INTEGRATED SMART POWER CIRCUITS INTRODUCTION, DESIGN AND APPLICATION

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Abstract: Integrated smart power circuits gain more and more importance, as many segments of microelectronics move towards system integration. The combination of many functions - analog, digital and power - on a single chip enable the design and production of even more miniaturised systems for different applications in the fields of automotive, telecommunication and electronic data processing. This paper gives an introduction to the available semiconductor technologies, shows some circuit design examples specific to the problems of smart power devices and focuses on available real products in different application areas. A discussion of future technical trends under the constraints of an extremely price-sensitive market concludes the paper.

Inteligentna močnostna integrirana vezja Uvod, načrtovanje in uporaba

Ključne besede: mikroelektronika, IC vezja integrirana, vezja integrirana močnostna inteligentna, tehnologija avtomobilska, EDP procesiranje, tehnologija polprevodnikov, snovanje vezij, telekomunikacije, trendi prihodnji, elektronika porabnikova, aplikacije, SIPMOS tehnologija, SPT tehnologija močnostna inteligentna, regulacija moči, proženje aktivatorjev, pogoji okolja, zmanjšanje stroškov

Povzetek: Pomembnost inteligentnih integriranih močnostnih vezij narašča iz dneva v dan, saj se posamezni segmenti mikroelektronike gibljejo v smeri vse večje sistemske integracije. Kombinacija velikega števila funkcij - analognih, digitalnih in močnostnih - na enem integriranem vezju, omogoča načrtovanje in izdelavo vse manjših sistemov za uporabo na različnih področjih elektronike, kot so npr. avtoelektronika, telekomunikacije ter elektronska obdelava podatkov. V prispevku uvodoma opišemo razpoložljive polprevodniške tehnologije in nato podamo prikaz nekaterih načrtovalskih prijemov, ki so specifični za načrtovanje močnostnih integriranih vezij. Kot primer opišemo tudi nekatera vezja, ki smo jih dejansko načrtali, izdelali in so trenutno v uporabi v zgoraj naštetih sistemih. Na koncu prikažemo in komentiramo nekatere tehnične trende, ki bodo v bodočnosti pod vplivom cenovno izredno občutljivega trga narekovali smernice razvoja inteligentnih močnostnih integriranih vezij.

1. INTRODUCTION

Integrated circuits show a significant growth potential, not only in the traditional segments as information- and signal processing (electronic data processing, telecommunications and consumer electronics) but also in the fields of power electronics and sensor systems. Modern smart power technologies on silicon enable innovative solutions, which substitute conventional elements as fuses, relays and switches. But furthermore they open up complete new opportunities by system integration. A more complex functionality of the single IC can be combined with higher reliability and less volume and weight. The most important area of application for smart power ICs seems to be the automotive industry. Higher safety standards, tighter environmental legislation and the demand for increasing comfort on board lead to a constantly increasing amount of microelectronic components built into modern cars.

Anti-lock braking and airbag systems, an efficient motor management, anti-theft devices and electronic devices for all conveniences in the car will be standard equipment in the near future. Besides smart power devices the sensor elements play a key role in these applications. Active hall effect sensors for position and rotational speed can be produced as low cost devices with high reliability as integrated circuits.

The development of modern, system oriented smart power technologies as Smart-SIPMOS® and SPT (Smart Power Technology) have fostered today's widespread use of microelectronic components in these new fields of application. These technologies allow the monolithic implementation of power output stages together with complex analog and digital functions. Currently maximum supply voltages of 80 V, in special cases up to 170 V and switching currents of several amps can be handled.

2. SMART POWER TECHNOLOGIES

Depending on the different application areas, various smart power technologies provide the best possible solution considering technical and economical aspects. These technologies are characterised by the available active and passive elements - mainly in the power electronics part - the isolation technique applied, the direction of current flow and last but not least the breakdown voltage. A key feature of modern technologies is the integration of standard CMOS and bipolar transistors together with DMOS-devices, which allow low power control circuits for the output stages and guarantee a large safe operating area.

2.1 Smart SIPMOS® Technology

As an example of a CMOS based self isolated technology, the Smart SIPMOS® technology is shown in fig. 1. The power device, realised as a vertical n-channel DMOS-transistor, uses an epitaxial drift layer, grown on a highly doped substrate. The current flows in a vertical direction through the wafer and is collected at the backside via the die attach area to the package. This allows very high current densities and makes the technology the ideal choice for low on-resistance (Ron), high current high side switches (s.fig. 15). But there is a significant limitation: Due to the construction (common n+substrate) all switches on the same chip have to share the positive supply voltage in a common drain configuration. In addition CMOS devices for low and high voltage are available.

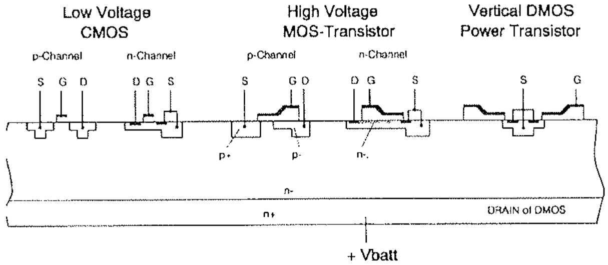

Fig. 1: Cross section of the Smart SIPMOS®-technology

2.2 Smart Power Technology SPT

Fig. 2 shows the cross section of a junction isolated smart power technology (SPT), which is based on BiCMOS enhanced by an optimised DMOS power device. The application of a junction isolation with a p-substrate and a n+epitaxial layer offer the combina-tion of high voltage DMOS, low voltage bipolar and CMOS for high and low voltages. As the current path in the power device is vertical, but is brought back to the surface via a buried layer and sinkers (updrain configuration) this approach allows the integration of several power devices on the same chip without any wiring constraints. In this advanced concept the benefits of CMOS for high integration of logic functions, of bipolar circuits for high precision analog functions (low noise, offset and drift) can be combined with power devices such leading to "systems on silicon".

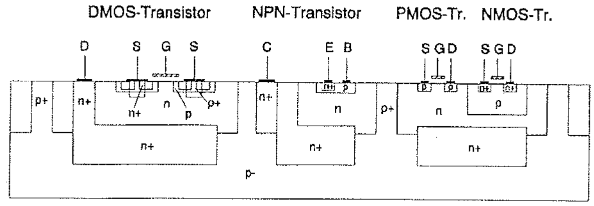

Fig. 2: Cross section of junction isolated SPT-technology

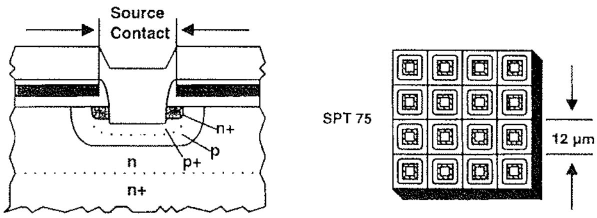

Fig. 3: Detail of DMOS-transistor (cross section and top view)

Today SPT75 as a leading technology using a selfaligned DMOS (Fig. 3) is available for production of smart power devices, mainly for automotive applications.

As a central load-dump protection will be a standard feature in new cars, a reduction of the maximum blocking voltage will be possible. Together with the general trend of reduced feature size in integrated circuits, current developments focus on further reduction of the Ron and a significant increase of packing density in digital and analog circuit areas, thus leading to substantial cost reduction for the customer.

3. FUNCTION BLOCKS FOR SMART POWER

Today's automotive electronic systems must provide highest reliability and robust operation. This includes withstanding voltage spikes, a very extended temperature range and immunity to electromagnetic interference, while not being a source of electromagnetic interference by themselves. Therefore self diagnostic monitoring on chip is important to report the system condition to the controlling microprocessor and to protect the circuit. This leads to different function blocks, which are required for smart power devices in automotive applications (Fig. 4).

An interface part connects the smart power switch to the controlling microprocessor - a good application for the CMOS components. The smart part is responsible for all the diagnostic and protective functions. It is the area of analog circuits using the bipolar or low voltage CMOS components. Last but not least the power switch itself is defined by the DMOS transistor.

INTERFACE	SMART PART	POWER OUTPUT
serial parallel bus status output for diagnostics	over temperature short circuit open load over voltage load dump protection under voltage current limiting di/dt - limiting	high side switch low side switch
CMOS Digital	Bipolar or MOS Analog	Power DMOS

Fig. 4: Functional blocks of smart power circuits

The following figures show some typical functional building blocks and some remarks on their respective functions:

Current Measurement Circuits

For the detection of overcurrent or open load conditions a current measurement circuitry is needed. A simple solution is the direct measurement via a shunt resistor (fig. 5) usually implemented as a part of the metal layer. The reference voltage Vref defines the current threshold, the output of the comparator can be used as diagnostic signal or be directly connected to the gate in a feedback loop to control the current.

The circuit shown in fig. 6 needs no comparator and no voltage reference. Assuming the same collector currents for Q1 and Q2, the current limit threshold is well defined by the ΔVBE of Q1 and Q2, which is known as

$$\Delta VBE = Vt \cdot \ln (AreaQ1 / AreaQ2)$$

Vt = kT/q depends on the absolute temperature, but this temperature coefficient is first order compensated if the resistor RS is made using the aluminium interconnect metal. Therefore this circuit leads to a good temperature compensated current limiting and is therefore often used.

A disadvantage using a shunt resistor is the voltage drop, because the resistor is connected in series to the load circuit. To avoid this voltage drop, the use of a

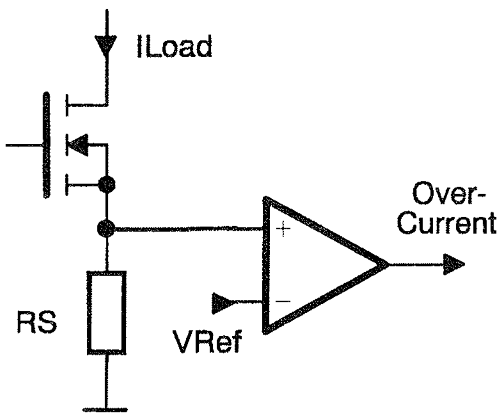

Fig. 5: Current measurement by using a shunt resistor

sensing transistor is known, as shown in fig. 7. For this sensing transistor M2 a few cells of the power transistor M1 are separated and used like a current mirror.

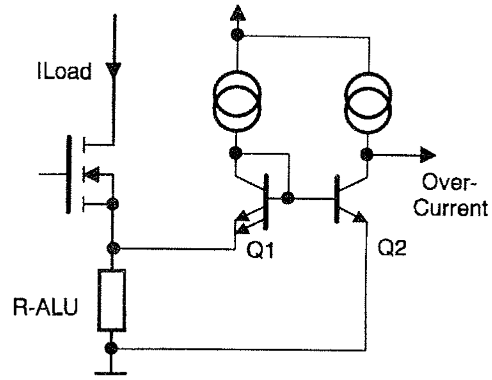

Fig. 6: Current measuring circuit which needs no reference voltage

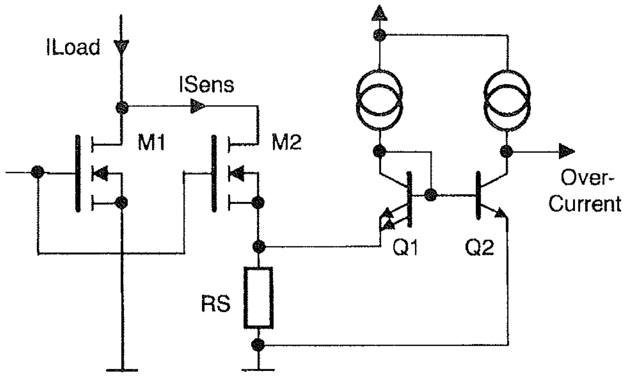

Fig. 7: Current measurement/overcurrent detection with a sensing transistor

Gate Drive Circuits

According to the required switching speed or frequency of the power switch a driver circuit to switch on and off the power DMOS has to be designed. To minimise the power dissipation during switching a fast transition always seems to be a good choice but it can cause significant problems within the circuit and in the surrounding circuitry due to radiated and conducted electromagnetic noise. An appropriate and simple countermeasure to control di/dt-transients is the use of current sources for driving the gate (fig. 8). In the design process a careful balance has to be found between speed and acceptable EMI (electromagnetic interference).

Besides the power loss in the DMOS during the on-state, which has to be dissipated via the package also the protection measures against overvoltage when switching inductive loads and the subsequent heating of the chip has to be taken care of. Fig. 8 shows optional protective circuitry consisting of diodes and zener diodes. This path being turned on during overvoltage conditions switches on the DMOS device and such leads to a reduction of the voltage across the power stage.

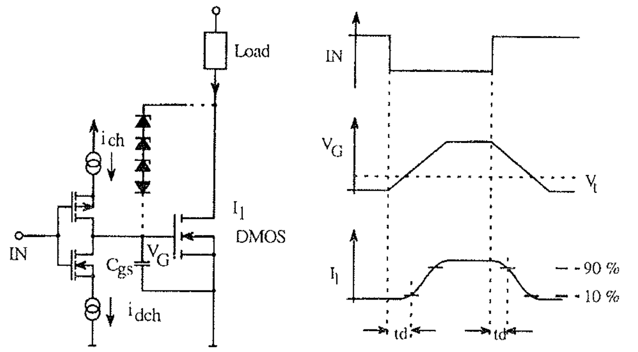

Fig. 8: DMOS-driving circuits with optional overvoltage protection for inductive loads

Temperature Sensors

In applications for smart power circuits as e.g. in the automotive industry the highest possible level of reliability is required for obvious reasons. To achieve this, it has to be guaranteed for all thinkable conditions of the circuit, that critical parameters are recognised in time and that appropriate countermeasures are taken immediately. In addition the circuit has to report status signals to the central unit and to protect itself and other external components in such a way, that no destruction may occur. Besides over-voltage and overcurrent the temperature of the die is a valuable indicator, as overheating can destroy the element. Temperature sensors are built into the circuit for these reasons at appropriate locations. Fig. 18 shows the microphoto-graph of a PROFET® switch, right in the centre of the DMOS-cell array a small circuit to monitor temperature on chip has been placed. The following fig. 9 shows the circuit of such a temperature sensor, which makes use of the well known temperature dependence (fig. 10) of the VBE of a bipolar transistor (Q1).

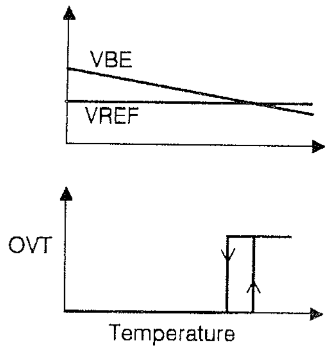

Fig. 10: Characteristic of sensor circuit

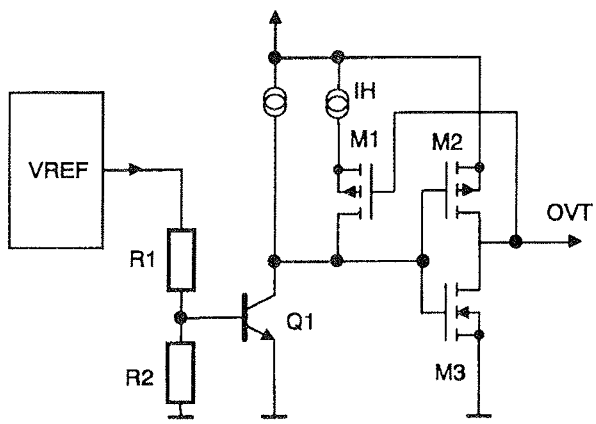

Fig. 9: Temperature sensor with hysteresis

The circuit compares the VBE (Q1) with a temperature independent reference voltage, usually supplied by a bandgap reference circuit. The CMOS output stage M2/M3 is connected to the gate of M1 which switches an additional current IH on or off depending on the output level, this defines the hysteresis characteristic. This principle is used frequently, via the voltage divider R1/R2 it is possible to adjust a well defined switching temperature because the VBE voltage is not so sensitive to fabrication tolerances.

Charge Pump Circuit

In a high side switch the power transistor, which always is an n-channel device, is used in a source follower configuration. This requires a positive voltage higher than the supply voltage for the gate to achieve a low Rds-ON, see fig. 11.

Sometimes also low side switches should use a high gate drive voltage to improve the Rds-ON if they are working at low supply voltages (fig. 12). This high gate voltage is commonly generated by a charge pump circuit.

Fig. 13 shows a simple voltage doubler circuit, fig. 14 a practical realisation used in a Smart SIPMOS® high side switch. As bipolar diodes are not available in this process, lateral high voltage n-channel MOS-diodes are

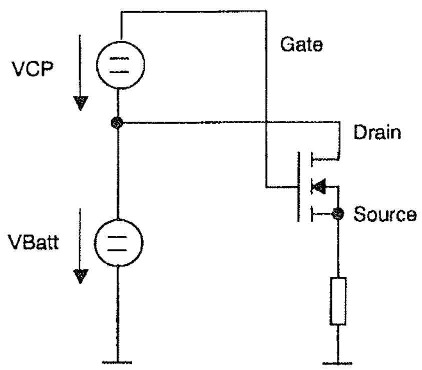

Fig. 11: High side switch requires a high voltage for the gate

used in this circuit. An oscillator is needed to activate the charge pumping operation. Frequency stability is in general not a question, so simple circuits like a ring oscillator or a simple R-C oscillator are used. The working frequency usually is in the range of a few 100 kHz to a few MHz.

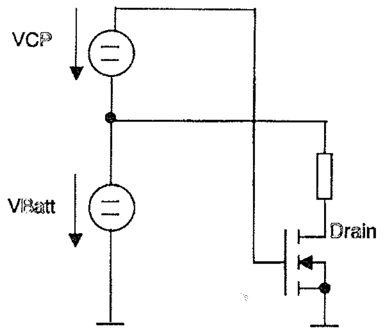

Fig. 12: High gate voltage improves the Rds-ON for a low side switch

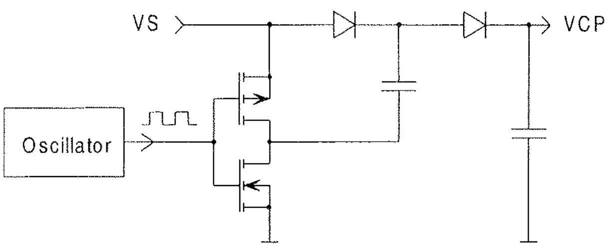

Fig. 13: Simple charge pump circuit (voltage doubler)

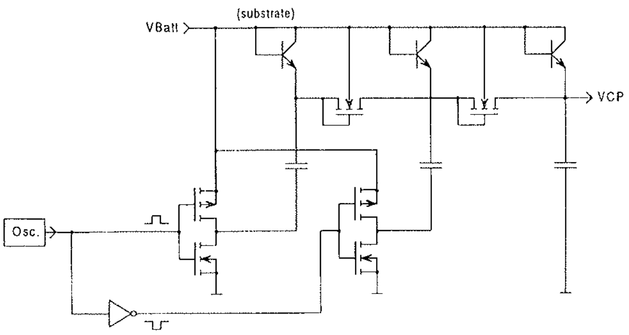

Fig. 14: Practical implementation of a dual stage charge pump circuit for a high side switch in a MOS-based self isolating technology

4. APPLICATION AREAS

As smart power technologies allow the integration of analog and digital functions together with power output stages, robust system ICs can be implemented, which are perfectly matched to the system requirements. They are the interface elements between the electronic system and the environment. They provide reliable and stable power supply for the system, drive signal lines and busses and they control actuators as lamps, motors and valves. In the latter cases the smart part plays a key role: current, voltage, temperature and load conditions are monitored continuously, the switches protect themselves in this way and signal eventual malfunction to the central controller. Switching transients are limited to reduce EMI from the power circuits. Only now these smart power ICs enabled the production of low cost systems with utmost reliability.

The most important application field for smart power is the automotive market. Electronic components can be found in three main areas there:

- Substitution of relays and switches
- Dedicated systems (e.g. motor management, airbag, anti-lock brakes)
- Bus systems (e.g. CAN-bus) for reduction/elimination of cable harness

For the substitution of conventional switches and relays primarily intelligent power switches produced in the Smart-SIPMOS®-technology are used in the configuration as Highside, Lowside or Bridge (fig. 15).

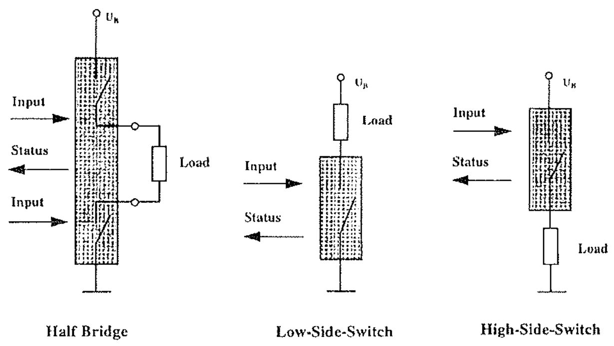

Fig. 15: Different types of smart power switches

The latest generation HITFET® (Lowside) and PROFET® (Highside) provide optimal solutions from the economic and technical point of view.

The HITFET® contains an integrated sensor system including a double overtemperature protection by an integrated and an add-on temperature sensor (fig. 16 and /1/). This feature enables the circuit to react individually to puls-type and continuous overload conditions, such a destruction of the device is not possible. The current limiting function leads to increased lifetime of the light bulbs and the limited di/dt reduced the emission of EMI.

The PROFET® BTSxxx-family provides similar functionality as the HITFET®, but is used in highside applications. In addition these circuits provide a status signal for the system, which indicates error conditions as e.g. overtemperature or broken lamps. Significant progress in reduction of package volume could be achieved in this device family in the last time, a very important achievement for the automotive customer. The innovations are: combination of several switches into one package (2, 4, 8 channels), change to SMD-packaging (P-DSO-20) and modern design concepts (silicon substitutes heatsink).

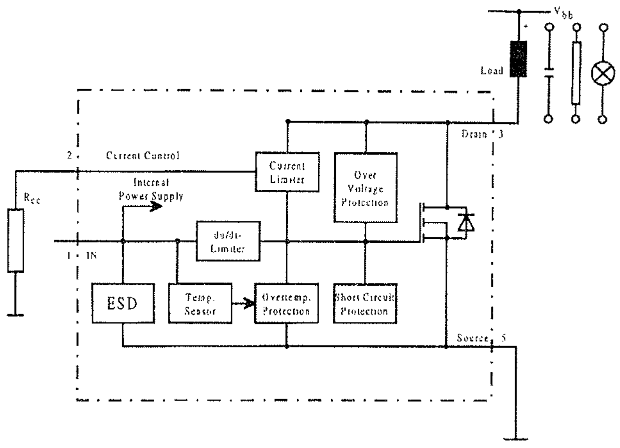

Fig. 16: Block diagram of a HITFET®

„Silicon substitutes heatsink" expresses the advantage for the system designer: spending some more silicon area for the output driver leads to lower Ron and to lower power loss inside the chip; intelligent protective functions turn the device off in critical conditions and such designs became possible, where additional heat sinks are not needed any more, which saves a lot of printed circuit board space and therefore cost for the customer /2/. Fig. 17 is a schematic representation of these innovations, fig. 18 shows a microphotograph of an advanced switch of the PROFET® family.

Integrated sensors also are of key importance for dedicated systems for automotive applications. Hall effect sensors, which can be designed in smart power processes very effectively, gain increasing significance for the picking up of movement, rotation and position. These components do not wear out, deliver an easy to process digital signal are very reliable and can be produced at moderate costs today.

For sensing position hall switches, as e.g. SILC® family is used. Fig. 19 shows as block diagram. In this design, the output switches depending on the absolute value of the magnetic field. The thresholds are generated internally and contain a hysteresis to avoid signal bouncing /4/.

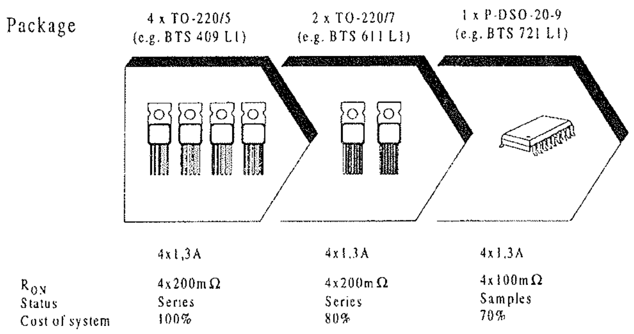

Fig. 17: Innovation with PROFET®-highside switches

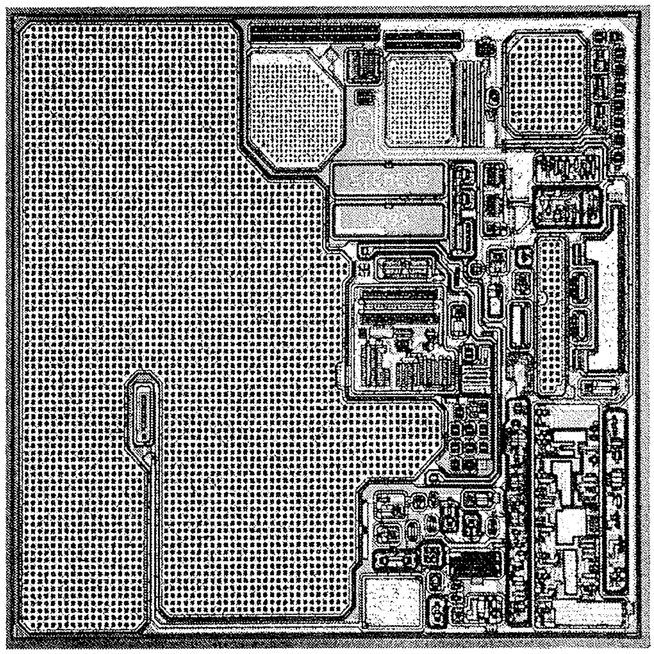

Fig. 18: Microphotograph of a PROFET® highside switch

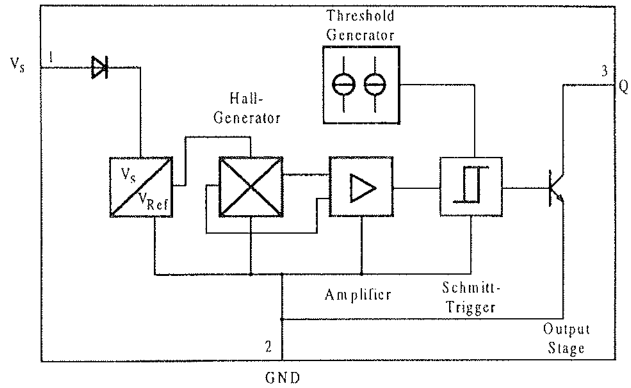

Fig. 19: Block diagram of a SILC®-hall device

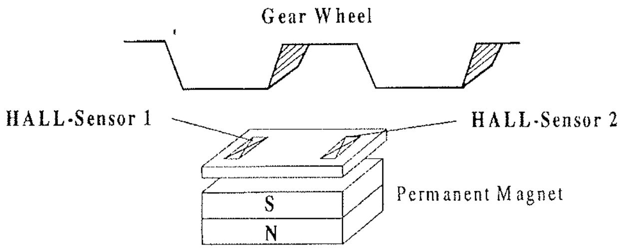

Fig. 20: Functional principle of differential hall IC

To record speed, especially the rotational speed of wheels, differential hall designs are well suited, they are often called gear wheel sensors. Two integrated hall elements are implemented on the chip at a distance of approximately 2.5 mm (fig. 20,21).

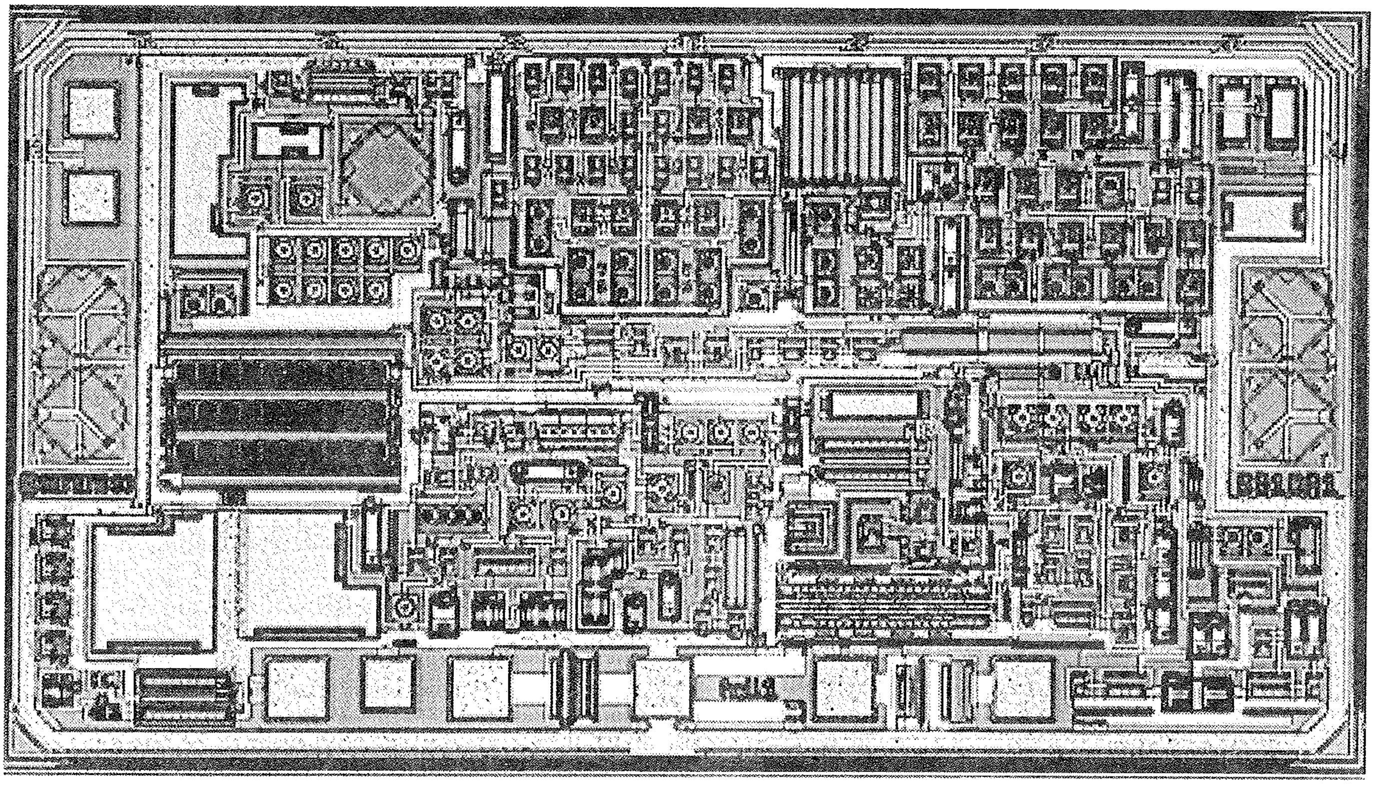

Fig. 21: Microphotograph of the TLE 4921-U3 differential hall sensor chip

Using this approach differences in magnetic field as low as a few mT (milli-Tesla) can be detected. The principle is not sensitive against vibrations on the wheel and generates a very reliable output signal. To give an example the TLE 4921-3U shall be mentioned. The device features very stable thresholds over an extended operating range -50 °C up to +200 °C and is hardened against disturbing pulses in the sense of DIN 40839 standard /5/. It is currently used e.g. in BMW cars of the 7-series /6/.

Many smart power functions, initially developed for automotive applications, are as used in industrial electronic applications (intelligent switches, driving circuits for stepper motors, etc.).

5. SYSTEM INTEGRATION

System integration means the combination of all necessary functions of a dedicated electronic unit as e.g. anti-lock braking system, airbag systems or motor management on as few chips of silicon as possible. In the field of industrial electronics or in peripheral devices for electronic data processing as printers or disk drives similar approaches are needed. System integration leads to a systematic miniaturisation of the systems but needs the combination of many different functions as power control, analog and digital functions up to controllers and memory on a single piece of silicon. In many cases a higher integration level leads to reduction in cost, but this has to be investigated in more detail looking on all the requirements as:

- Implementation of many different functions
- Voltage generation and stabilisation within the system
- Blocking voltage up to 80 V
- Low impedance driving stages at several pins

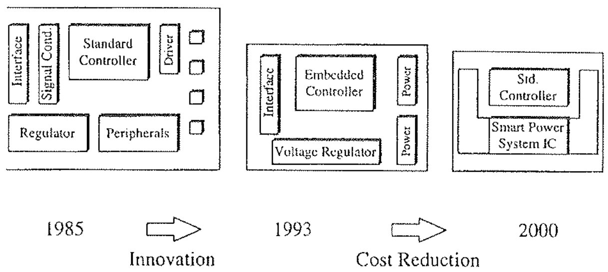

Fig. 22: History of system integration for automotive applications

	Smart Power Technologies	µC-Technologies
Blocking Voltage	30 V - 75 V	5 V --> 3 V
No. of masks	approx. 18	approx.. 15 (18 with NVM)
NVM (non volatile memory)	no	yes (E²PROM, flash)
Feature size	2 µm --> 1 µm	0,8 µm --> 0,5 µm
Analog circuits	yes (BICMOS)	no (only ADC)
DMOS (power)	yes	no

Fig. 23: Comparison of different technologies

- Several pins for signal I/O and some power pins for high current

Fig. 22 shows an overview of system solutions, how they where are and will be approached in the future. At the beginning several low level integration chips and discretes had to be combined into a system, the solutions with so called embedded controllers have been designed.

But nowadays due to the high costs of complete systems many applications use a cheap standard controller and one or a few smart power parts, which comprise all the rest of the system. The smart power system of today typically contains the following building blocks, the available technologies are matched to these tasks and differ significantly from advanced CMOS technologies as used for cost optimised controllers (fig. 23):

- Power supply/regulation for the whole system
- Power output drivers for actuators
- Analog circuits for supervision and diagnosis
- Interface circuits for analog/digital parts

Fig. 24 shows an example of a smart power system IC for automotive applications and its respective functional blocks. The IC is built in the SPT75 technology and contains approx. 5.000 devices.

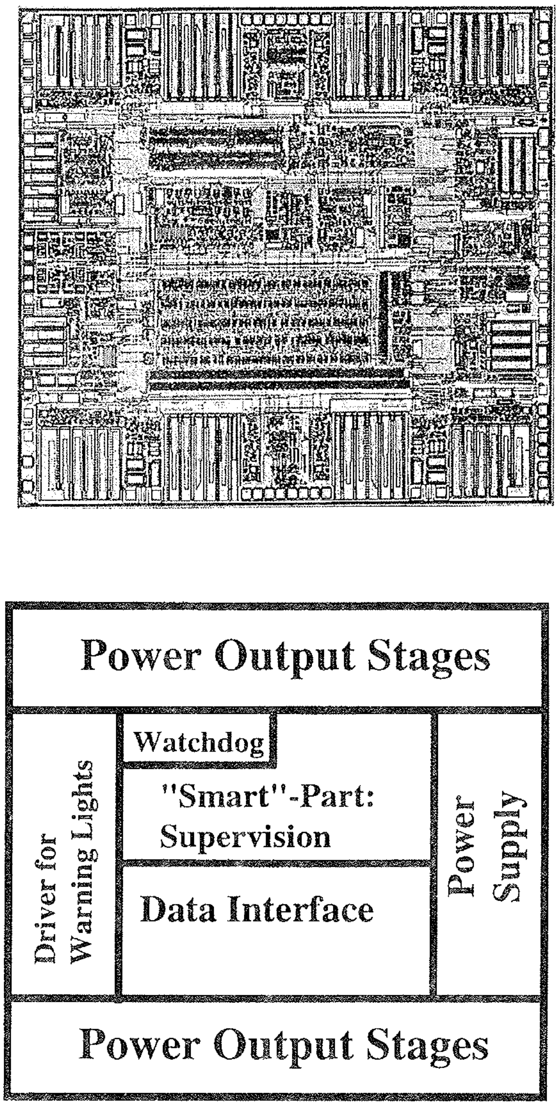

Fig. 24: Microphotograph of a smart power system IC and its respective building blocks

6. SUMMARY AND DISCUSSION

Smart power technologies are the key to further development of dedicated systems, as e.g. anti-lock braking, airbag or motor management in automotive applications, but also for systems structured in a similar way in the industrial, telecommunication and electronic data processing fields. The chips that are now available supply and regulate the power, trigger actuators and monitor and diagnose systems to recognise irrgeular or even dangerous conditions. Smart power ICs make it possible to develope systems with higher reliability, lower volume and weight, less power dissipation which are last but not least even cheaper than their predecessors.

The future evolution of smart power technologies has to be closely related to the system designers benefit. Reduced feature size, innovative circuit design and packaging concepts as space saving SMD-packages lead to ever more advanced and complex smart power circuits and to strongly increased demand for them. The rough environmental conditions, the safety relevant operation together with an extreme cost pressure will force partnerships between silicon supplier and user. In this way concurrent engineering and joint qualification procedures will enable the best possible solutions for both partners. A continuous cost reduction program will be necessary to foster the migration of microelectronics even in the middle and lower price ranges of automobiles.

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