A High Current Dual Inline Packaged Trench MOSFET Three Phase Full Bridge as Contribution to Automotive System Integration

Andreas Lindemann
IXYS Semiconductor GmbH
Postfach 1180, D – 68619 Lampertheim
www.IXYS.com

Abstract

A new power semiconductor component is proposed which integrates a three phase full bridge of trench MOSFETs. Its compact, isolated package shall provide high current capability and reliability. The device is intended for use in automotive auxiliary drive systems, where it helps to overcome limitations of state of the art power sections.

1 Introduction

An increasing number of electric drives in a power range of several hundreds of Watts up to few Kilowatts is used in automobiles, e. g. as starter generator or as actuator for electric power steering, fans, pumps and in future brake by wire systems [1]. Frequently three phase AC machines are applied which necessitate an inverter according to **figure 1**, generating an AC system L_1, L_2, L_3 from the car's DC bus voltage L_+, L_- with today's 12V level or 42V aimed for in future. Resulting currents become high towards the upper range of nominal power, reaching some 500A in starter generator's power section during cold start of combustion engine. The power electronic system faces hostile environmental conditions, the devices having to bear a wide range of operating temperatures of some $-30°C \leq T_S \leq 120°C$, with a value around $T_S = 90°C$ over longer periods of time when tempered by the coolant of combustion engine. In spite of this, the components must be highly reliable over the expected lifetime of the vehicle.

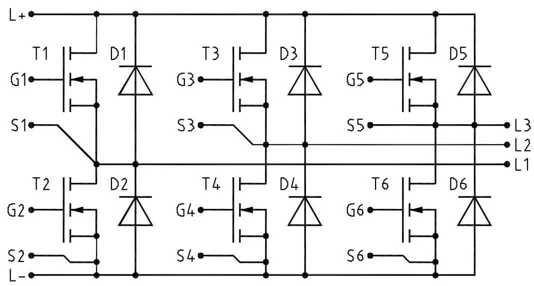

Figure 1: MOSFET three phase full bridge

2 State of the Art

2.1 MOSFETs

Several measures have been taken to make sure that power semiconductor components comply with those demanding requirements: New generations of MOSFETs, in particular trench MOSFETs [2][3], have been developed. Their low on state resistance R_{DSon} in the order of magnitude of few Milliohms guarantees high efficiency or low power losses in the converter respectively. An appropriate, in particular sufficiently fast and soft, switching behaviour of body diode — depicted separately in figure 1 — makes them suitable for use in bridge circuits of AC motor drives.

2.2 Conventional Discrete Components

MOSFETs have frequently been assembled in conventional packages, e. g. TO220 as depicted in **figure 2**:

Figure 2: single MOSFET device: symbol, external view and cut-off view of TO220 package $15mm \cdot 10mm \cdot 4,5mm$

The chip is soldered onto a copper leadframe which must be thermally coupled to heatsink through an additional, electrically isolating pad. This significantly contributes to thermal resistance from junction to heatsink R_{thJS}, thus limiting current capability. The electrical isolator may lead to a considerable coupling capacity C_P between MOSFET drain and grounded heatsink; it may reach values as high as $C_P = 124pF$ for TO220 with a thin plastic insulator [4], which bears the risk that circuit operation may be disturbed. Further, thermal cycling capability of those devices is limited by a mismatch between thermal expansion coefficients of copper carrier and silicon $\alpha_{Cu} \approx 6,6\alpha_{Si}$; a sufficient reliability level to meet standards such as AEC-Q-101 [5] is achieved, restricting chip size to some $A \leq 25mm^2$.

Gate and source pads on the top side of the chip are wire bonded to the solder terminals of the leadframe. As shown in the cut-off view figure 2, for geometrical reasons the number of source wire bonds is typically limited to three. Thus resistance of the current path within the package between chip source and outer board or busbar — i. e. chip metallization, bond wires and leadframe terminal — reaches the same order of magnitude as on state resistance of the trench MOSFET chips according to section 2.1 $R_M \approx R_{DSon}$. Consequently, current capability of a packaged device, maintaining a reasonable degree of reliability, frequently is not any more determined by silicon but by the surrounding package.

For constructional reasons evident in figure 2, conventional discrete MOSFETs are always single switches; a three phase bridge for an AC drive system according to figure 1 is configured with at least six components $T_1/D_1 ... T_6/D_6$. The commutation paths of each phaseleg from plus L_+ to minus L_- of DC link thus necessarily pass external connections; the resulting parasitic inductances L_σ lead to overvoltage peaks across MOSFET switches turning off with a drain current change rate of $\frac{di_D}{dt} < 0$ according to $\hat{u}_{DS} = U_Z - L_\sigma \cdot \frac{di_D}{dt}$, where u_{DS} is MOSFET drain-source voltage and U_Z DC link voltage.

Those properties as summarized in table 1 make conclude that useability of conventional discrete components for reliable electrical drive systems in automobiles is limited.

2.3 Isolated Discrete Components

A recently developed packaging method has helped to overcome several of the aforementioned limitations of conventional discrete packages: They use an isolating DCB — i. e. a **d**irect **c**opper **b**onded ceramic substrate [6][7] with a structured copper metallization on the top side — as carrier for the chips, maintaining the known moulded style plastic body. Exemplarily a MOSFET phaseleg of ISOPLUS i4™ series [8][9] is shown in **figure 3**:

The use of DCB permits to integrate a phaseleg — thus incorporating the whole commutation path — with low parasitic inductance L_σ. Isolation against heatsink is integrated with coupling capacity C_P and thermal resistance R_{thJS} being lower compared to many plastic insulator pads. It can easily be derived [10] that converters equipped with this kind of devices either run cooler and — partially due to

Table 1: essential properties of trench MOSFET devices with different degrees of integration

	TO220	ISOPLUS i4™	GWM160-0055P3
circuit	single switch	phaseleg	sixpack
isolation	external	integrated	integrated
current capability	low	medium	high
assembly resistance R_M	high	medium	low
thermal resistance R_{thJS}	high	low	low
coupling capacity C_P	high	low	low
parasitic circuit inductance L_σ	high	low	low
assembly effort	high	medium	low
reliability	low	high	high

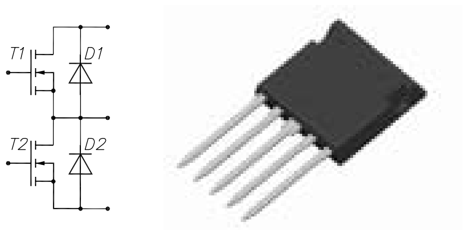

Figure 3: MOSFET phaseleg: symbol and external view of isolated ISOPLUS i4™ package $21mm \cdot 20mm \cdot 5mm$

positive temperature coefficient of MOSFET on state resistance R_{DSon} — consequently provide a higher efficiency, being essential because of the high cost of electrical energy in the car [11] — or that they may be operated at higher current.

The source connections of the chips are again effectuated by wire bonds. It is possible to reduce mounting resistance R_M by paralleling a considerable number of wires at least between chips and DCB substrate: Devices with six wires per chip are in production. Finally the better match of thermal expansion coefficients of DCB carrier and silicon chip $\alpha_{DCB} \approx 2,9\alpha_{Si}$ reduces stress during thermal cycling, thus increasing reliability or permitting to use larger chips respectively.

3 Proposed New Component

3.1 Concept

The aim of the development work presented in this paper is to increase the degree of integration [12] achieved by ISOPLUS™ technology according to section 2.3: A further optimized power semiconductor component for automotive auxiliary AC drive systems would incorporate the complete three phase MOSFET bridge according to figure 1. This subsystem provides the electrical interfaces of high current terminals for the DC link L_+, L_- and the motor outputs L_1, L_2, L_3, additionally the control pins for the six MOSFET gates; besides, an electrically isolated thermal interface towards heatsink is required. Electrical and thermal interfaces should be optimized with respect to the use of the component in low voltage, high current automotive drive converters, operating under harsh environmental conditions according to section 1.

3.2 Realization

The outline of the proposed new device with the type designation GWM160-0055P3 is shown in **figures 4** and **5**: Like the other ISOPLUS™ components described in section 2.3, its black plastic body consists of moulding compound, covering a DCB substrate. To minimize thermal resistance from the chips on top of the DCB to the heatsink below the latter, while maintaining an isolation voltage sufficient for the battery supplied automotive system, a ceramic thinner than $0,63mm$ known from devices for industrial use has been employed.

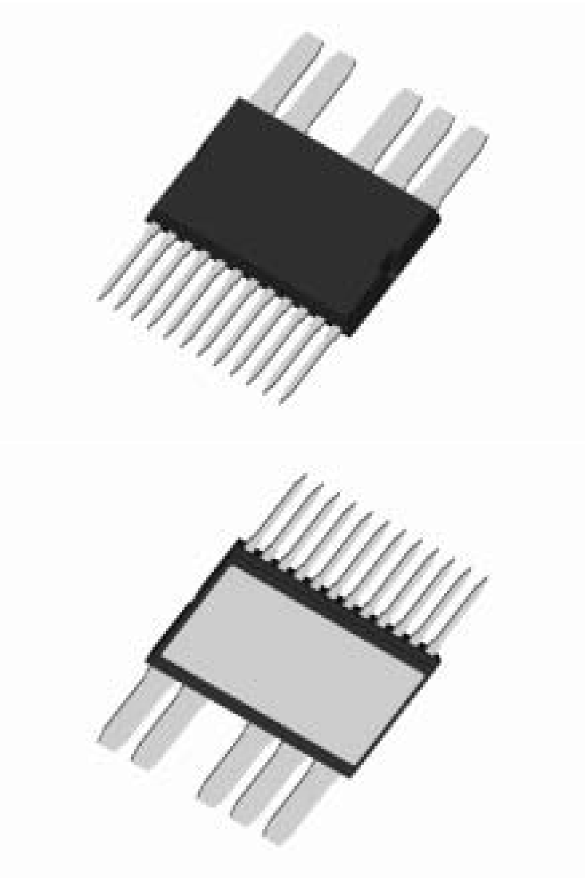

Figure 4: external top and bottom view of proposed GWM160-0055P3 component

As can be seen in **figure 6**, giving an insight into the package, the number of wire bonds per MOSFET source has been increased to five, compared to three in conventional TO220 as described in section 2.2. All of those bond wires end on DCB metallization, thus on cooled conductors able to carry high current. The outer connections of the high current paths — i. e. to DC link L_+, L_- and motor outputs L_1, L_2, L_3 — are effectuated by wide leads with a considerable cross section of at least $2mm^2$. Current capability with-

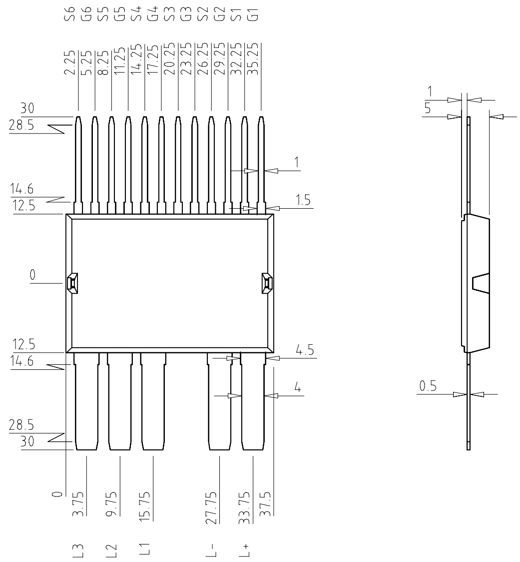

Figure 5: pinout and dimensions of proposed GWM160-0055P3 component

in the main current paths thus is significantly higher than of state of the art devices, correspondingly mounting resistance R_M remains low. The pin arrangement with neighbouring DC link terminals together with the arrangement of plus L_+ and minus L_- rail on the DCB substrate leads to low parasitic inductances L_σ in the commutation paths.

The control signals are electrically and geometrically separated from the power circuit by connecting MOSFET gates and sources with dedicated wire bonds visible in figure 6 directly to control terminals, placed opposite to the main terminals in the dual-in-line package. The pinout of the control terminals with six pairs of gate and corresponding auxiliary source pins $G_1/S_1...G_6/S_6$ is indicated in figure 5 using the nomenclature of figure 1.

Table 2 indicates the essential tentative ratings and characteristics of the new sixpack component. A comprehensive test and measurement program to be carried out after current realization, the results of which are intended to be published in a later paper, shall validate the described concept and the tentative characterization of the proposed device.

Table 2: tentative ratings and characteristics of proposed GWM160-0055P3 component; data per MOSFET switch unless otherwise specified

blocking voltage	U_{DSS}	=	$55V$		
DC current capability	I_{D90}	=	$120A$	max.	at $T_C = 90°C$
on state resistance	R_{DSon}	=	$3m\Omega$	typ.	at $U_{GS} = 10V$, $T_J = 25°C$
body diode reverse recovery time	t_{rr}	=	$100ns$	typ.	at $U_{DS} = 30V$, $I_D = 20A$, $\frac{di_D}{dt} = 100\frac{A}{\mu s}$, $T_J = 25°C$
thermal resistance junction-case	R_{thJC}	=	$0,85\frac{K}{W}$	max.	
thermal resistance junction-heatsink	R_{thJS}	=	$1,7\frac{K}{W}$	typ.	with heat transfer paste
coupling capacity circuit-heatsink	C_P	=	$150pF$	typ.	terminals shorted

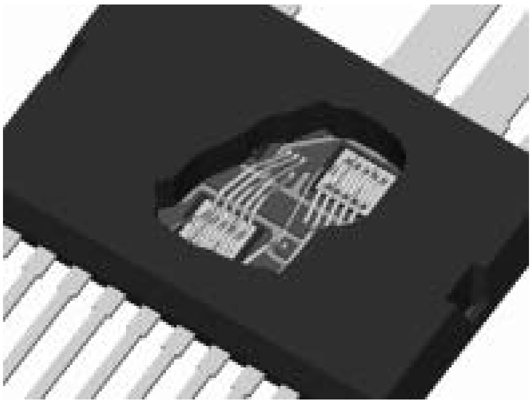

Figure 6: enlarged cut-off view of proposed GWM160-0055P3 component

3.3 Application

The MOSFET sixpack described in the previous section 3.2 with its properties as summarized in tables 1 and 2 is intended to replace at least six TO220 discrete MOSFET devices in automotive applications such as electric power steering, steer-by-wire etc.:

The device will be clamped to heatsink; this for example might be effectuated by spring clips as used for TO247 or TO264, pressing via the narrow sides of the package. The use of thermal compound between the DCB bottom side and heatsink is recommendable but no insulator pad will be required, additionally saving mounting effort and optimizing thermal resistance R_{thJS} or coupling capacity C_P respectively. The DCB base further contributes to high reliability when temperature cycled as may occur regularly when combustion engine's coolant heats up.

The power terminals of DC link L_+, L_- will be connected via a capacitor to the automotive DC system, the motor terminals L_1, L_2, L_3 to the windings of the machine. The integration of the complete three phase bridge obviously significantly simplifies power section compared to a TO220 solution: No punched metal grid is needed to provide high current electrical connections between devices, which saves cost and helps to optimize operational behaviour of the circuit, minimizing external contributions to inductance in commutation paths L_σ. A higher current capability or efficiency can be achieved in the system with the same silicon content, because losses in the current paths outside the chips are reduced.

The control terminals $G_1/S_1...G_6/S_6$ will be soldered into a dedicated printed circuit board, carrying the driver circuitry. The small area of loops in the different signal paths from gate to source together with the decoupling from main current paths using separate terminals shall lead to a high degree of noise immunity, which is favourable especially regarding possible transients in the system, body diodes' turn off tends to contribute to.

4 Conclusion

A sixpack of trench MOSFETs is proposed, being integrated in a single, isolated high current package with enhanced current capability and reliability. A power section consisting of one or several of those devices promises to be a very efficient solution for automotive auxiliary AC drives. This new development thus shall significantly contribute to the current process of increasing system integration.

References

[1] K. Rajashekara: Power Electronics for the Future of Automotive Industry; PCIM Conference, Nürnberg, 2002

[2] R. Lappe, H. Conrad, M. Kronberg: Leistungselektronik; Verlag Technik, Berlin, 1987

[3] S. T. Peake, R. Grover, R. Farr, C. Rogers, G. Petkos: Fully Self-Aligned Power Trench-MOSFET utilizing Lum Pitch and $0,2\mu m$ Trench Width; 14th international symposium on power semiconductor devices and ICs, 2002

[4] A. Lindemann, P. Friedrichs, R. Rupp: New Semiconductor Matreial Power Components for High End Power Supplies; PCIM Conference, Nürnberg, 2002

[5] Automotive Electronics Council — Component Technical Committee: AEC-Q-101 rev. B, 2000

[6] A. Neidig: Neue Montagetechnik für Leistungsmodule; Mikroelektronik, vol. 5, issue 2, Fachbeilage Mikroperipherik, 1991

[7] J. Schulz-Harder, K. Exel: Recent Developments of Direct Bonded Copper Substrates for Power Modules; PCIM Conference, Shanghai, 2002

[8] M. Arnold, R. Locher: The Revolution in Discrete Isolation Technique; PCIM Europe, Issue 3/1999

[9] A. Lindemann: Combining the Features of Modules and Discretes in a New Power Semiconductor Package; PCIM conference, Nürnberg, 2000

[10] A. Lindemann: Impact of MOSFET Components on Power Density and Efficiency of Drive Converters for Industrial Vehicles — Splendid Isolation; Industrial Vehicle Technology — Lift Truck and Materials Handling, UK & International Press, Dorking/Surrey, 2003

[11] K. Ehlers: Konsequenzen des 3-Liter-Autos auf die Architektur des elektrischen Bordnetzes; XVIII. Tagung Elektronik im Kraftfahrzeug, München, 1998

[12] J. A. Ferreira: High Power Densities with Three Dimensional Integration; EPE Journal vol. 12 no. 4, November 2002