State of the art and trends in power integration

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Keywords: Power electronic, power integrated devices, functional integration, hybrid integration.

Abstract:

A review of some approaches currently used to integrate power electronic functions is presented. In the field of power electronic, semiconductor devices are used in energy control and conversion circuits. The power function (switching or protection) is achieved through use of data and signal processing circuits separated from the discrete power device. The evolution naturally involves the integration of whole or part of low voltage elements with the power device in order to obtain a power integrated function. However, the electrical problems involved differ from those encountered in signal processing integrated devices. Indeed, it has to take into account high levels of current and voltage, dV/dt and di/dt, thermal effects... Thus an overview of the different modes of integration required according to the power level needed by the application is presented. For these different modes we describe, the structure, design and technology.

In the last section of this paper we detail some of the trends in power integration. In low power area there exists a growing need to reduce the size of switching converters in portable equipment (note-book type personal computer, cellular phones) or for microsystem power supply. So, a second step in power integration consists in integrating passive elements as capacitors and inductors with semiconductor devices. For higher power applications, a new hybrid technology must be developed to integrate reactive components into fully integrated converters.

INTRODUCTION

Power devices used in many electric and electronic applications are strategically important. Over the last two decades the technology of power semiconductors has made impresive progress. Until the second half of the seventies, improvements in power devices (diodes, thyristors, bipolar transistors) allowed the increase of power by a surface unit. In parallel, the development of IC's was characterised by an increase in the number of transistors by surface unit (Fig 1). The most decisive step in the development of a new generation of power devices was the introduction of power MOSFET [1]. The development of these new devices provided a direct link between integrated circuits and power devices. This evolution has led to power device development in terms of structure, design, size reduction, and manufacturing [2]. The design rules reduction in power MOSFET (VDMOS devices) over the last 15 years have also allowed a reduction (i) in the ON-resistance by a factor of 10 and (ii) in power dissipation. For the first time size reduction in power devices has led to enhanced electrical preformance as shown in Figure 1. Another important step over the last ten years has been the development of IGBT [2], combining the advantages of MOS transistors, such as low power drives, with the advantages of bipolar devices, such as low forward voltage drop. Improvements in these new power devices, MOS and IGBT, are linked to MOS technology and size reduction using the background of integrated circuit technology. These devices are produced in the same production facilities which were used for integrated circuits. The introduction of MOS technology in power electronics paved the way for power integration as the technology of power devices and integrated circuits has become compatible.

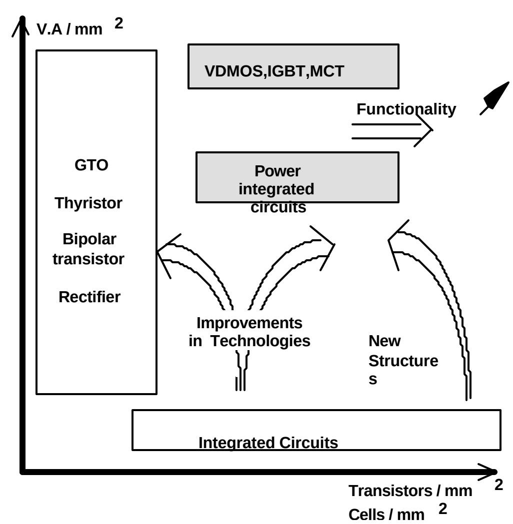


Figure 1: Evolution of Ics and Power Devices.

According to the different fields of application and the required performance, different modes of integration have been developed over the last ten years. A distinction must be made between monolithitic and hybrid integration. The different developments have clearly shown that the lower power range (I<10 A, U<600 V) can be implemented using monolithic integration of power semiconductor components and integrated circuits. The power range 30 A<I<100 A and 600 V<U<1200 V can be implemented in hybrid system integration. However, suitable modes of functional integration can also be the solution to specific applications. Higher power requirements I>100 A, V>1200 V can be implemented using standard modules. So, we will give an overview of the different modes of integration and will present the state of the art and current trends in structure, design, and technology.

I MONOLITHIC INTEGRATION

I.1- Power integrated cicuits.

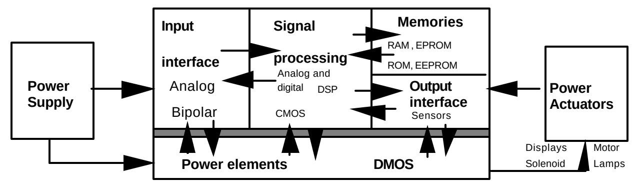
I.1.1- State of the art and applications.

For applications without high galvanic insulation and for low current and voltage levels, monolithic integration can be viewed as a design and technology continuation of conventional signal Ics. This type of integration includes power elements and signal processing circuits in the same crystal. In this new family of power semiconductors, all drive and protection functions are integrated on one chip with system and diagnostic functions. One of the main features of these devices relates to the isolation techniques used between the power part and the IC part.

In the past, two different families of power technologies have been distinguished [3,4,5,6]: « Smart Power » and « High Voltage Integrated Circuits » (HVIC) which essentially differ from the power device:

i) in the former, the power device was vertical, generally a double diffused MOS transistor,
ii) in the latter, VLSI circuit is improved by output buffers that consist of low current integrated power devices with coplanar electrodes like high voltage lateral MOS power devices (LDMOS).

In the first generation of « smart power » devices, the logic and analog parts making up the control circuits feature a low integration density [7]. They have been elaborated by a technological process used for power devices. These could be viewed as power devices to which an analog and digital capability has been added. The new generation (Smartmos 5, BCD5, SIPMOS, ...) is more accurately described as VLSI technology with added power capability. This technology allows very complex digital cicuits to be integrated as digital Signal Processor (DSP) and microcontrollers. While in earlier smart power devices, the die area was dominated by the power device, this increase in logic complexity leads the logic blocks the higher users of silicon area. Today for this Power Integrated Circuits the aim is to integrate an increasing number of functions with the power device; this on-going trend leads to new fabrication processes with reduced design rules and greater chip complexity. Figure 2 shows a block diagram of this kind of Power Integrated Circuits known as « New Smart Power ».



New smart power » device [8].

Among these new power integrated devices, three parts are worth distinguishing: the input interface, the control and processing circuits, and the power elements. In the input interface part the most relevant circuitry is analog and generally designed using bipolar devices. However it can be replaced by efficient CMOS or BICMOS functions.

The control and processing part corresponds to a logic circuit achieved with CMOS with respect to its low power consumption and high density integration. This part contains microprocessor, and digital signal processors (DSP). The power device is generally a lateral (LDMOS) or vertical (VDMOS) DMOS structure.

In order to add flexibility and improve the system, memories are now used for different purposes. Memories up to a few megabits are generally used to store microprocessor software and data [8].

In this kind of devices BCD technologies using bipolar, CMOS, and DMOS processes (BCD, Smartmos,..) remain the most flexible ones in terms of the various circuit topologies and allow use of MOS and bipolar structures up to 250 V (Figure 3) [8,9].

Isolation between the power part and the low voltage part is achieved by junction isolation techniques or dielectric isolation. The conventional dielectric isolation with polysilicon deposited as a substrate layer is very expensive. Over the last years a cheaper solution based on bonded Si-SiO_2/SI wafers has been developed [10,11,12]. However, a development of this kind of isolation is linked to cost reduction. Thus, isolation by means of a junction remains the preferred solution for standards applications, the dielectric isolation being only used for specific applications requiring a high level of isolation.

A new generation of devices designed for specific applications is the monolithic structure of high voltage bridge circuits for motor control [13] with a 600 volts range using lateral IGBT (I=1A) at the power output. A dielectric isolation is often used to implement the different LIGBT required for the three phase bridge circuits [14].

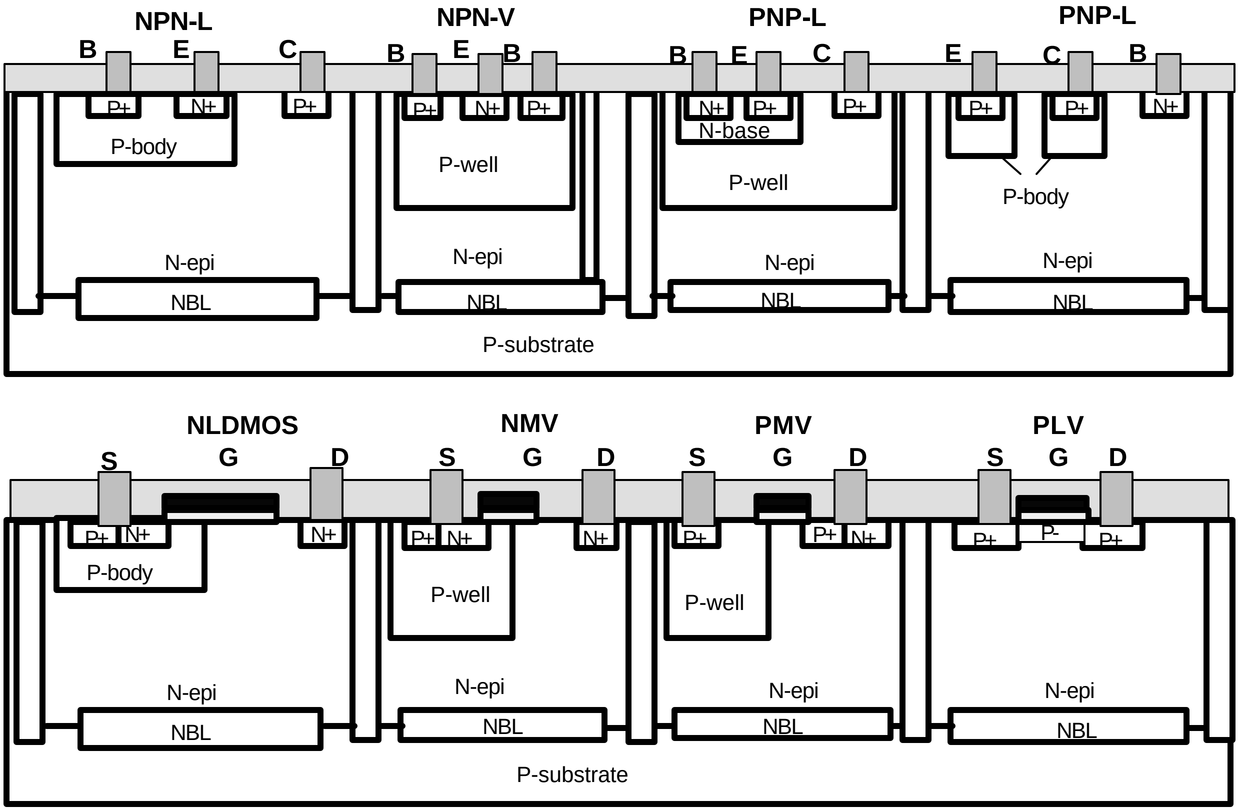


Figure 3: Schematic cross-sections of some important bipolar and MOS devices in power integrated devices mixing MOS and bipolar devices [8,9].

The major fields of application of these power integrated circuits are portable equipment, domestic appliance, ligthning, and the automotive industry. In these different areas, the motor control is an important niche. The development of these integrated circuits has been essentially driven by the automotive electronic requirement for applications such as motor control, fuel injectors drivers... The choice of a power structure, the level of integration and the isolation technique are based on the type of application and, therefore, on the power range desired. However, the best performance of the power component is considered (R_{ON}-V_{DBR} trade off) as well as the highest level of integration of the detection, control, and protection elements.

I.1.2 Trends in design and technology

Smart Power devices have been always used design rules and technology which are less efficient than ULSI and VLSI devices. In the early eighties the first smart power devices were fabricated with 2.5 or 4 µm design rules while ULSI used 1 µm design rules. After when ULSI devices used submicronic design rules Smart Power devices were fabricated with 1.5 or 2 µm design rules. This difference was essentially linked (i) to the more complex fabrication that must be taken into account: isolation, edge terminations for power devices, combination of different kinds of devices, CMOS, DMOS, bipolar, and (ii) to the important development of VLSI and ULSI devices driven by an important market. The technology developed for ULSI and VLSI circuits has always been used a few years later for Smart Power devices [15].

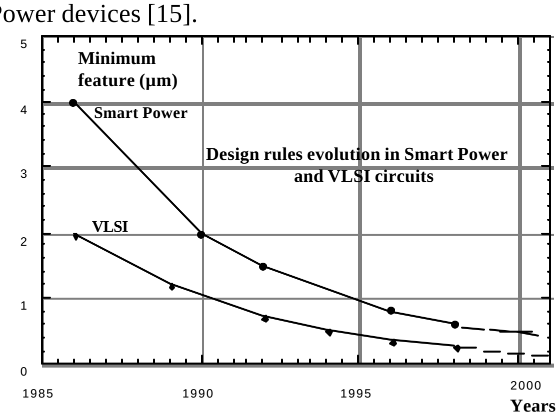


Figure 4: Evolution of minimum features in Ics and in Smart Power devices.

Today Smart Power devices used 0.6 µm or 0.8 µm design rules and the state of the art for ULSI or VLSI is 0.35 µm with five metal layers for interconnection purposes. This gives an indication about the future in power integrated circuits. This uninterrupted drive toward greater integration leads to single chip system for low power applications. Thus, many low power subsystems or systems can be produced on a single chip. By reducing the number of interconnections in chips, assembly costs are also lowered and the system becomes more reliable.

In order to minimize design time, libraries for logic and analog blocks can be used. However, improvement essentially concerns the power device. Indeed, improvements in power devices (RON-VDBR) have been limited ever since the introduction of the 1.4 µm technology. So, new structures are needed to enhance performance (VDMOS with superjunctions [16], LUDMOS [17]). The figure 5 shows a schematic cross-section of a new lateral DMOS structure allowing to reduce the ON resistance. The know-how of the designers of power devices will allow to develop this kind of new structures. They will helped in this task by specific 2D simulation tools (PISCES, MEDICI, ISE) .

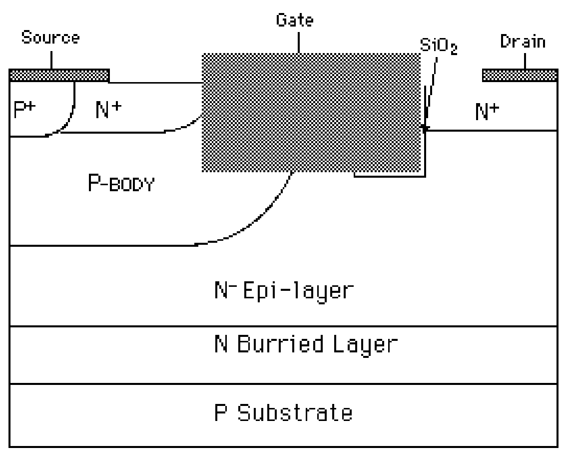


Figure 5: Schematic cross-section of a new LUDMOS device [17].

During this Smart Power evolution towards the reduction of the minimum lithography, many problems are solved both by design and by a technology approach in spite of the conflicting demands of VLSI and power function. However, numerous problems will have to be solved and designers will rely on 2D general purpose simulations tools or dedicated programs. The former deals with the energy capability of DMOS devices. The capability to sustain energy is not progressing in the same way as the R_{ON} performance. Energy density increases when the device scales down. Generally the failure causing a drain source short circuit is due to a thermal condition. So, electrothermal simulation tools have been developed. This approach has been used to study the impact of the metallization thickness of power integrated circuits on their energy capability and most generally can be used to design power integrated devices in accordance with the thermal aspect [8,18].

A second problem regards the induced parasitic effects with junction isolation solution, by over voltage supply in power stage when they drive inductive load (typically when power transistors are used in the bridge configuration for motor driving). In this configuration the activation of parasitic bipolar results in the injection of hole current into the substrate. Such current causes the substrate potential to rise and to forward bias the low voltage N region containing low voltage circuits. New designs will have to be put forward in order to suppress these failures [8]. 2D simulation tools (PISCES, MEDICI, ISE) are particularly well-suited to help the designer in this task.

I.2 Intelligent discrete power device

I.2.1 State of the art and applications

As seen above, today's power integrated circuits increasingly rely on an integrated logic, analog functions, and are based on lateral power devices. These lateral power devices have a lower power current capability than vertical devices. Therefore for higher power applications, (higher current and higher voltage), vertical power discrete devices have to be developed with diagnostic and protection functions.

Polysilicon is used in MOS technologies for Power device fabrication (VDMOS or IGBT). Hence layers of polysilicon can be employed to produce active devices as well. These devices can be integrated on the top surface of power semiconductor insulated by the thermal field oxide. In the self-aligned process N+ and P+ implantations are performed after polysilicon deposition and simple devices (e. g. resistors, diodes diodes zener) can be created [19,20,21]. Also 600V/10 A clamped IGBT has been developed for automotive ignition system [22]. Thus 600 V, up to 50 A IGBT with monolothic over-voltage and over-current protection circuit can be developed (Fig. 6). In this kind of integration, the fabrication process remains basically unchanged as the standard IGBT process, only two or three additional photo masks allow integration of protection functions and the most important surface area is dedicated to the power device.

I.2.2 Trends in design and technology

More complex devices can be fabricated, if two levels of polysilicon are used. A first layer is used as substrate insulated from the power device and the second is deposited as gate material after oxidation of the first layer. Implantations of N and P region allow source and drain of the poly TFTs (Thin Film Transistors) (Fig. 6). Various active devices (diodes, n-

MOSFETs, p-MOSFETs), sensors, analog and elementary logic circuit (CMOS) can be fabricated and insulated from the power device [23]. So far these TFTs give limited performance compared to single cristal silicon device, but further development of their technology makes an application to simple integrated circuits possible and advantageous. This can be an inexpensive way to add protection functions for discrete high power devices like IGBT or MOS gated thyristors.

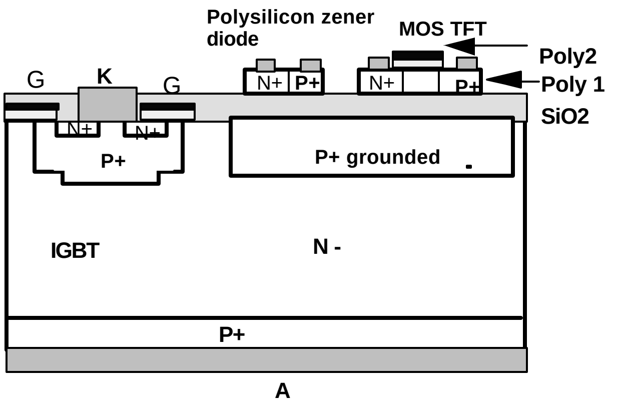


Figure 6: Schematic cross-section of discrete power device integrating protection functions [23].

I.3 Functional integration
I.3.1 State of the art and applications

In the industrial sector (static supply, variable speed, ...) and more generally in the public at large (household appliances, small electric equipment, heating ...), numerous power conversion and protection applications connected to the electrical supply network can benefit from the advantages brought about by integration.

This is more particularly true for functions based on diode or thyristor devices like protection and current or voltage bidirectional functions. The electrical performance required for this kind of applications sets the integration mode. In actual fact, the range of voltage required (in excess of 600 V) leads to a vertical design of power devices. Furthermore, with respect to the current levels required (from several amps to tens of amps), the power device uses the greater part of the integrated device area. So, the active area of this power device becomes larger than signal processing circuits. To cut down on fabrication costs, the basic structure and technology used to obtain the integrated function have to be that of the power device and additional elements can be integrated by adding a minimum number of technological steps. This type of integration ideally suits the capabilities of the « Functional Integration » concept already used in the field of power devices and seems particularly well-suited for this kind of application linked to the electrical supply network. Indeed, the very first semiconductor structures dedicated to power, i.e, thyristor and triac, correspond to this mode of integration. The function results from the interactions between semiconductor layers judiciously arranged and sized and not from the interconnection of separate devices. The application of M.O.S technologies to power devices led to a new dimension of this concept by offering an additional degree of freedom provided by M.O.S effect at the top surface that can be combined with the bipolar interactions occurring in the semiconductor volume. Since then, new families of power structures have been developed, combining the high current capability of bipolar devices with the simple drive capability of the M.O.S transistors: IGBT (Insulated Gate Bipolar Transistor) and MCT (M.O.S Controlled Thyristor) [24], these being the most representative examples. At present, the concept of functional integration can be utilized, on the one hand, to achieve new switching functions monolithically integrating the power device with the protection, amplification and validation of the control [25,26] and, on the other, to create new devices suitable for particular applications like the protection of electronic equipement [27].

For example, Figure 7 shows a programmable lightning protector for a subscriber line interface circuit designed and fabricated by ST-Microelectronics. This device integrates a bipolar transistor, a thyristor and a diode [27]. Physical and geometrical parameters of this kind of integrated device, called ASD (for Application Specific Discrete), are optimized for specific applications. There also exist examples of integrated power switches associating MOS and bipolar effects [25].

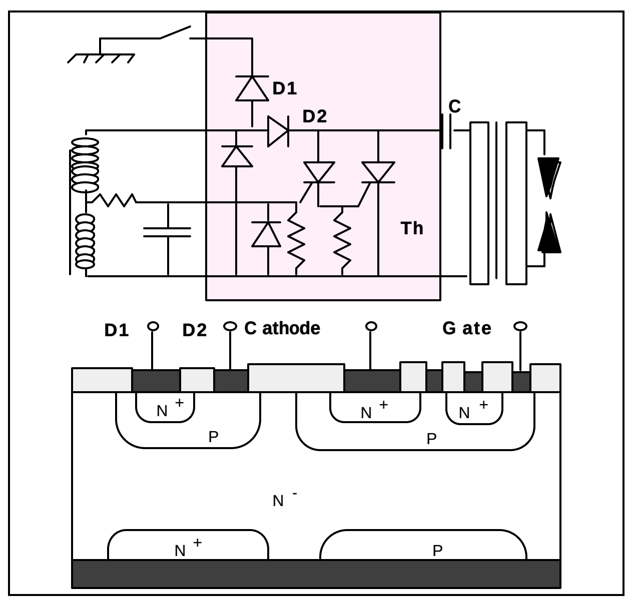


Figure 7: Programmable lightning protector for a subscriber line interface circuit by STM.
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By way of example, a new power structure entirely based on the concept of functional integration and providing a circuit breaker-type protection is presented in figure 8 and 9. In the equivalent electric circuit of this function where one can distinguish the different basic functions, the main power device consists of a serial self-triggered thyristor with a low voltage current limiting function which provides for current limitation [28]. Figure 9 shows a cross-sectional view of the equivalent integrated device where the basic elements can be seen. Design of these elements is based upon the different integration solutions presented above. In this example, design relies on the association of several interconnected elementary cells.

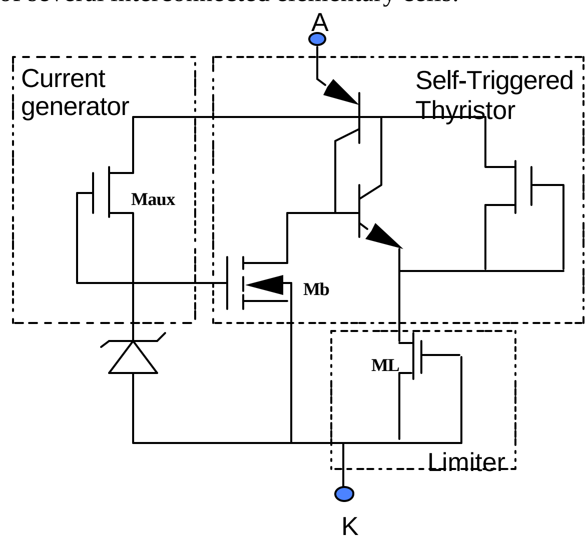

Figure 8: Equivalent electric circuit of the breaker-type protection function.

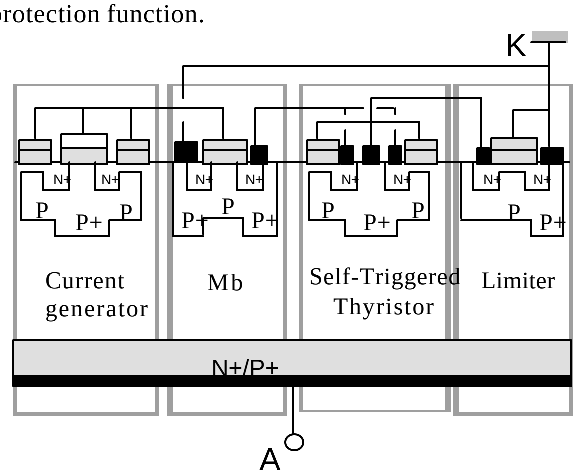

Figure 9: Cross sectional view of the integrated device.

I.3.2 Trends in functional integration

As in the past for the ICs of signal and information processing, it is essential to develop new CAD tools for this field of integrated power devices. Thus, a new interactive design environment based on basic elements has to be created whose philosophy bears much in common with that implemented over the last years for ASICs. However, this approach is different because the functionality and the electric characteristics of a device depend on surface topology (as in the case of ICs), but also on the physical and geometrical characteristics of semiconducting layers and on their layout.

When considering the greater part of the new devices based on the functional integration concept, their design appears to be derived from a generic method. Thus, it is essential to identify the basic elements for the semiconducting architectures and to associate an analytical model based on physics and on an equivalent electric circuit representation. The models suited to this type of design will have to take into account the specificities associated with the mode of functional integration (interactions between the basic elements, etc,...) [28]. This approach will enable the study the influence of the physical and geometrical parameters of a structure on electric characteristics and the rapid design of structures prior to their optimization with the use of 2D software.

In the long run, model libraries that form an integral part of design modules will help the designer in carrying out phases between the functional description of the specifications and the integrated device. In the longer term, this approach will result in the development of synthesis tools allowing the architecture corresponding to the functionality desired to be built on silicon.

The functionality and electric characteristics of these devices depend on the geometry of the different connections at the surface as well as on the characteristics of the vertical structure such as the type, succession and physical parameters of the layers. At this stage, two devices exhibiting distinctive functionalities in terms of technological process (annealing temperature, doses and implantation energy...) and mask geometry, can be considered. This approach is different from that of families of ICs which relies on the same technological processes and only differs in the mask patterns. So, new MOS/bipolar flexible technological processes based on optimized steps will have to be developed to achieve new specific functions [28].

I.4 Integration of passive elements
I.4.1 State of the art and applications

The weight and size reduction of portable equipement such as cellular phones, microcomputers, microrecorders requires an enhanced micro power source with a low voltage consumption. This increasingly important strategic niche has boosted research for the development of a chip converter consisting of semiconductors and passive components such as inductors, capacitors in order to minimize the number of components and interconnections for smaller, lighter and cheaper products. Numerous filtering applications also exist which require R,L networks whose integration would lead to a reduction in the electrical equipment size while increasing reliability.

An additional application area is that of integrated microactuators that requires an integrated supply voltage [29].

In recent years, new micromachining techniques have revolutionized the conventionally mode of microstructure fabrication. These micromachining techniques provide interesting approaches to the integration of inductors on silicon. Magnetic cores and conductors up to hundred microns in thickness and with a controlled width can be easily fabricated with low temperature process fabrication. These technologies essentially require, on the one hand, a high aspect ratio lithography (thickness/resolution) using thick resist films (50 to 100 µm) [30] to provide matrix with excellent dimensional control and vertical sidewalls, and on the other electroplating of nickel/iron (Ni 81%/Fe 19%) for the magnetic core and electroplating of metal for the conductor [31,32]. Different photoresists needed for the matrix and various materials required for the magnetic core have been investigated with a view to their application in microsystems. These could be considered for the fabrication of integrated coils in silicon. Generally low temperature process fabrication can be compatible with active semiconductor components; microelectronic fabrication techniques have been used to fabricate bar-type inductor switch high current capability [32]. Integrated inductances of 35 nH/mm^2 at 1 Mhz have been achieved. The fabrication sequence of these inductors must be entirely compatible with post processing of standard CMOS circuit. Integrated DC-DC microconverters with an ouput power of approximativelly 1 or 2 W will be fabricated [33, 34, 35].

I.4 Trends in integration of passive elements

Voltage supply in integrated circuit has been decreasing for several years. In the future DC-DC converters will have to integrate close by the integrated circuit. The feasibility of an integrated switched DC/DC converter using micromachined inductive component integrated on silicon has been demonstrated. As the inductor can potentially be integrated onto a chip, complete DC/DC converter integration can be envisaged [32,35]. New investigations on magnetic materials and their associated processes compatible with semiconductor device fabrication will allow to improve electrical characteristics of low power voltage microconverters by a few watts (microconverters).

II HYBRID INTEGRATION

High power applications have been implemented using hybrid integration. It will be shown that hybrid integration covers a large range of power electronics and we will distinguish the IPM (intelligent power modules) or ASIPM (application specific intelligent power modules) for voltage rating up to 600V from a current rating from 4 A up to 30 A, and the standard modules for current range greater than 100 A and voltage >1200 V [36,37].

II.1 Intelligent Power Modules IPM

The use of inverters in motor drive and servo applications has been increasing in recent years. These solutions allow power transistors (generally IGBT) to be integrated with the drive circuits and protection functions as well as with the power supply in the single package. So IPMs are becoming the most obvious choice for inverters because of their many attractive advantages.

ASIMP IGBT gate drive and protective functions are provided by power integrated circuits [38]. With the help of the level shifter included in the HVIC, ASIPM's provide its user with the advantage of opto-coupler-less control interface. The DC isolation of the gate signals allows the module to be directly driven from microcontroller. Power part contains IGBT and soft recovery free-wheeling diode. These IPM's are only a step away from system integration. However the temperature limitations of these modules (including the power device with Ics and Power Integrated Circuits in the same package) tend to limit their use in medium power applications.

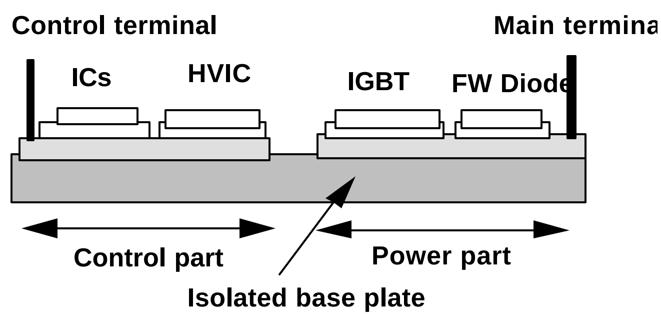

Figure 10: Schematic of ASIPM assembly.

II.2 Standards Power Modules

Higher power requirements (100 A< I > 2000 A) and (V < 3.5 kV) can be implemented with standard power modules using conventional system design [36,39] (Fig. 11). Integration is restricted to parallel IGBT dies to increase current rating and free-wheeling diodes. These modules use clasical assembly technologies; solder mount on the backside of the die and ultrasonic bonding of aluminium wires for the top side contacts. These modules are limited in terms of reliability, thermal performance and voltage performance (blocking voltage and insulation voltage of the overall module) [36,40]. As an exemple of the reliability requirement in railway traction applications these modules will have to ensure about 10 million power cycles during their life time. Much of the thermal fatigue is due to the stress on the solder resulting from the use of different materials which expand and contract at different rates during the thermal cycle. The cathode and gate connection wires which are bonded to the aluminium metallization on the top side of the IGBT are particularly vulnerable to thermal cycling. However technology development; alternative materials, and the thermal design of these modules have already allowed improvements in reliability and an increase in the power range.

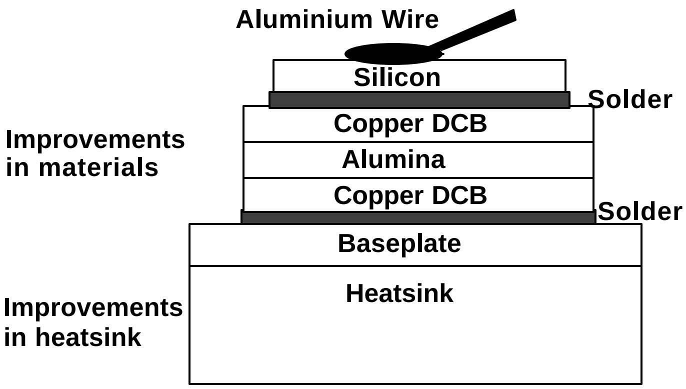

Figure 11: Schematic of conventional module assembly.

II.3 Trends in hybrid integration.

Innnovative package design using new materials, new deposition technology, and powerful design tools, can enhance the thermal capabilities and reliability of high power modules. Improvements in high voltage IGBTs, with a new structure design such as trench IGBTs can also give improvements in electrical characteristics. However, because of the quasi homogeneous electrical performance of the semiconductor part, the packaging will be the key to reliability, performance and system added value [40,41]. Further improvements will be achieved by sectored base plates, which allow an even better attachment of the base plate to heatsink: new materials like AlSiC will improve this interface while eliminating solder fatigue at the substrate to base plate boundary. In integrating the base plate can give considerable improvements to the thermal resistance, so further improvements are possible by associating the use of new materials with the heatsink design. Pressure contact assembly is also one solution to enhance reliability for higher power range.

In many applications, like the production of converters delivering several kilowatts, the integration of electromagetic component is a fundamental requirement to reduce size and weight. This leads to a hybrid technology where power semiconductor devices are integrated on a planar substrate with other planar components including integrated LC structure [42]. This planar technology is well-suited to high volume, and lower production costs. Then, suitable materials and manufacturing for conducting, dielectric and magnetic layers are required. In this perspective new developments regarding new technological processes should lead to a collective type of production (as in microelectronic) so as to cut down costs and propose optimized solutions at the electrical, magnetic and thermal level.

III CONCLUSION AND GENERAL TRENDS IN POWER ELECTRONIC INTEGRATION

From a general point of view, the current trend in power electronics points to an increasingly complex systems integration [37]. The first attempts aimed at integrating the main element, the power component, with amplification, drive and protection functions. This has first been achivied monolithically and then in a hybrid mode. In both cases, the evolution was based on the integration of a greater part of the power system. Maximum complexity has been reached for new smart power circuit families integrating monolithically protection circuits, microprocessors and memories. At this stage, the standardization efforts made between the various technologies (ie, that of IC's and that of the power MOS structure) and the reduction in size have contributed to tacking up the challenge of fully integrated power functions like low power motor controls (less than 1 kW) which can now be envisaged. For high power applications discrete devices (particularly IGBT which is the most efficient in this voltage range) are provided with monolithically integrated close-protection elements.

Functional integration is equally a monolithic integration mode which allows for an extensive use of the judicious interactions between semiconducting layers and MOS sections to create new switching or protections functions that can be directly used for applications on the industrial or household electric network. For this range of power applications ($I<50$ A, $V> 600$ V) hybrid IPM or ASIPM solutions also permit the integration of relatively complete systems or functions (inverters, motor control). For higher power, Standart Power Modules essentially consists of parallel-connected IGBT chips designed to increase the function nominal current. These IGBT's are usually associated with diodes and integration cannot go any further.

A new trend concerns the integration of passive elements for low power applications in the order of a few watts, monolithic solutions are based on technologies that were developed for microsystems fabrication. In this case, integration is heterogeneous since magnetic materials are deposited on silicon. For a higher power use a heterogeneous approach must also be considered but a ceramic (and no longer silicon) support is needed with a higher inductance or capacitance.

Integration in power electonics must evolve towards systems integration with technological solutions that are suited to the power range considered [37]. However, these technologies will not compete against each other but will be seen as complementary or even essential for each other. Indeed, in the coming years, monolithic integration of the complete systems will be reserved for low power applications even if the frontier tends to shift towards higher values. For the highest power values, integration will rely on several chips and at this level, the complete system will include circuits based on new generations of Smart Power, Discrete Intelligent Power devices, new functions derived from the concept of Functional Integration or even integrated microconverters for the supply of low voltage circuits and even passive elements obtained from planar technology.

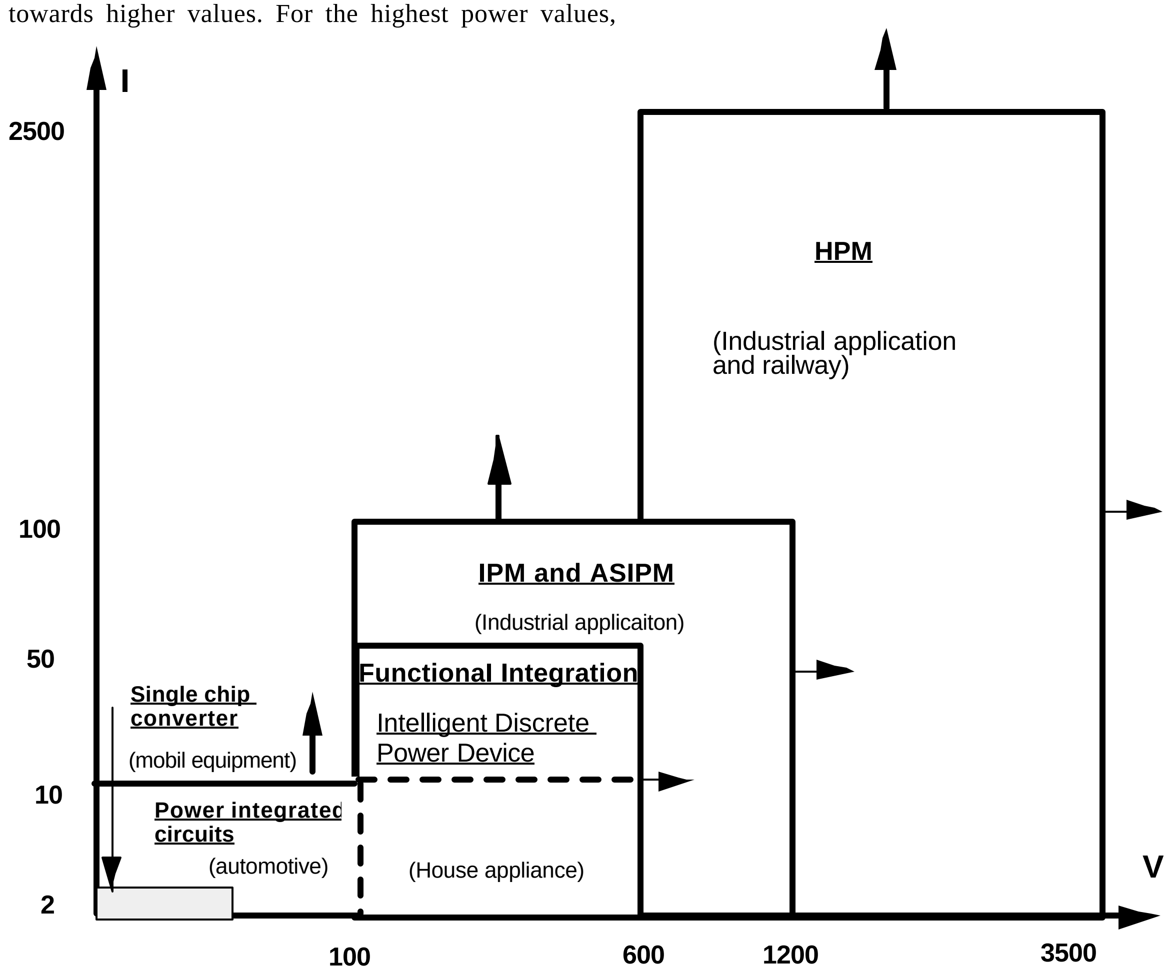

Figure 12: Application areas of the different integration modes.

This complete power systems integration will be monolithic or hybrid according to the power range desired, but must of the time heterogeneous. Technological improvements are, therefore, needed with respect to new dielectric and/or magnetic materials and to technological process fabrication and assembly. Development is also required in terms of design tools for these sophisticated systems which will have to take into account the electric and thermal aspects [18].

Acknowledgment

The author has to thank his colleagues: Ph. Leturcq, P. Rossel, P. Austin, J-P Laur, J. Jalade for the many fruitful discussions.

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