance is so degraded that it is almost impossible to find a transistor that work's. SiC transistors shows far less temperature dependence than Si transistors.

8. Conclusions

The SiC BJT's superior performance at high temperatures makes the SiC BJT a good choice for use in an inverter for a hybrid vehicle. The calculation shows that even a standard water heatsink would be enough to cool the inverter. With the SiC-technology it will be possible to cool the inverter with the regular water cooling system of a hybrid car. This will not be possible for a Si-based inverter because of the Si's poor performance at even moderate temperatures.