UDK621.3:(53+53+621+66), ISSN0352-9045 Informacije MIDEM 26(1996)4, Ljubljana

INNOVATIVE SMART POWER SEMICONDUCTORS FOR AUTOMOTIVE APPLICATIONS

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INVITED PAPER
24th International Conference on Microelectronics, MIEL'96
32nd Symposium on Devices and Materials, SD'96
September 25.-September 27., 1996, Nova Gorica, Slovenia

Key words: SPT, Smart Power Technology, Smart Power Semiconductors, automotive electronics, fuel reduction, energy saving, increased safety, increased comfort, automotive industry, smart power devices, smart power switches, smart power IC, drive actuators, power supplies, bus interfaces, TEMPFET transistors, HITFET transistors, MINI-PROFET transistors, PROFET transistors,sensPROFET transistors, senseFET transistors, MULTIFET transistors, motor control, DC motors, motor bridges, high currents.

Abstract: The paper gives an overview of the manifold benefits of smart power semiconductors and over silicon and assembly technologies. Today, these devices are the key for further fuel reductions of cars, for energy saving and for increased safety and comfort. The presentation links technology features, circuit implementations and device characteristics in order to show the interdependence of all required aspects for practible electronics system solutions.

Inovativna pametna močnostna integrirana vezja za uporabo v avtoelektroniki

Ključne besede: SPT tehnologija močnostna inteligentna, polprevodniki močnostni inteligentni, elektronika avtomobilska, zmanjšanje potrošnje goriva, prihranek energije, varnost povečana, udobje povečano, industrija avtomobilska, naprave močnostne inteligentne, stikala močnostna inteligentna, IC vezja integrirana močnostna inteligentna, aktivatorji gonilni, napajalniki močnostni, vmesniki vodil, TEMPFET transistorji, HITFET transistorji, MINI-PROFET transistorji, PROFET transistorji, sens-PROFET transistorji, senseFET transistorji, MULTIFET transistorji, krmiljenje motorjev, motorji enosmerni, mostički motorni, tokovi veliki.

Povzetek: V delu je podan pregled prednosti pametnih močnostnih polprevodniških vezij, kakor tudi ustreznih tehnologij za montažo in njihovo izdelavo na siliciju. Danes so to ključne komponente pri nadaljnem zniževanju porabe goriva pri avtomobilih, pri varčevanju z energijo ter za povečanje varnosti in udobja. Glavne značilnosti tehnologije, izvedbe posameznih vezij in karakteristike komponent so prikazane na tak način, da bralec spozna medsebojno odvisnost vseh teh dejavnikov pri praktični rešitvi in izvedbi elektronskega sistema.

1. INTRODUCTION

The evolution of the car towards an environmental-friendly, easy to use, save and comfortable transport vehicle is continuously bound to progress in automotive electronics. Smart power semiconductors play an ever increasing role to achieve reliable and high performant electronics systems. Today, a wide range of smart power devices, made possible by dedicated smart power technologies, are offered by the semiconductor industry and used by the electronic system producers. Is has become evident, that the symbiosis between electronics and car technology is the key for future success of both industries, in order to achieve such ambitious goals like to build cars that consume less fuel than 3 l / 100 km. Intensive cooperation between semiconductor producers, electronics systems and car manufacturers lead to further optimization of systems, smart power devices, silicon and assembly technologies with regard to system performance and system cost. The implications on smart power electronics coming from the 3 l car challenge conclude the paper.

2. APPLICATION AREAS AND REQUIREMENTS ON SMART POWER DEVICES

Smart Power ICs are highly appreciated in electronics systems for the following purposes:

- drive actuators (lamps, motors, magnetic valves,...)
- power supply
- signal conditioning (accomodation of high voltage signals)
- bus interfacing
- or combinations of these functions.

The key element of smart power devices is its switching element, the power transistor. While the first generation of power transistors in the 60'ies have been built as bipolar transistors, in the 70'ies the development of the DMOS-(Double Diffused MOS)-transistor allowed to break the limits of 2nd breakdown and high drive current imposed on bipolar devices. In the late 80'ies, the advent of smart power technologies made possible to combine the DMOS power transistor with analog and

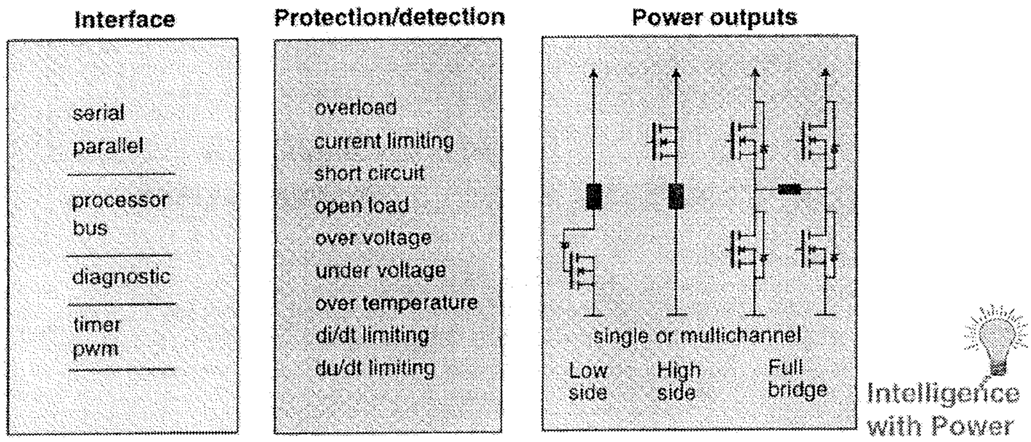

Fig. 1: Smart Power Devices

digital circuitry, thereby realize devices with enhanced functionality so-called "Smart Power Devices (fig.1). In the current decade, the industrialization of smart power applications with the automobile as a technology driver takes place as well as the evolution of smart power towards system-oriented value-adding smart power IC's.

The main technological challenge of smart power is to provide the required voltage capability, reliability and ruggedness of the semiconductor devices to withstand the harsh environmental conditions in cars. Although the nominal battery voltage of cars is 12 V, smart power devices need technologies with about 60 V standoff capability, as can be seen from fig. 2. This is due to instable board nets, some irregular conditions like load-dump, EMI interference and switching of inductive loads.

Also, the temperature requirements of smart power are higher than for most other devices. Generally, an operating range of -40°C.....125°C is specified for smart power devices. However, the devices have to protect themselves and have considerable power dissipation. As a consequence the junction can reach temperatures up to 170°C. Especially for safety-critical applications like ABS, also this is not sufficient. Here the device will give a warning signal at overtemperature, however it has to be guaranteed by design that it maintains its functionality also beyond 200°C.

To maintain functionality under normal and exceeded operating conditions and to operate in a well-defined way under irregular conditions is of utmost importance for smart power devices. This is one of the most challenging design issues of smart power devices. It can be accomplished only by a close cooperation between IC and system designers.

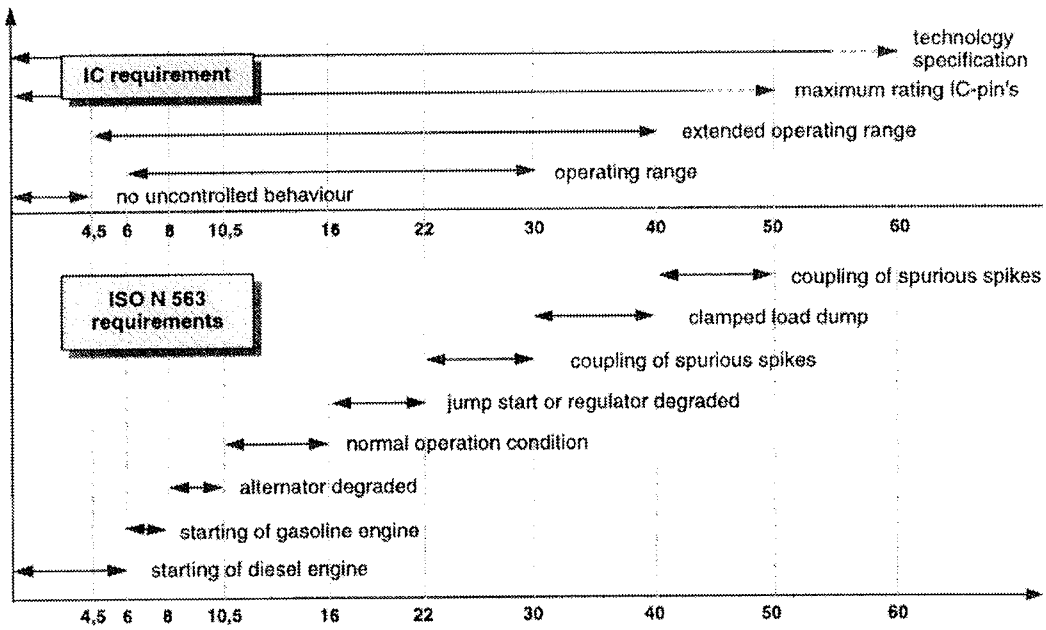

Fig. 2: Voltage standoff requirements

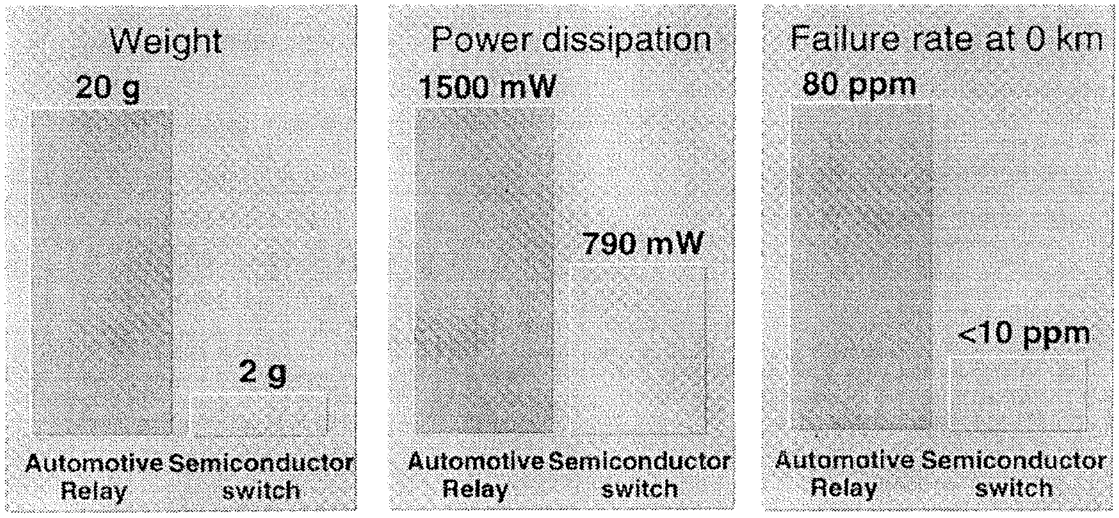

Fig. 3: Benefits of semiconductor switches versus relais

2.1 Smart Power Switches

The most important element in smart power electronics is the "Smart Power Switch". It is needed either in highside or lowside configuration, see fig.I. Since several years, smart power switches continuously are replacing relais and mechanical switches in cars due to their 4 main benefits: reliability, size, weight and power consumption, with the reliability advantage as the most important from an economical point of view. This is illustrated in fig. 3. Of course, the protection and interface functions of smart power devices cause additional costs due to higher die area, needed around the power transistor for this circuitry, and more expensive wafer or assembly technologies. However, higher costs pay off at the system and maintenance level. In addition, smart power semiconductor devices make possible applications that cannot be realized by relais like PWM operation or inductive switching.

Today, several product families of smart power switches are offered by the leading companies that have focused on this innovative field of semiconductor application like Siemens, SGS-Thomson Philips or IR. The smart power switch product families available today comprise solutions for highside and lowside switches and bridges, implementations of different protection levels and digital interfaces as well as adaptions to specific loads and applications. Within each product family, usually several switches with different on-state resistors of the DMOS power transistor (R_{ON}) are offered.

The TEMPFET, HITFET and PROFET smart power switch product families have been well introduced into the market. Fig. 4 gives an overview over these families and their protection and interface concepts.

All these smart power devices are produced with the Smart SIPMOS, S-Smart and the SPT technologies, which are described in chapter 3. As the PROFET concept is already well-known from the literature /3/, the following paragraphs will concentrate on recent developments, which address the following directions:

- Increase system value / decrease overall costs
- Expand the application horizon

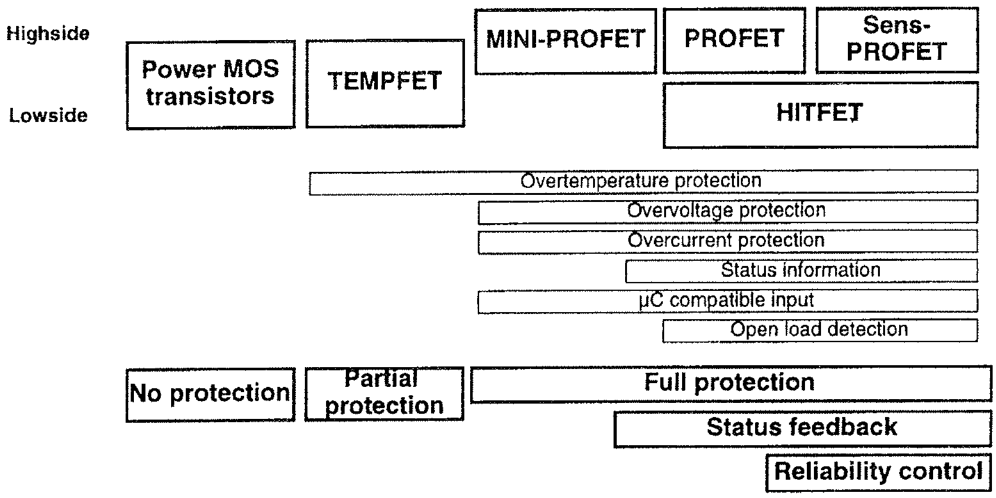

Fig. 4: Smart Power Switch product families

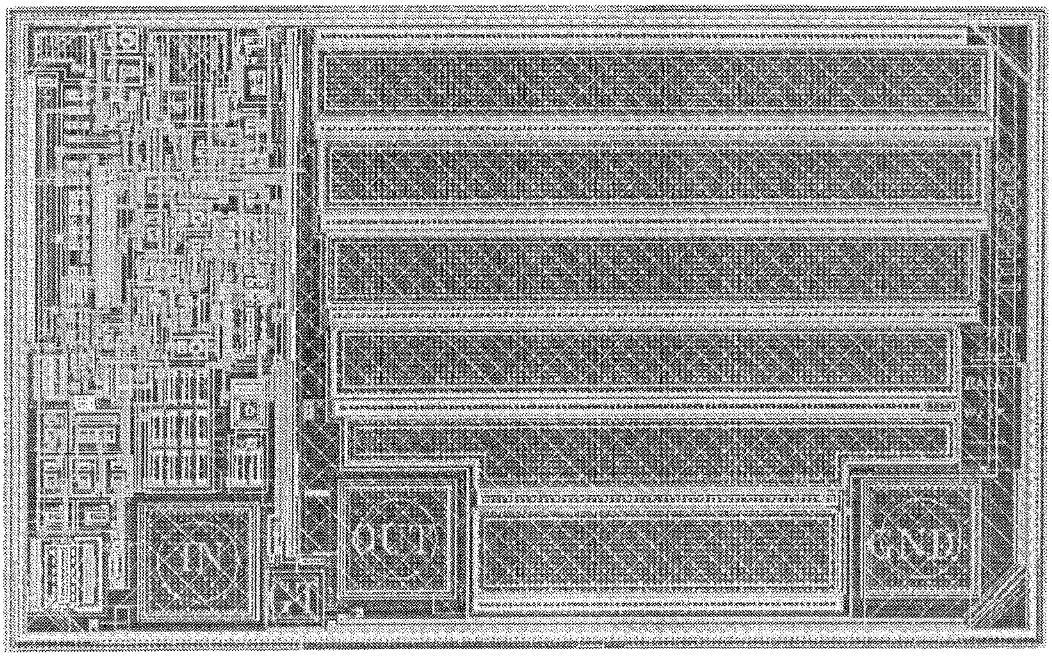

Fig. 5: BSP75 Mini-HITFET chip layout

2.2 MINI-Smart product family:

A large number of applications doesn't require low RON's for switching of high currents. What is urgently needed, however, is the ruggedness and voltage capability of the device, i.e. the protection functions, and an attractive price. As a solution to these requirements, the MINI-Smart product family has been developed. These devices combine the high performance of the PROFET or HITFET switches with small die sizes due to small power transistors and the low-cost SMD package SOT223. The product family comprises highside and lowside switches. As an example of recent developments the BSP75 Mini-HITFET is shown in fig. 5. The MINI-Smart devices are ideally suited for driving of relais and small lamps, for climate control or data line driver. There are also manifold applications in industrial control.

2.3 SenseFET product innovation:

As the most recent enhancement of the PROFET family, a so-called "Sense Highside Switch" (SensPROFET) has been developed. This power switch delivers a sense signal proportional to the load current in addition to the normal status line. With this signal processed by a µC with ad-converter, the system has precise control over the load status and all irregular conditions. Fig. 6 shows the system configuration of the current sense feature. Of course, the SensPROFET contains all the protection features already known from the PROFET. With the SensPROFET, also the fuse can be replaced electronically, thus this device saves the relais plus the fuse! As the µC exactly knows the current consumption of the system improved diagnosis as well as more sophisticated concepts for energy saving may be realized.

The first member of the SensFET family is the BTS640S2 /1/, a highside switch with 30mΩ on-resistance, which has been realized with the new S-Smart technology (see chapter 3.2). Fig. 7 shows a layout diagram of the device.

2.4 High current MULTIFET motor bridges:

The bidirectional control of dc-motors requires the combination of high- and lowside switches in a motor bridge configuration. Today, several motor bridge ic's are offered in bipolar and SPT technologies. The MULTIFET is a new and costeffective approach utilizing existing PROFET and Lowside switches. A dual-channel

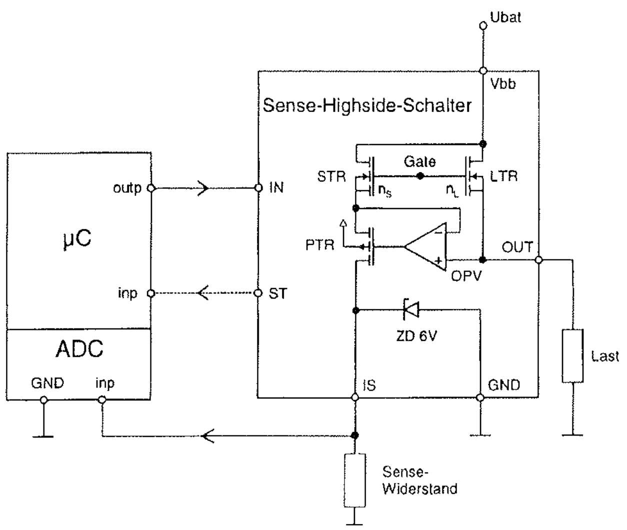

Fig. 6: Circuit Diagram of the Sense Highside Switch

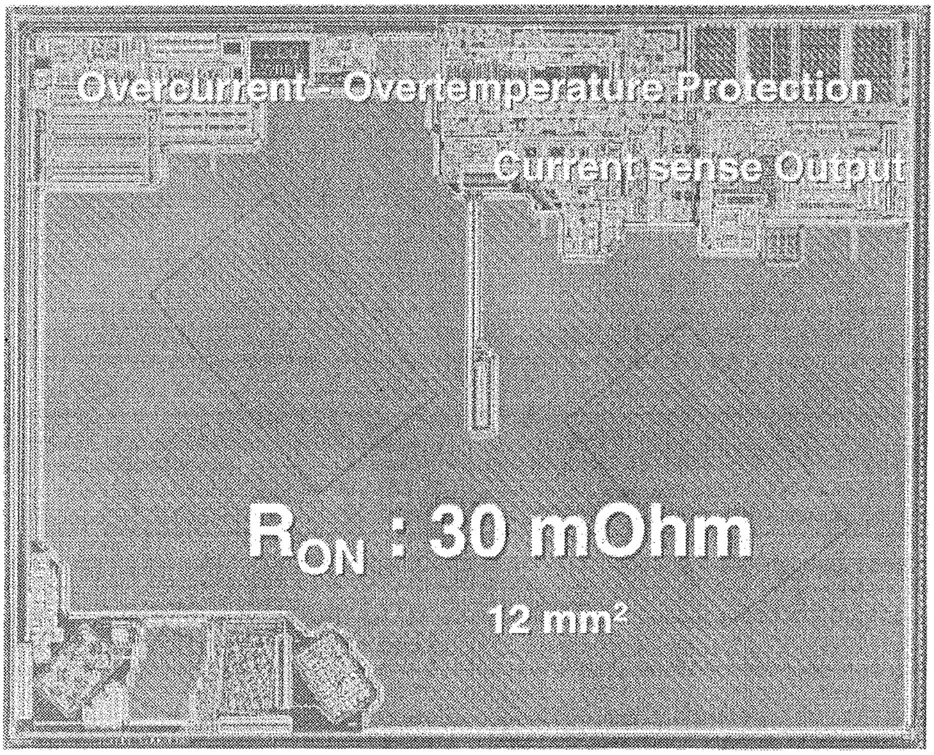

Fig. 7: BTS640S2 Sense PROFET chip layout

Features:

- **Short circuit protection**
- **Charge pump**
- **Current limitation**
- **Thermal shutdown**
- **Diagnostic feedback**
- **Open load detection in on-state**
- **CMOS compatible input**
- **Under- and overvoltage shutdown with auto-restart and hysteresis**

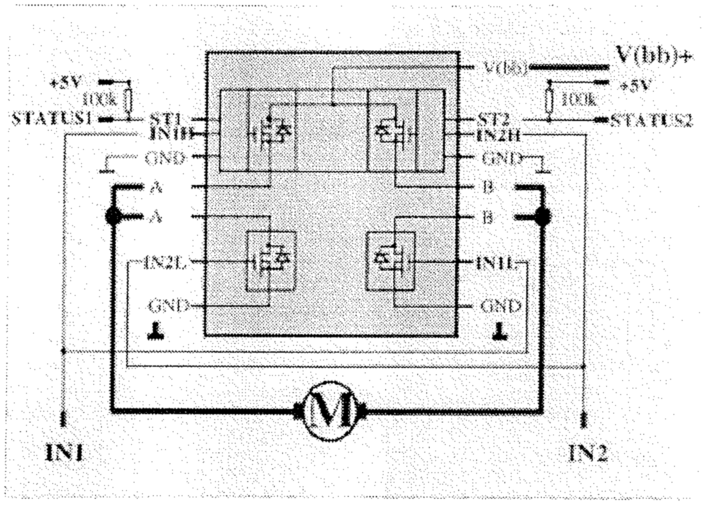

Fig. 8: High Current MULTIFET Motor Bridge

PROFET is combined with two standard power transistors in a DSO-20 plastic package with splitted lead carrier (see fig.8 block diagram). The MULTIFET concept thus allows to use the most cost-effective solutions for the high- and lowside switches seperately and combine them with standard assembly techniques. The leadframe arrangement is shown in fig. 9.

The MULTIFET devices are designed to handle currents as high as 2...4 A. The product familiy can be easily and quickly expanded according to market needs.

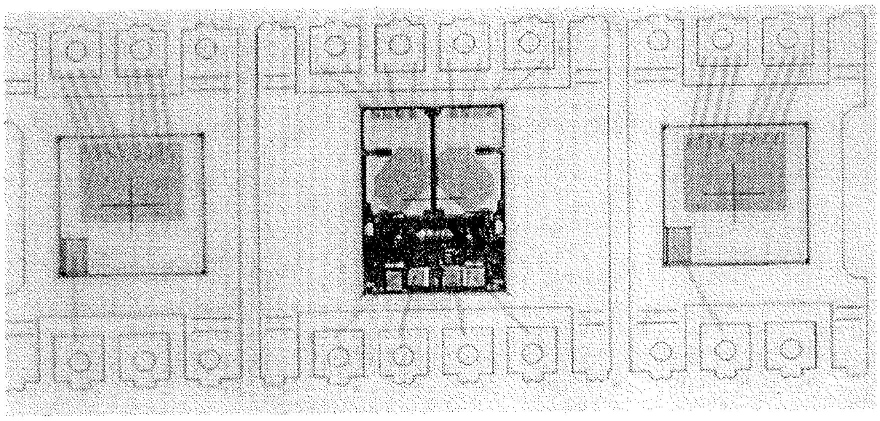

Fig. 9: MULTIFET split leadframe carrier

2.5 Smart Power System Integration

Compact electronics systems like door modules, engine control, airbag or ABS require the integration of all functions on quite a few highly integrated devices. The evolution of most systems can be generally described by fig.10. It turns out that a 2-chip approach is a very cost-effective partitioning, comprising of a standard µC and a system-specific smart power IC containing the power driving, analog processing, system supply and interfacing functions (see fig.11).

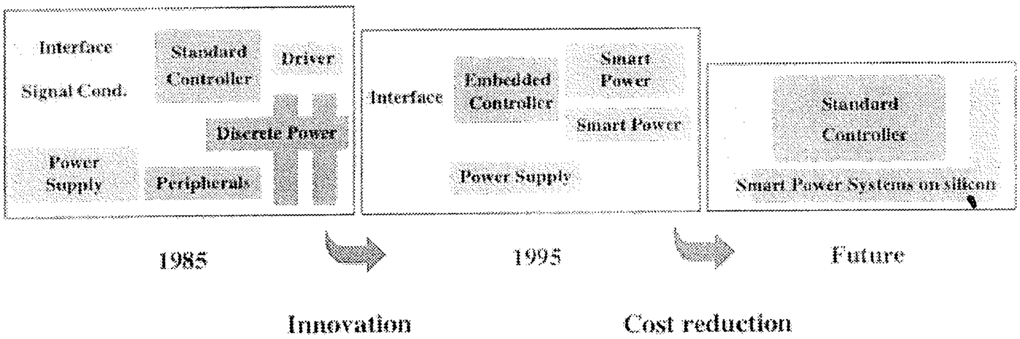

Fig.10: Automotive System Evolution

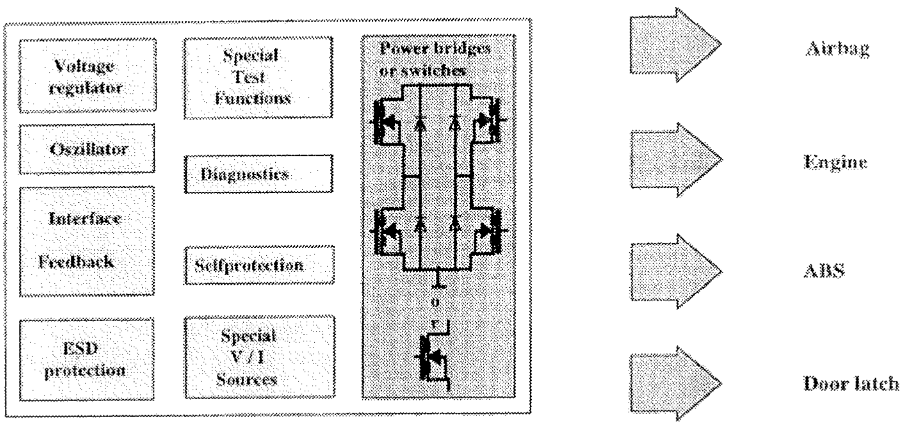

Fig.11: Smart Power Systems on Silicon

3. SMART POWER TECHNOLOGIES

As already mentioned, the application area of "Smart Power" comprise the realization of a big variety of different functions within electronics systems. The common and final measure is the overall system cost. As a consequence, smart power technologies have to be dedicated to the specific system architectures, partitionings and implementations, and have to make possible system solutions providing an overall benefit. Of course, progress in silicon technologies is a pacemaker. However, also assembly techniques, mounting and cooling concepts play a very important role especially in the field of smart power. These issues will be viewed now.

The workhorse of today's smart power technologies are silicon technologies with the DMOS transistor for power switching and CMOS and bipolar for logic and analog functions. Technologies with self-isolation and junction-isolation are in massproduction, technologies with dielectric-isolation in the experimental phase.

3.1 SPT, a versatile junction-isolated smart power technology

The SPT is a bicmos power technology with an optimized dmos transistor. The technology is optimally suited for complex smart power ics with multichannel power switches, analog processing and logic interfaces. Fig. 12 shows the crossection of some major devices and the junction isolation concept. The junction isolation is performed by a seperate bottom and top p+-implant. Thickness and doping level of the epitaxial layer is optimized to provide the required drift region for the dmos. The dmos current flow is lateral, i.e. it is fed to the surface via the buried layer and an n^+-sinker, which allows multiple transistors at arbitrary voltage levels. A large variety of devices can be constructed with the SPT by utilizing the available implants skillfully. The cmos and bipolar devices are provided in different versions, in order to optimize packing density, standoff voltage or analog behaviour, as needed for the specific circuit function. For high voltage circuits, beside the dmos, a high voltage pmos can also be realized by inclusion of a tapered lateral drift region.

The SPT uses an advanced fully self-aligned dmos cell (fig. 13). Not only body and source implants are defined by the same mask, also the source contact is applied to the same structure, after a deep etch controlled by spacers. This selfaligned dmos cell yields a very high cell density, resulting in low on-resistance (R_{ON}) of the dmos power transistor.

The SPT technology is improved continuously in order to increase the packing density of cmos, bipolar circuits and dmos cells.

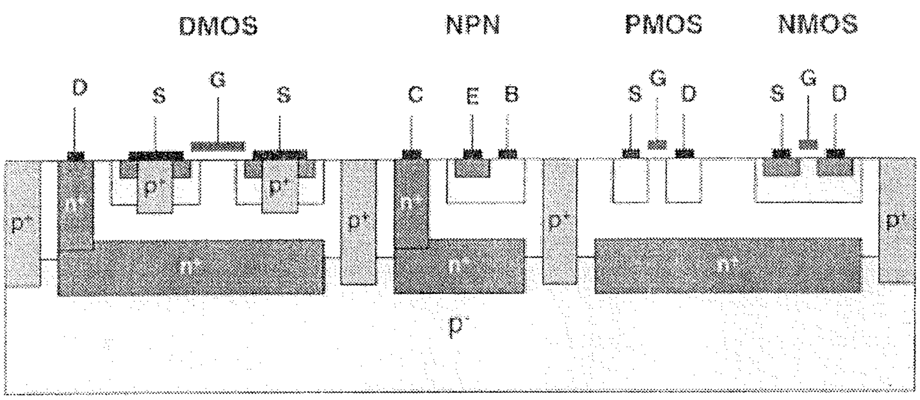

Fig.12: Cross-section of SPT Technology

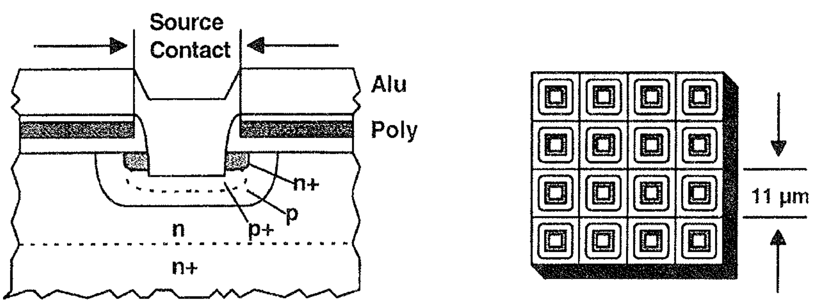

Fig.13: DMOS Transistor of SPT

3.2 Smart SIPMOS, the highside switch technology

As mentioned earlier, the protected switch is the most important device of smart power. For ist realization, only processing steps absolutely necessary for protection circuitry should be added to a power transistor process. This is the idea of the Smart SIPMOS process, a self-isolated technological approach to smart power. A simplified crosssection is shown in fig. 14. Chargepump, overtemperature and overvoltage protection as well as status feedback can be realized with low- and high-voltage cmos transistors. Smart SIPMOS, with several technological improvements, has made possible 5 generations of PROFET devices up to now. Furthermore, designers have learned to realize cost-effective HITFET lowside devices with this technology too.

In recent development, the conventional Smart SIPMOS has been improved and combined with the self-aligned SPT dmos cell. The new technology is called S-Smart and it provides an increase in packing density of up to 40%. It is first applied to the current sense PROFET.

3.3 Packaging and assembly technologies

Today, the TO-220 is the package with highest production quantities used for smart power electronics. With its 5-pin and 7-pin configurations, 1- and 2-channel smart power switches and motor bridges can be assembled in a cheap standard plastic package with excellent thermal properties. The TO-220 can also be delivered in a SMD compatible lead configuration. However, the trend towards higher integration, reduced volume and fully automated pcb handling gives a strong driving force for advanced SMD-type packages with small outlays (like SOT, DSO and MQFP) and pincounts ranging from at least 3 for mini power devices over 20...28 for medium integrated power devices to 64 and more for complex smart power system ics (see fig.15).

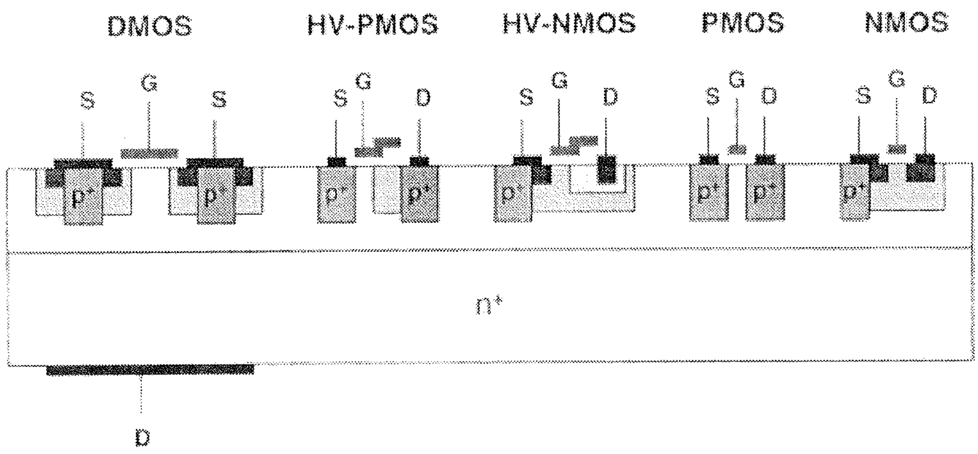

Fig.14: Smart SIPMOS Technology

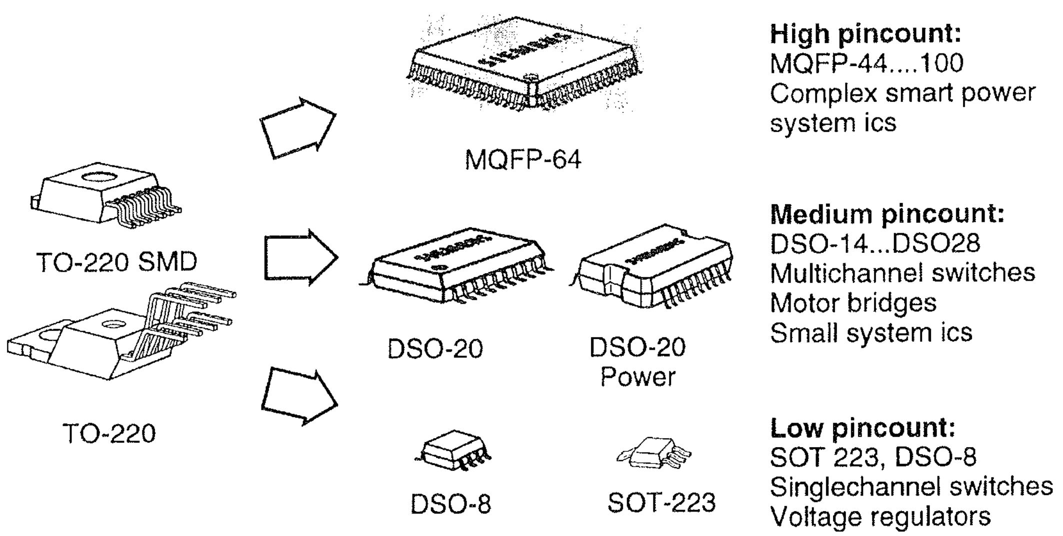

Fig.15: Smart power package trends

In order to provide low-cost solutions, it is very important to use high-volume production lines with no or only small modifications for smart power devices. Modifications are required e.g. for enhancing thermal properties (special leadframes, additional Cu-blocks), for electrical isolation purposes (leadframes with multiple carriers). Additionally, the system aspects also for packaging has to be taken into account. As an example the "silicon vs. heatsink" concept shows, that heatsinks can be avoided by switches with low R_{ON}. Although these semiconductor devices are more expensive, the overall system cost is lower, and weight and volume benefits are provided.

The product examples mentioned earlier show the importance of these innovative assembly concepts. With further minituarization its importance will even increase. Hybrid assembly, multichip modules and the integration of micromachined sensor elements are current trends, that make mechatronics concepts a big challenge of the next years.

4. THE 3 l CAR CHALLENGE

The automotive industry today faces the challenge to drastically reduce the toxic exhaust and the fuel consumption of cars within the next 10 years. As a common wording, the 3l-car is the goal of this effort. With this target in mind, engineers worked out the dependencies of fuel consumption and found that 50 kg additional weight as well as 100 W additional electric power yield an additional fuel consumption of about 0,15 l /4/. The consumption of electric power of an average car is about 500 W, with a rising tendency for the next years. This means that today about 0,75 l / 100 km fuel is needed for the electrical power generation. For high-end cars this value has to be doubled, and for the future the situation would get worse.

As a consequence, energy and weight saving is essential to achieve a 3 l-car. Future cars therefore will require an efficient power management system with all loads controlled by semiconductor switches. Mechanical solutions like the fuel pump as an example, will be replaced by an electronically controlled pump, adapting the power to the actually required amount. Advanced control systems like PWM operation and switched-mode DC-DC conversion, which reduce electric losses, will dominate over conventional systems.

Furthermore, it is becoming clear that the current 12 V board net also is a severe limit. Leading european car manufacturers have founded the initiative "Bordnetz 2005", to define a next generation architecture for the car board net. Results are not yet available, however it is obvious, that the supply voltage will increase, may be towards 40 V. A higher supply voltage, together with new electric and electronic components, especially designed for high yield and less weight, are required to face the challenge. What consequences will this have on power semiconductor devices?

As can be seen from fig. 2, the breakdown voltage requirements of power semiconductors today are defined by supply voltage irregularites rather than by the battery voltage. A higher battery voltage therefore doesn't necessarily imply a higher standoff voltage for the technology. The standoff voltage of the semiconductor devices will depend on the stability of the new boardnet that can be achieved. A higher battery voltage will help to increase the stability of the net, as the current levels will decrease accordingly. Lower current levels will as a further benefit reduce ohmic losses in the wiring cables.

5. CONCLUSION

The application of smart power devices in cars is increasing, as a high level of maturity of the electronic systems could be achieved with respect to system functionality, reliability and cost. The available smart power device palette, ranging from switches for high- and lowside configurations up to smart power system ics is refined and enlarged continuously by close cooperations between semiconductor and system manufacturers. The improvement of dedicated smart power silicon technologies and assembly technologies both is of equal importance to achieve the growing perfomance and price requirements.

However, this development by far has not come to an end now. As has been shown, the challenge to achieve more environmental-friendly cars will bring about a new push to rework the car board net architecture with respect to weight and power savings.

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Prispelo (Arrived): 01.09.1996   Sprejeto (Accepted): 09.11.1996