A new power module concept for automotive applications

P. Beckedahl
Semikron International GmbH
Nuremberg, Germany
E-mail:
Peter.Beckedahl@semikron.com

T. Grasshoff
Semikron International GmbH
Nuremberg, Germany
E-mail:
Thomas.Grasshoff@semikron.com

M. Lederer
Semikron Elektronik GmbH & Co. KG
Nuremberg, Germany
E-mail:
Marco.Lederer@semikron.com

Automotive and high end industrial applications require a new approach for power modules to fulfill the requirements in terms of power density, reliability and cost. A key to higher power densities of the over all drive system are higher operation temperatures and high switching frequencies. A sophisticated low inductive mechanical design and a careful selection of matched materials are a key factor to meet these goals. A new family of SKiM® (Semikron Integrated Module) Sixpack power modules has been developed, taking the base plate less pressure contact module design to the next level. The robust high power and thermal cycling module design makes these modules the ideal choice for hybrid electric vehicles and other high end applications.

I. Requirements

The environmental requirements for electric drive systems in hybrid or electric vehicles are very demanding in terms of ambient temperatures, power and temperature cycling and size.

With the next generation of hybrid vehicles a single coolant loop will be used, taking the water temperature as high as 105℃ for regular operation and up to 120℃ with power derating. Therefore the maximum ambient air rating for the power electronic components is >125℃.

On top of the ambient temperature cycles comes the active power cycling stress of the power semiconductors and their interface materials like bond wires, substrates, solder, etc.

Equally important is the need for a small over all package and a robust design in terms of vibration and shock. Figure 1 gives an overview of the environment and reliability requirements.

These partially conflicting requirements have to be taken into consideration when designing a new power module.

High power densities at coolant temperatures of 105℃ can only be achieved with a maximum junction temperature above 150℃. On the other hand it is well known that in traditional power module designs the power cycling capability is drastically reduced with higher operation temperatures. [1]

Matched materials with a careful consideration of the Coefficient of Thermal Expansion (CTE) and advanced packaging and bonding technologies become essential to success.

Temperature / Environment

Ambient air	-40℃ to 135℃
Coolant water	-40℃ to 105℃
Junction	-40℃ to 175℃
Vibration	10g
Shock	50g

Reliability

Operational Life	15 years
Power Cycling	30.000 cycles @ ΔT 100K
Temperature Cycling	1000 cycles @ ΔT 165K

Fig 1: Environmental and Life requirements of power modules for hybrid vehicles

II. Power module construction principles

Conventional modules have a massive base plate, normally made of 3 mm copper (figure 2).

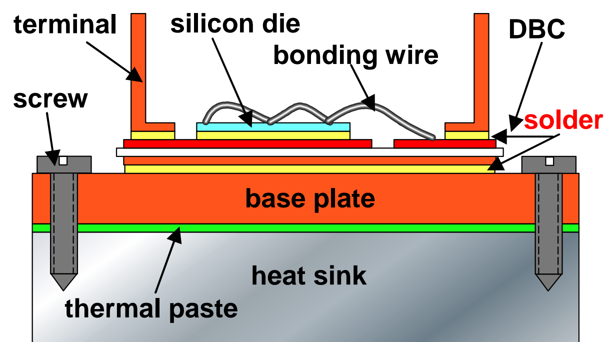

Fig.2: Cut through a conventional power module with base plate (housing not shown)

Coefficient of Thermal expansion (CTE)	
silicon	$4.1 \cdot 10^{-6}\ K^{-1}$
DBC-substrate	$7.4 \cdot 10^{-6}\ K^{-1}$
copper	$17.5 \cdot 10^{-6}\ K^{-1}$
aluminum	$25.5 \cdot 10^{-6}\ K^{-1}$

Fig.3: Coefficient of Thermal Expansion (CTE) of the main module materials

As can be seen in figure 3 the CTE of the used materials are quite different. Most critical is the difference in the CTE of copper (base plate) and DBC substrate because of the large area solder connection between DBC and base plate. This joint is most critical at passive temperature cycling. The failure mechanism is solder fatigue which will cause an increase of thermal resistance and early module failure. To improve this reliability problem it is common for heavy duty traction modules to replace the copper with an AlSiC base plate which matches the CTE of the DBC substrate and therefore reduces the stress on the large area solder joint. Because of its high price and the relative poor thermal performance AlSiC base plates are not an option for cost sensitive and high power density requirements.

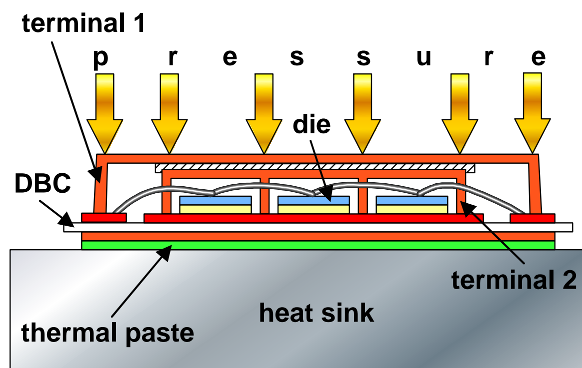

Fig.4: Power module without base plate in SKiiP technology (housing not shown)

An alternative construction principle for power modules is the SKiiP (SEMIKRON integrated intelligent Power) technology. Here no base plate is used. This eliminates the large area solder connections totally and replaces them by a pressure contact (figure 4).

The large area joint between DBC substrate and heat sink is not soldered and the substrate has the ability to "move" on the heat sink with virtually no limitation in terms of temperature cycling reliability.

The DBC substrate with the power dies is pressed directly to the heatsink. Multiple pressure contacts next to each die are used, keeping the DBC flat and no bimetal effect known from modules with base plates is disturbing the thermal performance. This allows a thinner layer of thermal grease (typ. 20µm) compared to modules with base plate (typ. 100µm). Since the thermal conductivity of thermal grease is only about 1 W/mK, this has an significant impact on the over all system performance, giving modules without base plate the same thermal performance of modules with a copper base plate but with a superior reliability comparable to an AlSiC base plate design.

III SKiM 63 and SKiM 93 Module Design

The new SKiM 63 and SKiM 93 power modules are the next generation of ultra compact Sixpack pressure contact modules without base plate. These modules have been specially designed for automotive applications with high power densities and harsh environmental conditions. The electrical circuit is a Sixpack module with 3 individual half bridge sections. Each half bridge section has its own DC terminals and an integrated NTC temperature sensor. The auxiliary contacts to control the IGBTs are made with spring contacts. The gate drive PCB does not have to be soldered to the module. Instead the driver is screwed on top of the module assuring a high reliable spring contact. Even under high temperature cycling conditions no solder fatigue occurs.

The power terminal position and height (17mm) of the SKiM 93 power module is identical to the known industrial standard SEMiX33c and Econo Pack+. The module outline dimensions are 150mm x 160mm. The SKiM 63 power module has 2/3 of the current capability and the dimensions are 114mm x 160mm. Both modules have the same DC terminal positions and construction principle, which makes them the optimum choice for modular designs with different current levels utilizing the same DC-Link and AC terminal interface. Figure 5 shows the package outline and a cross section of the pressure contact system and the auxiliary gate springs.

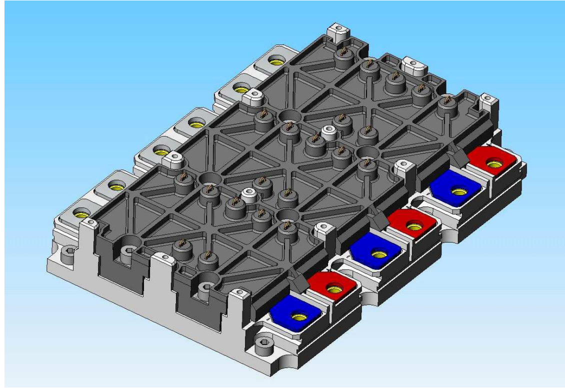

Fig. 5a: Package outline SKiM63

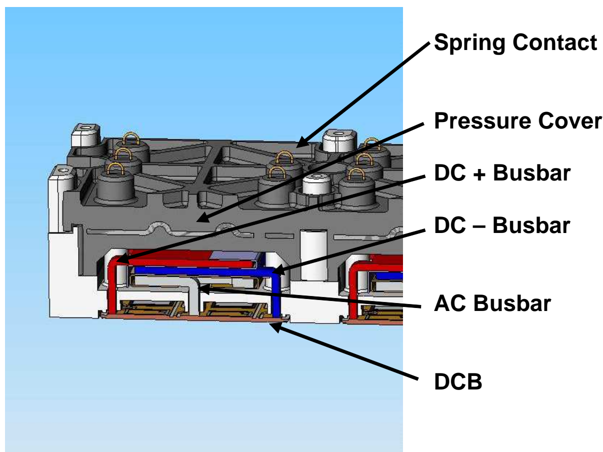

Fig. 5b: Cross section of SKiM Module

What separates the new SKiM modules from traditional base plate less power modules is the laminated internal busbar structure. The DC positive, negative and the AC busbar are made of stamped and folded copper sheets that assure an ultra low internal inductance. The busbar sandwich construction is pressed to the DBC substrate with multiple pressure contacts next to each of the paralleled dies (Fig. 6)

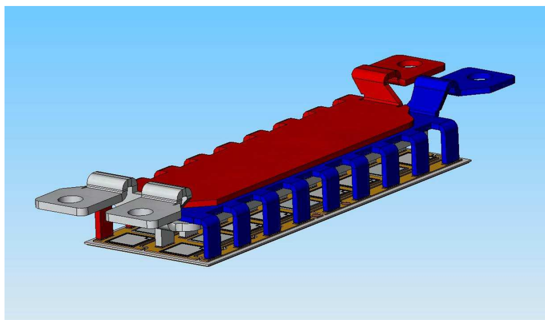

Fig. 6: Laminated busbar sandwich with multiple pressure contacts to the DCB

High contact forces assuring a low contact resistance, no additional solder joints are necessary. The busbar contacts to the DBC are not only electrical pressure contacts. In addition they act as mechanical pressure contacts that press the DBC to the heatsink for a low and uniform thermal resistance junction to heatsink of each die. No additional pressure spreading element is necessary.

To achieve the high reliability requirements even at high temperatures a new Polyamide housing material has been selected. This material has the a CTI (Comparative Tracking Index) of > 600 and a RTI (Relative Temperature Index) of 150℃, which is the ideal material for high temperature and high voltage applications.

To improve the power cycling reliability even at high junction temperatures low temperature sintering technology will be used to attach the dies to the DBC substrate. A solder joint degrades during load cycles, which will lead to increased thermal resistance and module failure. The sinter joint is a thin silver layer that has a superior thermal resistance than solder and at the same time due to the high melting point of silver (960℃) no joining fatigue can be observed leading to an increased lifetime of the over all system [3].

Due to the pressure and spring contact and the sinter die attach these modules are completely solder free power modules.

IV Selection of Die

Vehicle applications require mainly 600V and 1200V silicon but the clearance and creepage distances of the package allow also the use of 1700V die for high end industrial and traction applications in a pollution degree 2 environment.

For 600V applications the well known chipset IGBT3 from Infineon Technologies and the CAL3 freewheeling diode from Semikron will be used. The 1200V chipset is based on the new developed IGBT4 and CAL4 [4]. Both chip technologies support a maximum junction temperature of 175℃ which allows high overload currents and a high power density even at elevated cooling conditions.

	SKiM 63	SKiM 93	
$R_{thjs\ IGBT}$	0,14	0,095	K/W
$R_{thjs\ Diode}$	0,27	0,18	K/W
$I_{C\ nom,\ 600V}$	600	900	A
$I_{C\ nom,\ 1200V}$	300	450	A
$I_{RMS,\ 600V}$ 1)	280	410	A
$I_{RMS,\ 1200V}$ 2)	165	250	A

Table 1: Main module parameters

1) Output rms phase current with U_{DC}=400V, U_N=230V, cosφ=0,8, fsw=10kHz, Tjmax=150℃, Ta=80℃, Rth cooler = 8K/kW (SKiM93); 12K/kW (SKiM63)

2) Output rms phase current with U_{DC}=750V, U_N=400V, cosφ=0,8, fsw=8kHz, Tjmax=150℃, Ta=80℃, Rth cooler = 8K/kW (SKiM93); 12K/kW (SKiM63)

V Electrical Performance

Since the DC-Link voltage of a 600V IGBT module can go as high as 450V during regenerative breaking it is important to reduce the parasitic inductance of the package to a few nH. At the same time uniform switching is important which has been achieved by a symmetrical current path to the paralleled dies. Figure 7 is demonstrating the construction principle. Each of the paralleled dies sees the same package impedance. Equally important is the commutation path from the IGBTs to the freewheeling diodes and back. Always two IGBTs are sharing one diode, the current path is perfectly symmetrical, assuring a smooth commutation and low switching over voltages as well as a uniform heat distribution of the package.

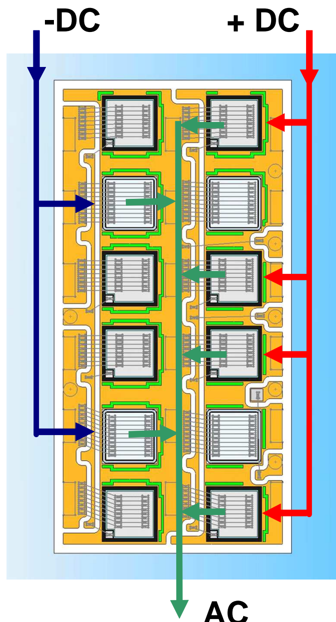

Fig. 7: Symmetrical current path for each paralleled die

Another advantage of this busbar concept is the low package resistance. On the SKiM 63 package a $R_{CC'-EE'}$ of 0,3mΩ has been achieved, which is less than 1/3 of the comparable standard industrial packages.

Figure 8a and 8b are showing switching waveforms of the 1200V SKiM63 module at 2x rated current and 900V DC-Link. Switching losses, over voltages and di/dt are almost identical between the TOP and the Bottom IGBT. No oscillations or critical over voltages even at high switching speeds can be observed.

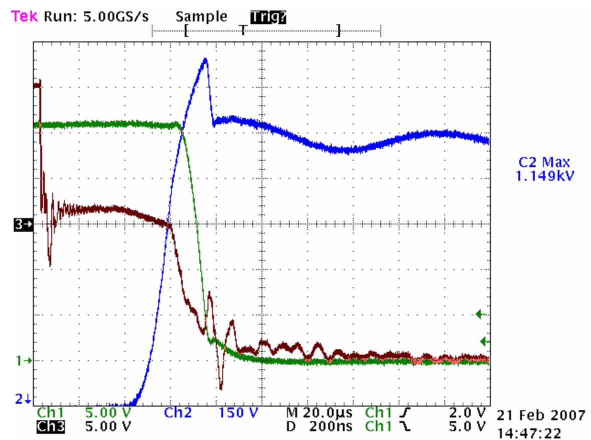

Fig. 8a: Bot IGBT turn off switching waveform with double rated current, 900VDC, 125℃

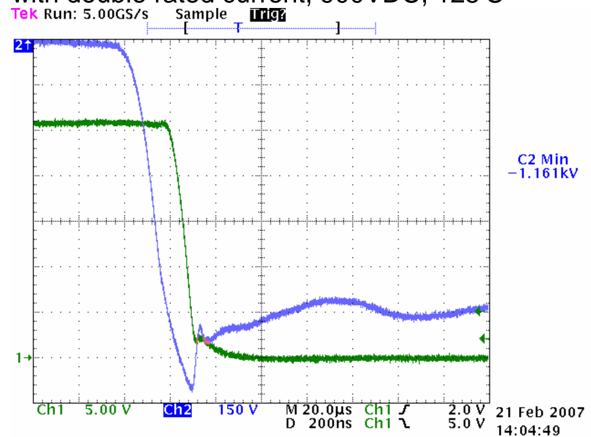

Fig. 8b: Top IGBT Turn off switching waveform with double rated current, 900VDC, 125℃

The equal gate - emitter coupling of each IGBT ensures a good current distribution especially during short circuit operation. The dynamic gate – emitter voltage controls the saturation level of each paralleled IGBT. Figure 9 shows the switching waveform of an external IGBT short circuit via cable. The current rises up to 1700A

(approx. 6 times the nominal current). No oscillations or critical over voltages could be measured.

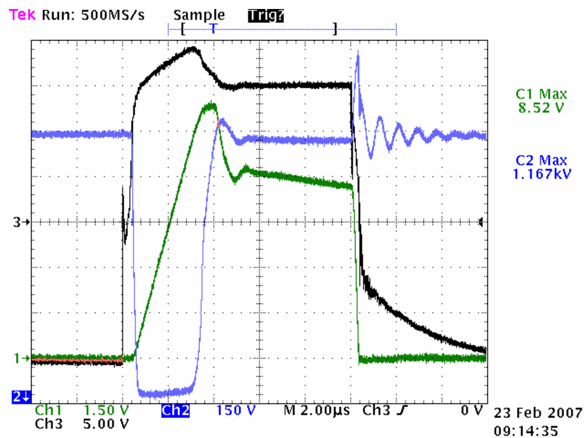

Fig. 9: Short circuit pulse on Bottom IGBT with 900VDC, 125℃

VI Conclusion

Vehicle applications require a dedicated power module design to meet the reliability, power density and cost requirements of this market. New materials and a solder free, pressure contact packaging concept assures highest reliability even at high operation temperatures. The unique symmetrical module architecture and the laminated busbar sandwich with multiple electrical and thermal pressure contacts assure clean switching transients, low switching losses and an extreme low package resistance.

Reference List:

[1] U. Scheuermann, U. Hecht: Power Cycling Lifetime of Advanced Power Modules for Different Temperature Swings, PCIM Nuremberg 2002

[2] P. Beckedahl, W. Tursky, U. Scheuermann: Packaging considerations of an Integrated Inverter Module for Hybrid Vehicles, PCIM Nuremberg 2005

[3] C. Goebl, P. Beckedahl, H. Braml: Low temperature sinter technology – Die attachment for automotive power electronic applications, APE Conference Paris 2006,

[4] V. Demuth, K. Häupl, B. König, W. Nichtl-Pecher: CAL 4: The next Generation 1200V Freewheeling Diode, PCIM China 2007