Semiconductor Solutions for Automotive AC Drives

Dušan Graovac, Benno Köppl, Frank Auer, and Michael Scheffer

***Abstract*—This paper gives an overview of the semiconductor solutions for the 3-phase automotive drives systems as based on the technologies existing today. The special attention is given to micro-hybrid systems, since they represent the most challenging application on low-voltage board net. The application requirements will be discussed and mapped directly into semiconductor requirements. An outlook in the future is given as well.**

***Index Terms*—Power electronics, automotive, semiconductors, drives.**

I. Introduction

CURRENT CO_2 discussion and the need for higher efficiency lead to the significantly growing market share of the hybrid automotive systems. One of the significant agenda points are so called micro-hybrid cars. In those cars the alternator is used also as a starter and the braking energy, or at least some part of it, is recuperated to the battery. The micro-hybrid (starter-alternator) systems are easy to integrate into the existing cars, since they can operate on the 14 V board net. Mild- and full-hybrids are high-voltage systems, based on IGBTs, while the micro-hybrids are low voltage systems based on power MOSFETs. The overview of hybrid technologies is given in Fig. 1. Table I shows an overview of AC drives on a classical 14 V board-net with their typical power and current requirements. The highest powers, apart from micro-hybrid, are required for electric and electro-hydraulic power steering (EPS & EHPS).

The aim of this paper is to give an overview of the semiconductor solutions for the automotive AC drives as based on the technologies existing today. The special attention will be given to micro-hybrid systems, since they represent the most challenging application on low-voltage board net. The application requirements will be discussed and mapped directly into semiconductor requirements. An outlook in the future will be given as well.

Since the micro-hybrid application is the ultimate challenge on low voltage power semiconductors in terms of need for high current, low power losses and the low voltage drop on the semiconductors, a special attention will be given to MOSFET technology. A comparison between planar and trench technologies for automotive power MOSFETs with their advantages and disadvantages will be shown. Further accent will be stressed on packaging of the discrete MOSFETs and on the solutions based on power modules. Bonding options based on Power Bond Technology for high current MOSFETs will be presented for discrete MOSFETs mounted on insulated metal substrate will be given, as well as the power module solutions. Reliability of the power module solutions, together with some failure modes will also be provided.

In order to achieve desired switching and steady state characteristics of the MOSFET, high performance bridge drivers are necessary and will thus be discussed. To complete the system picture, possible solutions for micro controller as well as the sensors and the communication devices will be presented.

System demonstrator for 3- and 6-phase alternator is presented, together with experimental results.

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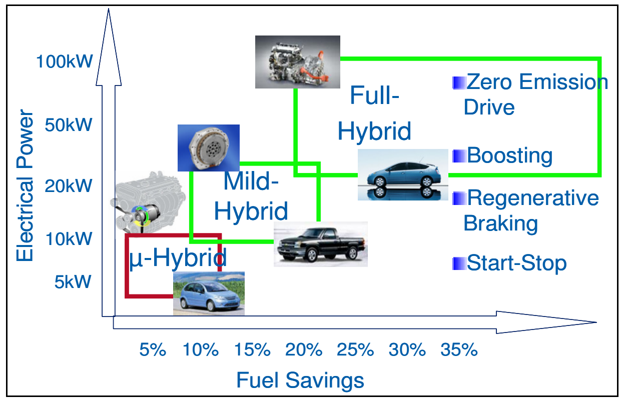

Fig. 1. Overview of hybrid automotive technologies.

TABLE I
Overview of Automotive AC Drives

EHPS	1 kW, 100 A peak
EPS	1.5 kW, 140 A peak
Water Pump	300 W – 1 kW
Fuel Pump	200 – 300 W
Clutch/Gearbox	peak currents up to 70 A
Engine Cooling Fan	400 W – 1 kW
HVAC Fan	250 – 450 W
Starter-Alternator	3 – 4 kW, High Currents

II. Application Overview

An overview of all start-stop systems (including micro-hybrids), together with different system voltages and required features is given in Fig. 2. A simplified block diagram of a belt driven starter-alternator ECU is shown in Fig. 3. It consists of the electric machine, 3-phase inverter with power MOSFETs and a bridge driver, micro-controller for motor control during both starting and generation mode, H-Bridge for excitation control, position/velocity/ sensor and current/voltage sensors.

The electric motor used is usually a classical claw-pole motor (Lundell alternator). It is a wound field synchronous machine with a three-phase (or six phase) stator, and a claw pole rotor structure where the claw poles close around a field winding. The field winding is supplied from the stator via slip rings. The rotor time-constant is rather high (~100 ms) and can cause both high amplitude and long load dumps, if not properly controlled and quickly de-energized. The reduction of the load dump is the reason for using the H-bridge in excitation control.

The most important task in alternator mode of operation is to maximize the efficiency of the electrical energy generation. Fig. 4 shows a typical split between individual power losses in alternator. Modern generators have typical efficiency of η≈70%. It can be seen that the diodes in the rectifier bridge cause 38% of generator losses. Exchanging them with MOSFET leads to increased efficiency.

During starting of the engine, it is necessary to provide the required ICE start-up torque. The typical alternator torque/speed characteristics are given in Fig. 5 together with excitation currents needed to achieve a maximum torque at given speed.

The MOSFETs in inverter have to drive high currents (up to 600A) with a minimum power loss and are driven by a 3-Phase Driver IC which is controlled by a μC which generates the PWM/SVM patterns. The whole system is controlled by engine management ECU via LIN interface.

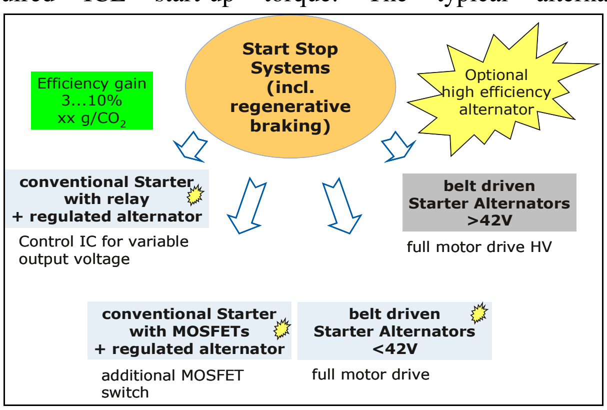

Fig. 2. An overview of the start-stop systems.

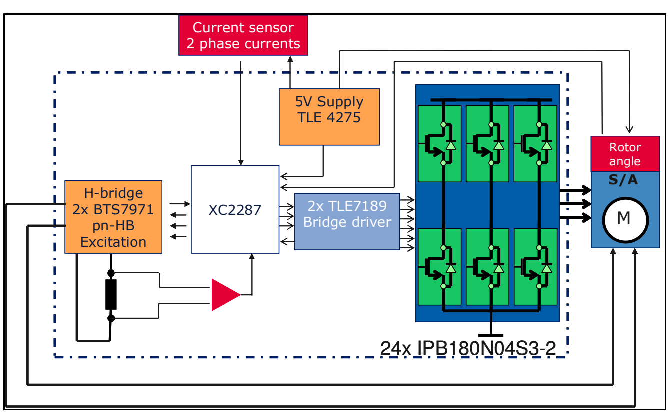

Fig. 3. A micro-hybrid (starter-alternator) ECU.

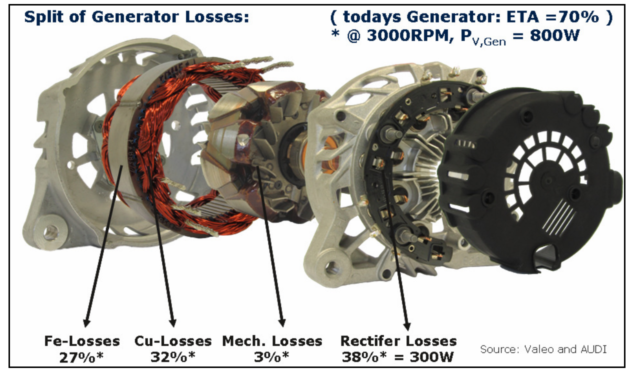

Fig. 4. Alternator losses split (source: Valeo and Audi).

III. Application Requirements for Power MOSFETs and Driver IC

The hardest requirements in a micro-hybrid system are set for power MOSFETs. Very high currents (600 A) and the need for low voltage drop and high efficiency require very low Rdson value and also a large chip area which is needed for placement of the bonding wires. Such large chip area could have a negative influence on both the gate-charge (important for the bridge driver current capability) and gate-to-drain charge (important for the minimization of the switching losses). An overview of the requirements on power MOSFET is given in Fig. 6. Modern low voltage MOSFETs are based on trench cell concepts. Advantage of a trench technology over a planar technology is the capability for much lower area specific on state resistances on chip level. This improvement is based mainly on the reduced channel resistance and on higher cell density. The performance difference as based on figure of merit (FOM=Rdson*Qg or Qgd or Qsw) comparison between classical trench and the IFX trench technology is given in Fig. 8. The IFX trench concept, compared to the classical trench, enables further reduction in Rdson, gate-to-drain

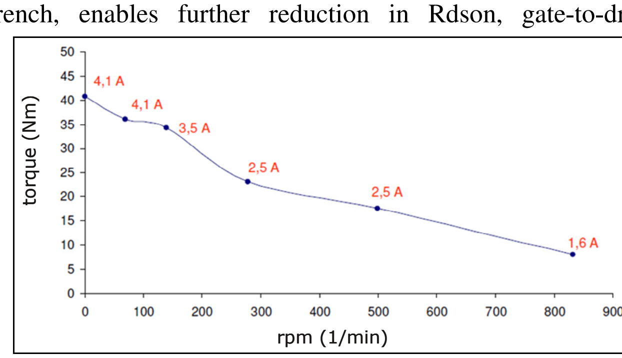

Fig. 5. Alternator characteristics during starting (source: BMW).

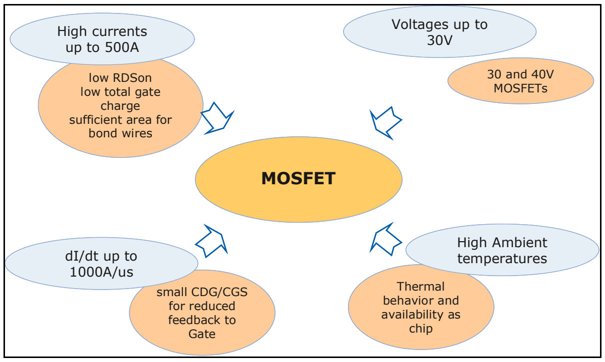

Fig. 6. Power MOSFET requirements.

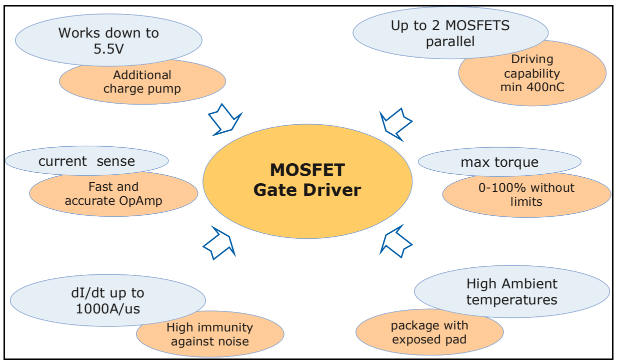

Fig. 7. Bridge driver requirements.

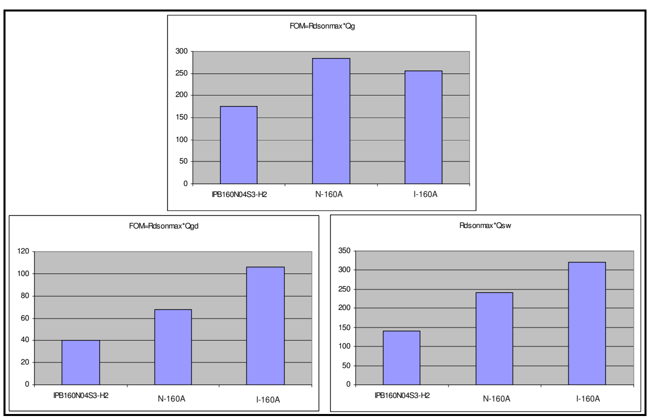

Fig. 8. FOM comparison between classical Trench and Infineon Trench technology.

charges, gate resistance and is more robust against the parasitic turn-on as triggered with high du/dt transients.

The driver IC is the interface between the µC and the MOSFETs. As the µC delivers the control signals, the Driver IC level-shifts, amplifies, and buffers the control signals to provide the necessary gate charge for the power stage. In addition, the driver IC incorporates protection functions and functions to reduce the external part count and cost. It also incorporates circuitry that allows operation at very low battery voltages or other extreme application conditions. The set of requirements of the micro-hybrid application on driver IC are given in Fig. 5. In addition to that it should be noted that the overcurrent, shoot-through, under-voltage and over voltage protection are necessary.

In order to achieve high currents using standard 7-pin D2PAK (packages), a PowerBondTM bonding technology is used. PowerBondTM was developed to respond to the increasing demand of current needs in high power applications. It also contributes to lower overall package resistance. This is especially important for new power MOSFET technologies. Today the package resistance is about 20% of the total MOSFET resistance. The other 80% are the chip contribution. In the near future with further decreasing of the specific on-resistances of a power MOSFET, the package share would be easily 50% without further development in assembly technology. Depending on the bonding configuration the current rating of a MOSFET is limited either by the chip itself or by the bonding wires, since the hottest temperature on the bonding wire has to be limited to 200°C. The reason is not the bonding wire itself, but the mold compound. In usual molding compounds decomposition occurs if temperature exceeds about 220°C. This temperature limit restricts the permissible current. This approach enabled achieving of a true 180 A DC current capability of a D2PAK. The bonding consists of 4x500 µm bond wires (Fig. 9) with the package resistance reduced to 0.3 mΩ only.

IV. Systems Demonstrator and Experimental Results

The system, which block-diagram was shown above in Fig. 3 is a starter-alternator prototype, which can start the internal combustion engine and once the engine is running, also act as a classical alternator with AC/DC converter using active rectification with power MOSFETs instead of the diodes. Such a system has a very high efficiency compared to the diode rectification in classical alternator solutions. The efficiency of the complete system, including generator, in AC/DC mode is improved for at least 6%. With modifications at the alternator itself efficiency improvements of more than 10% are realistic. The other significant advantage is the increase of the available generator current at low speed of around 40% (the exact amount is dependent on the alternator design). The 3-phase demonstrator platform is given in Fig. 9 and its 6-phase counterpart in Fig. 10.

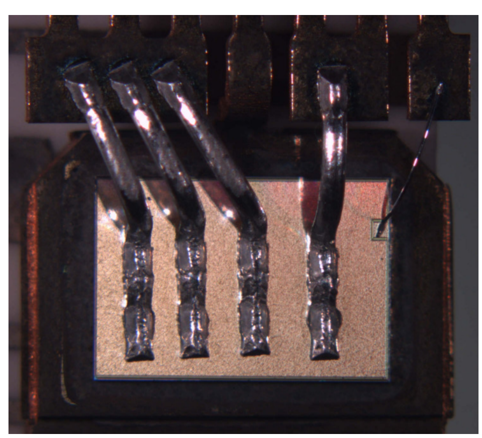

Fig. 9. FOM comparison between classical Trench and Infineon Trench technology.

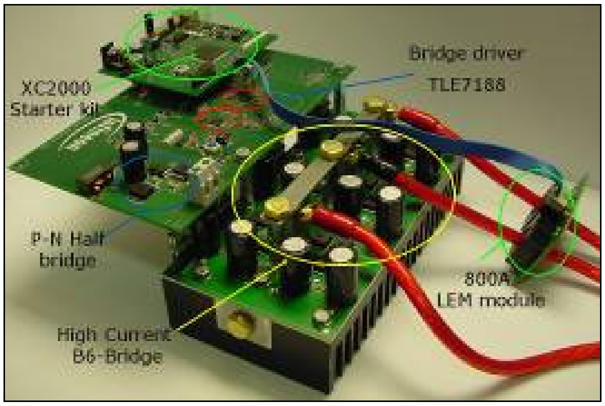

Fig. 10. 3-phase system demonstrator.

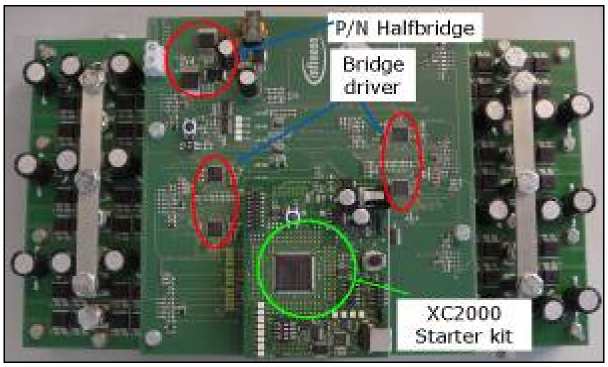

Fig. 11. 6-phase system demonstrator.

The control concept during starting mode of operation is shown in the Fig. 12. It is based on field oriented control of a Lundell alternator. The required velocity or torque profile is converted into q-axis current component, whereas the required flux is mainly driven by the excitation winding, supplied by the DC/DC converter. However, if a stronger magnetisation is required, an additional d-current component can be generated. To minimize the power losses in MOSFET inverter during start-up, a minimum loss space vector modulation with 30° shift (MLSV_30) has been implemented. It reduces the switching losses to 50% as compared with classical space vector modulation.

During alternator mode of operation, it is important both to switch on the appropriate MOSFET, according to conduction sequence and also to minimize the load dump. For the purpose of load-dump minimization a two-fold concept is used:

- DC/DC H-Bridge of fast de-excitation of the machine.
- Implementation of the zero voltage vector on the alternator (short-circuiting of the windings) for the periods of time when fast de-excitation alone is not enough.

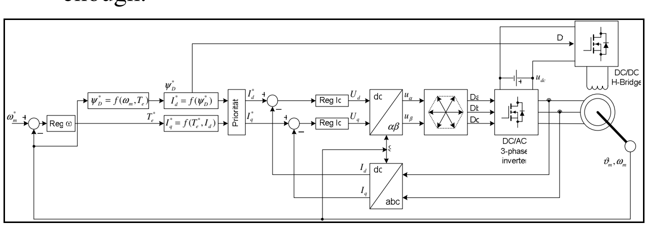

Fig. 12. Control for starting of ICE.

Based on the previous considerations, the following results were obtained:

Two examples of the MLSV_30 (with fixed and random carrier frequency) PWM during starting mode are given in Figs. 13 and 14. First trace (yellow) is the phase to phase voltage with 10 V/div, second trace (magenta) is phase current with 150 A/div, and third trace (purple) is the magnitude current spectrum, while the fourth trace (brown) is the magnitude voltage spectrum. For the spectra, the frequency axis resolution is 7.81 kHz/div.

The alternator mode of operation is illustrated in Figs. 15–17. Fig. 15 shows the board-net (alternator after rectification) voltage and current when an active (MOSFET) rectification is used.

It can be seen that over a whole speed range of interest the voltage is kept constant and a current margin is high. This current margin, or the availability of the board net current, is especially important at low speeds. Table I illustrates the superiority of the active converter compared to the passive one, i.e. at 1500 rpm and nominal load, 50% more current is available. Fig. 16 shows a comparison of power losses between passive and active rectification. The energy savings with active rectification are significant over the whole current range.

Finally, Fig. 17 illustrates a load dump behavior of the proposed alternator control in a so called "loss of battery" situation. It can be seen that when dumping the 100 A load, the

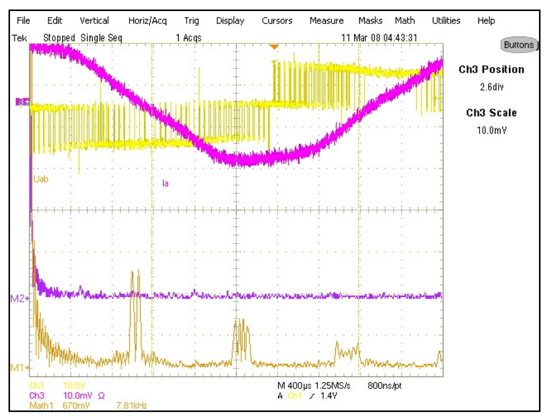

Fig. 13. MLSV_30, M = 1.

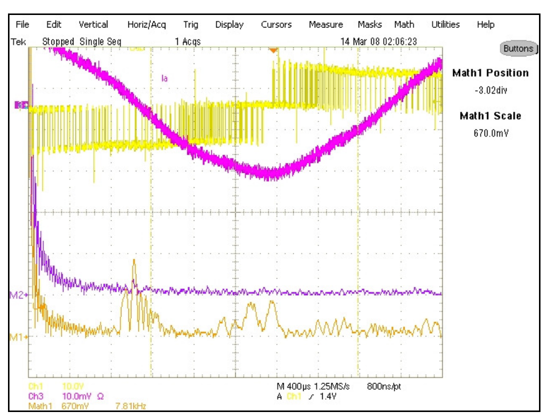

Fig. 14. MLSV_30, M = 1, variable pulse rate.

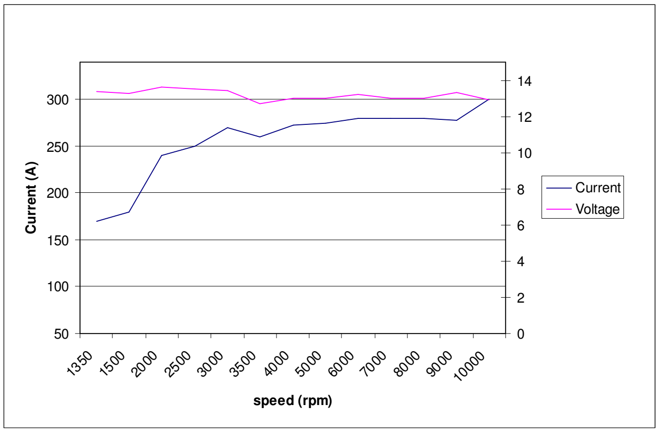

Fig. 15. Current margin with active rectification.

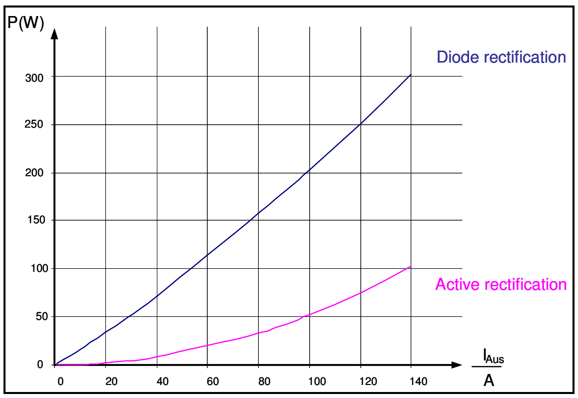

Fig. 16. Efficiency comparison.

TABLE II
AVAILABLE BOARD NET CURRENT AT LOW SPEED

U=13,5 V	Active (MOSFET)	Passive (Diode)
Speed (rpm)	1500	1500
Load	100 %	100 %
Current (A)	180 A	125 A

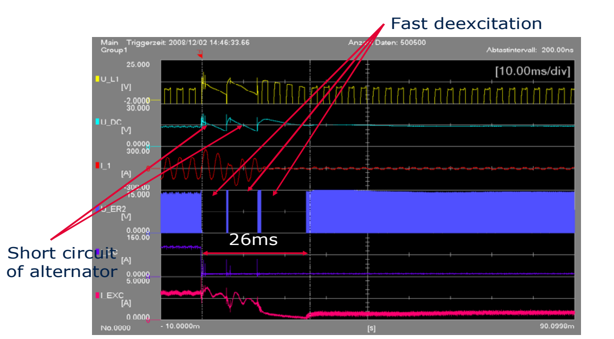

Fig. 17. Load dump with fast de-excitation and zero vector (short circuit).

overvoltage peak remains below 25 V and has a very short duration of below 5 ms. Compared with classical load dump condition, which vary between 32 V and 45 V for 400 ms, this concept bring significant advantage for the voltage classes of semiconductor components used in all automotive subsystems connected directly to board net.

V. PACKAGING AND INTERCONNECTION OPTIONS, QUALITY AND RELIABILITY OF POWER MODULES

Semiconductor devices in the micro-hybrid application are placed in the engine compartment with an additional goal of integrating both the power electronics part as well as the control circuitry into the alternator. Thus, they have to deal with both severe temperature cycles and high junction temperatures. ECU has to withstand 600.000 ICE starts over 17 years without failure, together with additional thousands of operating hours in generator mode. These requirements are summarized in Fig. 18.

Although it is possible to design an ECU based on discrete MOSFETs mounted on IMS (insulated metal substrate), as done previously with the system demonstrator, very high current and power densities, integration in the generator housing and reliability/life time requirements can only be achieved using the power module with a ceramic substrate (DCB – direct copper bonding). Fig. 19 shows a typical cross-section of an IGBT power module, as well known from industrial or railway applications: semiconductor chips (MOSFETs or IGBTs/Diodes) are soldered on a ceramic substrate and the DCB is soldered to the base plate. This classical build-up of a power module is, from automotive point of view, bulky and expensive for micro hybrid vehicles. For that reason, power modules without a base plate are often used in automotive applications. One module of this type is shown in Fig. 20.

Thermal advantages of ceramic substrate over discrete

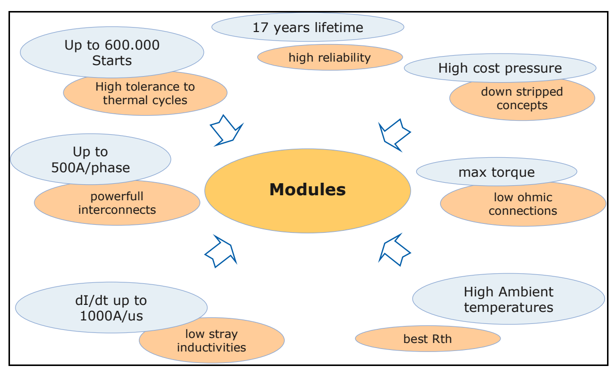

Fig. 18. Power module requirements.

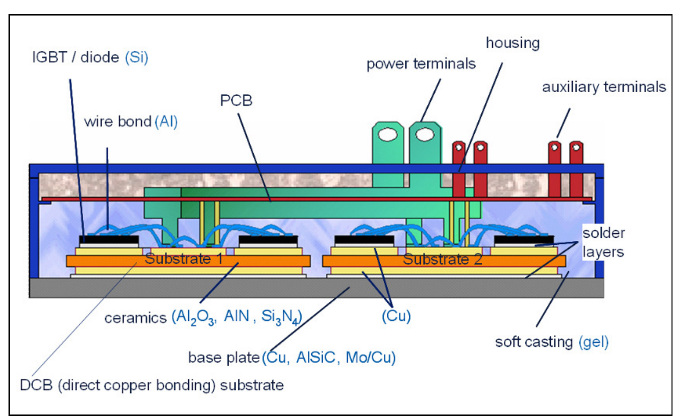

Fig. 19. Classical power module cross-section.

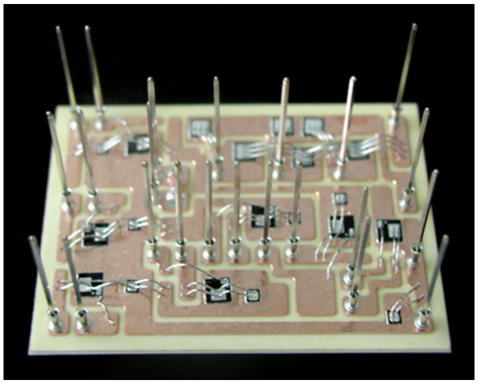

Fig. 20. Module without a base plate.

components mounted on IMS are illustrated in Fig. 21, which shows the thermal resistance (Rth) dependence on the chip area for. Compared are IMS with AL_2O_3 and AlN DCB. It can be seen that DCB offers lower Rth by the factor of 2-4.

To withstand high electrical and thermo-mechanical stress, interconnections inside the power module have to be as strong as possible. Fig. 22 shows the failure mechanisms for standard modules due to thermal load changes. These are:

- Bond wire lift-off
- Delamination of the upper side copper layer
- Solder cracks.

The main cause of these failures is different heating of the individual areas/layers and the different thermal expansion coefficients of the materials used in the inside the power module. This also shows the importance of the proper material choice for the module life time. The different expansion coefficients for different materials are given in Fig. 23. It can be seen that the ceramic substrate materials are much better match to silicon expansion coefficient, as compared to copper, which is a main leadframe material for the discrete components.

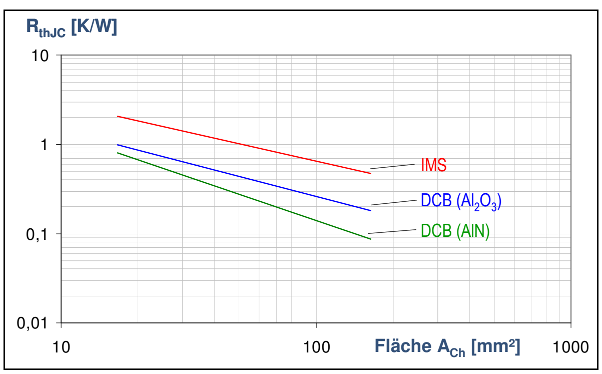

Fig. 21. Rth comparison between IMS and DCB.

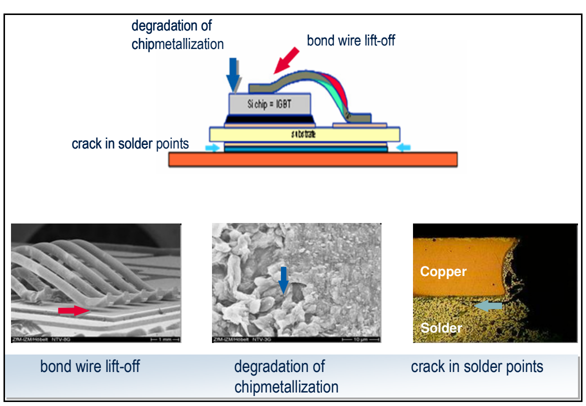

Fig. 22. Failure mechanisms in power modules.

VI. Future Outlook

In the power MOSFET technology, further minimization of both Rdson and charges is expected together with the increase in temperature capability. Changing the maximum allowable junction temperature of the power semiconductor will directly change the thermal stress on the interconnection of the chip surface. A typical wear out effect at the chip surface is the wire bond lift off. To test this interconnection power cycling tests are performed. The number of cycles that a device survives is related to the temperature swing, the maximum temperature and the slopes. For the introduction of a maximum junction temperature of 175°C the wire bonding process has already been improved from standard wire bonding to the IFX new generation wire bonding. For future designs results of the low temperature joining process are promising. As can be seen in Fig. 15 the tests were still ongoing after 70000 cycles with a temperature swing of 130°C.

Further innovation comes from the field of sensors. In the development, there is a rotor position sensor based on iGMR (integrated giant magneto resistance) technology. Compared to AMR (anisotropic magneto resistive) sensors, iGMR sensors have incorporated not only position measurement but signal processing, diagnostics and a calibration as well. It enables high precision position measurement over 360°C and requires a very small mounting space. Also, the multi functional alternator control IC with A/D converter and digital control logic (similar to LIN-VDA-Regulator IC) is very promising.

VII. Conclusion

This paper gave a detailed overview of the semiconductor solutions for the micro-hybrid vehicles, especially for the belt

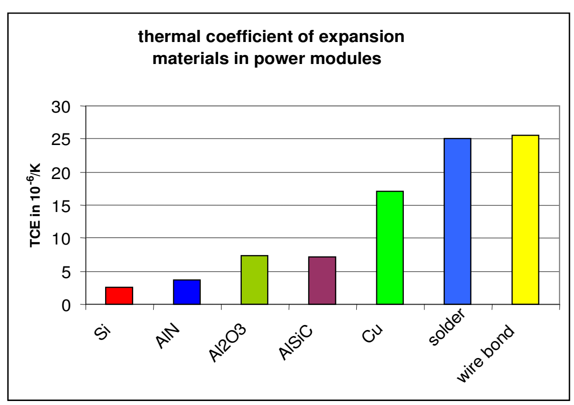

Fig. 23. Thermal coefficients for different materials.

driven starter alternators. The application requirements were given and mapped into semiconductor requirements. Special attention was given to power MOSFETs technologies, power modules and driver circuitry.

System demonstrator for 3-phase and 6-phase systems with the appropriate control design was presented, together with a load-dump minimization concept. The experimental results based on 3-phase system, confirm the validity of the semiconductor concepts presented in the paper.

It was shown that existing semiconductor devices existing today are already able to fulfill the application requirements and allow for first designs. The MOSFET module technology reaches the required lifetime level dependent on the choice of material. An outlook in the future was given as well.

REFERENCES

[1] Infineon Technologies AG, “Semiconductors”, 2004.

[2] C.Chan, K.Chau, “An Overview of Power Electronics in Electric Vehicles,” IEEE Trans. on Industrial Electronics, Vol. 44, No. 1, February 1997, pp. 3−13.

[3] E. Bretz, “By-Wire Cars Turn the Corner,” IEEE Spectrum, April 2001, pp. 68−73.

[4] D. Graovac, M. Pürschel and A. Kiep, “Power Stage for Permanent Magnet Synchronous Motors in High Current Automotive Applications,” EPE 2007, Aalborg, Denmark.

[5] AEC-Q101-REV – C June 29, 2005. Stress Test Qualification for Automotive Grade Discrete Semiconductors.

[6] I. Graf, “Semiconductors in Hybrid Drives Applications – A survey lecture,” PCIM 2008, Nürnberg, Germany.

[7] D. Graovac, B. Köppl, M. Scheffer, “Optimal PWM Method for Electric and Electro-Hydraulic Power Steering Applications,” PESC 2008, Rhodes, Greece.

[8] S. Chen, B. Lequesne, R. R. Henry, Y. Xue, J. J. Ronning, “Design and testing of a belt-driven induction starter-generator,” IEEE Transactions on Industry Applications, Vol. 38, No. 6, November/December 2002, pp. 1525−1533.

[9] W. Cai, “Comparison and review of electric machines for integrated starter alternator applications,” 39th IAS Annual Meeting. Conference Record of the 2004 IEEE, Vol. 1, 3−7 October 2004.

[10] H. Rehman, “An Integrated Starter–Alternator and Low-Cost High-Performance Drive for Vehicular Applications,” Vehicular Technology, IEEE Transactions on, Vol. 57, Issue 3, May 2008, pp. 1454–1465.

[11] S.S.Williamson, A. Khaligh, A. Emadi , ”Impact of Utilizing Selective Motor Topologies and Control Strategies on the Overall Performance of Integrated Starter Alternator (ISA) Based HEVs,” IEMDC '07, May 2007, pp. 134–139.

[12] Robert Bosch Patent DE19835316A1. Gesteuerte Gleichrichterbrücke mir Überspannungsschutz.