

9.2 Low Power Applications to Integrated Micro-System Design

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9.2.1 Abstract

Microelectronics opens new perspectives by the full integration of complete systems: including sensors, actuators, digital and analog signal processing, control and wireless communication. Compactness and ease of use require portability and battery operation. This chapter describes considerations of power usage in integrated systems design, with special emphasis on the power availability in batteries and the power usage in system components not dealt with in previous chapters of this book.

9.2.2 Introduction

The microelectronics VLSI technology [14] is in a steady evolution [2, 18]. This results in ever increasing system complexities that can be integrated on a single silicon chip. This is well illustrated with the evolution in complexities in RAM's and state-of-the-art microprocessors [30]. Every 1.5 year the amount of transistors that can be put on a chip doubles. By the year 2000, state of the art microprocessors will have 100,000,000 transistors on a die. This evolution is still expected and planned for the next decades [2, 18].

This trend gives rise to a wide spread usage of microelectronics e.g. in personal computers [30] as well as in novel applications that were previously impossible: digital mobile telephones, personal digital assistants (PDA's), multimedia, digital video decompression and compression etc., high speed communication, ATM... The progress has been the most extreme with digital circuits.

CAD tools for the design of complex digital systems are mature and ease the management of high complexity design. Novel aspects required by multiple interconnect layers and deep-submicron effects are being added to the functionalities. Currently there is also a large evolution in the supply of new CAD support for the power efficient design, estimation, verification and synthesis of digital systems [11].

Many applications however require the interaction of electronic circuits with a physical world or human beings. These are characterized by continuous physical quantities that have to be dealt with. Examples of such physical signals are: pressure (microphone), force, optics, chemical properties, electric and magnetic fields, temperature.

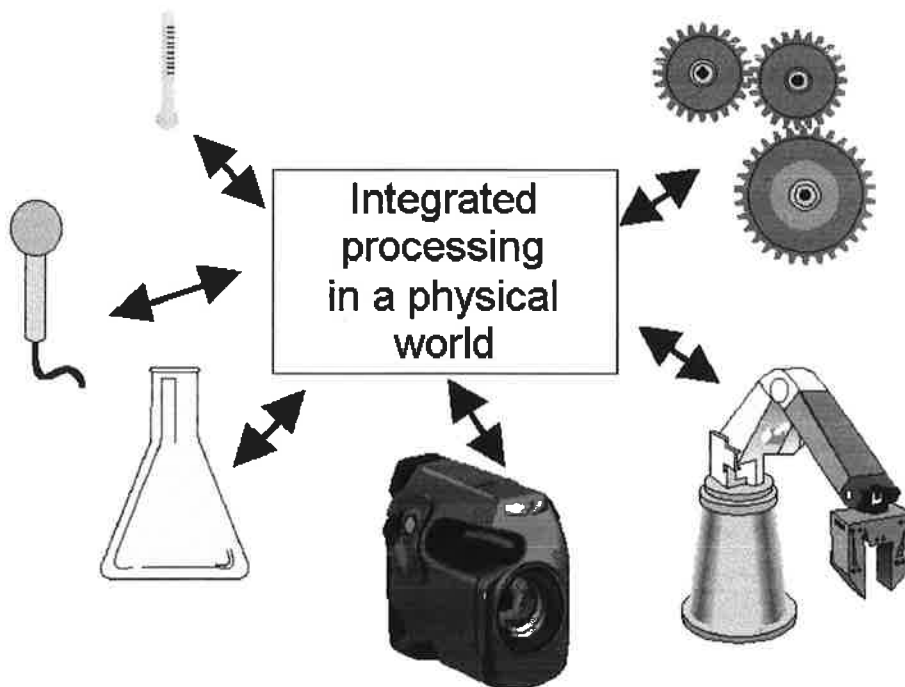


Figure 9.2.1: Interfacing in a physical world with quantities such as: pressure, force, chemical properties, electrical and magnetic fields, temperature, radiation...

These physical quantities need to be conditioned, processed and transformed in digital information for further processing in VLSI. Analog circuit design plays an important role here.

A mobile phone requires analog interfaces (Codec's) for the microphone and speaker as well as in the RF parts. In this respect there has already been a long time trend towards mixed-signal VLSI, combining digital and analog circuits. The analog part takes into account the preprocessing and conditioning of analog interface signals.

There is a continuous trend towards moving more and more of the signal processing from the analog side to the digital side with DSP (digital signal processing). DSP has interesting properties due to stability, reproducibility, calibration, programmability etc.. Analog signal processing is however very important in the front-end physical interfaces, as well as in the signal processing of RF parts (e.g. in mobile telecommunication). Usually analog signal processing is advantageous from a power consumption point of view, which is important in battery operated systems.

9.2.3. MEMS and Micro Machining

VLSI technology is not limited to the integration of digital and analog circuits as is usual in CMOS technology. The advent of MEMS (Micro Electronic and Mechanic Systems) allows the integration of sensors [26, 27] and actuators [22, 23, 25] in technologies related to VLSI. This even enables to realize circuits and sensors/actuators on the same substrate and making use of high volume production techniques as are currently in use for VLSI. This gives rise to new applications at low price or with higher quality than previously possible.

Micro machining based on selective etchants such as EDP and KOH allows to pattern 3D structures [21] in materials such as e.g. Si. This has been used already to fabricate accelerometers [24] (e.g. in airbag usage), gas sensors, temperature sensors, micro-pumps, micro-engines [22, 23] and gears [22].

In [22] a micro-engine realized in polysilicon is presented. An electrostatic comb drive actuation is used for generating a linear movement. By making use of two gear/link elements the linear movements of two perpendicular comb drive actuators can be converted in a gear rotation. The polysilicon gears have a diameter of 50 μm . With such a device, torque can be delivered for applications such as for example: optical switches, electrical switches, micro-positioners or other applications that require mechanical power. A very interesting aspect of such technology is that it allows to be completely batch processed, similar to other microelectronics technologies, without requiring piece by piece assembly as is the case in their macro counterparts. Given the appropriate

applications, such micro-mechanical devices can be mass produced and be cheap in volume quantities.

In [23] a thermally actuated micro-mirror is presented as fabricated in CMOS Si technology. The mirror is suspended on two bimorph cantilever beams. The applications for such devices are in spatial light modulators for use in printers, scanners and video projection systems.

Given the possibilities of current microelectronics technology, it is becoming possible to integrate complete systems in small dimensions and even on a single integrated circuit chips: including sensors, actuators, analog signal processing, digital signal processing and control.

These micro-systems allow for new applications often only limited by the imagination of designers. The miniaturization and use of VLSI technology is not only interesting when we need small dimensions (e.g. medical applications, space use, portable devices...), but also has advantages for high volume low cost production of intelligent systems.

In the following sections we will discuss aspects of the new design paradigms, called IMSD or Integrated Micro System Design, and specific aspects of low power design that are needed to the successful conception of such novel systems.

9.2.4 IMSD: Integrated Micro System Design

The design of complete systems goes far beyond the traditional design of digital circuits [14], for which the paradigms are very well established. Besides digital design [14], such micro-systems require an *integrated approach* to the conception of such complete systems called: **Integrated Micro System Design** (or IMSD). For the successful design, IMSD requires a overall approach to the system design. This is necessary because in such an integrated system most of the aspects (sensors, signal processing, packaging, testability, wireless operation, portability, low power consumption) influence one another. The traditional approach where all of the design aspects are done separately makes tradeoffs among implementation aspects more difficult.

An example of integrated system design is the Berkeley InfoPad project [4, 6, 7]. This project encompasses the design of a PDA with graphics capabilities, pen input, video decompression and wireless operation. Low power issues have got particular attention in the realization of this project.

The design and low power aspects involved in IMSD can be illustrated with portable systems such as for example the SmartPenTM [1]. The SmartPenTM is a novel computer

input device. It is portable and operates autonomously. It includes sensors, electronics, embedded processing and wireless communication. Small dimensions and battery operation require that in this device special care is taken for an appropriate low power design.

In what follows, individual aspects related to the low power design of integrated micro-systems are discussed: choice of batteries, overall system level power reduction, power reduction in wireless communication. Low power aspects in the embedded processing and ASICs are dealt with in other chapters of this book [11] and are not repeated here.

System level optimizations for low power should be done before proceeding to electrical level optimizations for low power, as in the initial system concept a large amount of power can be gained (or wasted) when making overall system implementation decisions.

9.2.5 Batteries

Autonomous integrated systems require powering by means of batteries. Especially hand held electronic devices are often battery operated. Customers do not want to be bothered by having to replace batteries too often. Most lap-top computers only operate autonomously during a few hours, which is still a major bottleneck in their flexible use. For other equipment, users do not want to be bothered at all with battery power. Replacing batteries is an activity that should only be done every half a year for most electronic devices. To help achieve this autonomy several applications (e.g. pagers, mobile phones...) etc. rely on the use of rechargeable batteries. The recharging can then be performed during times of inactivity in docking stations.

Besides the autonomous usage time, also the size and/or weight of portable electronic systems is constrained. A good balance between autonomous usage time, dimensions and the weight of equipment has to be made. The power use of the system will be the main factor determining the range in which these characteristics can be traded off.

Battery	Voltage	Charge-able?	Energy/ Mass J/g	Energy/ Volume J/cm ³
NiCd	1.20	yes	40 .. 90	150 .. 270
Ni/MH	1.20	yes	40 .. 90	150 .. 270
Lithium/R	3.00	yes	50..100	210 .. 310
Lithium	3.00	no	500 .. 1000	1100 .. 2600
Alkaline	1.50	no	50 .. 300	570 .. 1000
Mercury	1.35	no	300 .. 500	1000 .. 2200
Zinc-Air	1.40	no	800 .. 1800	2400 .. 5000

Silver	1.55	no	200 .. 450	850 .. 1700
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Table 9.2.1. Comparison of battery characteristics (diameters < 16 mm and length < 30 mm).

Table 9.2.1 gives an overview of a number of battery characteristics (including packaging overhead) for use in small sized electronic systems. Applications could be in pagers, calculators, thermometers, digital payment terminals, photographic equipment, game tools etc...

The information on batteries in this chapter has been derived from [15,16,31]. In table 9.2.1, we have characterized the weight factor by Energy/unit mass (in J/g). The size characteristic of batteries is given by Energy/unit volume (in J/mm³). The higher these numbers, the more preferable for light weight, small size portable electronic devices. The ranges in energy densities are caused by the overall overheads in specific packages in which the batteries are available.

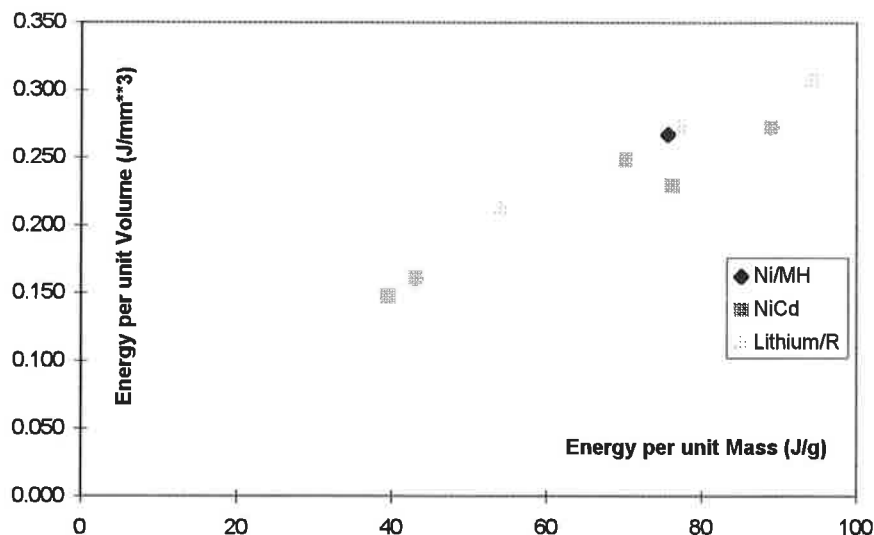


Figure 9.2.2: Energy density characteristics of rechargeable batteries.

In the density characteristics, the properties of the Zinc-Carbon batteries are not taken up as they are usually not available in the size range for which we did the survey. The characteristics are comparable and in the same range as the NiCd or Ni/MH batteries.

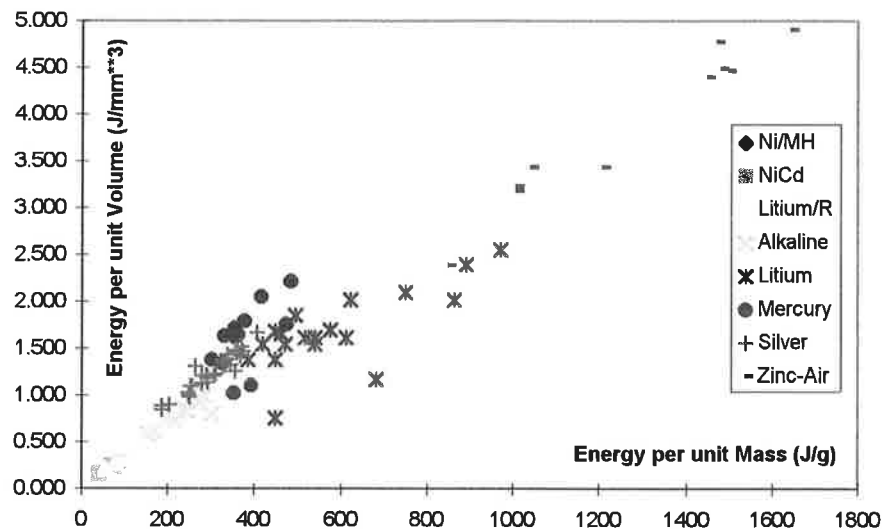


Figure 9.2.3: Density characteristics of several battery technologies.

A first major characteristic is the rechargeability of batteries. NiCd, Ni/MH and Lithium are industrial technologies for producing rechargeable batteries. As can be seen from the comparison in Table 1 and figure 9.2.3, the energy density for rechargeable batteries is a factor of 3..20 lower than the densities in battery technologies for single use (Alkaline, Silver, Mercury, Lithium and Zinc-Air). This means that the autonomous time between charges or battery replacements can be 3 to 20 times longer for single use batteries than for rechargeable batteries.

Besides the energy density of batteries, the cell voltage differentiates technologies. The power consumption is proportional to the square of the overall power supply voltage.

$$P \sim V_{dd}^2$$

When not relying on DC-DC converters, the voltages available from the battery cells can be exploited to achieve lower power. Power efficiencies of DC-DC converters are currently in the range 70 .. 90 %. The switching power supply versions require the addition of an external inductance coil, that can not be integrated on a chip. This adds to the system cost.

Higher voltages can of course always be obtained by cascading a number of battery cells. Also switched capacitor charge pump based DC-DC voltage up converters can be used. If the current required by the electronics is too high, the switched capacitors of the

charge pumps can not be integrated on the chip. External capacitors add to the system cost.

Applications that demand higher speeds or accurate analog electronics will often not allow the usage of the lowest voltages. Lithium batteries with cell voltage of 3 Volts or cascades of other batteries can be used. Power losses due to DC-DC converters can be avoided.

If possible however, it is advantageous to operate electronic circuits at voltages of one cell in the range of 1.2 volt up to 1.55 volt, as the resulting power consumption will be lower by a factor of 4 .. 6. The resulting battery usage time will also increase by that factor (e.g. from 1 week to over a month).

9.2.5.1 Design example

Suppose we want to design a portable application with an expected autonomy of 40 hours effective use. The electronics operate at 3 volt and the shape factor of the system allows space for 2 cm³ of batteries. What is the current that is available for the electronics?

We can choose e.g. for the high energy Lithium or two ZincAir batteries and can expect around 2500 J/cm³. For 2 cm³ of batteries we have an energy of 5000 Joule. With a supply voltage of 3 volt (Lithium) the current capacity available is: $5000 \text{ J} / 3 \text{ volt} = 1667 \text{ A.s} = 5000 * 1000 / (3.600) \text{ mAh} = 462 \text{ mAh}$. For a duration of 40 hours effective use, this leaves: $462 \text{ mAh} / 40 \text{ h} = 11.55 \text{ mA}$.

9.2.6 Overall power management strategies at the system level.

Most portable systems are not constantly in operation or in a similar level of activity. Mobile phones can be off, can be in attentive modes for incoming calls or can be communicating with base stations. Laptop computers usually have several modes of power operation (hard disk not spinning, screen blank to avoid back light power, DRAM memory powering only, cooling fan on/off depending on temperature, processor slow down...).

Therefore it is beneficial to exploit several modes of operation and power usage. Similar strategies can also be exploited in integrated micro systems [1]. The highest gains in system power usage can be obtained here.

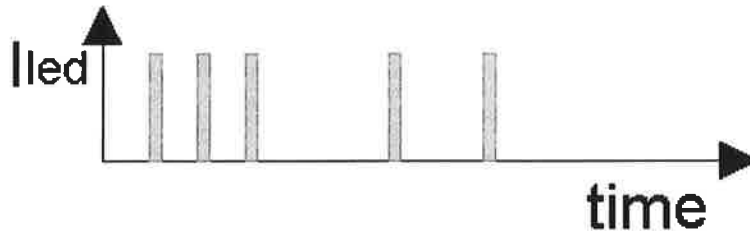
9.2.7 Power use in system communication.

9.2.7.1 *Wired communication*

9.2.7.4 IR communication

Wireless communication in the same room can be organized by means of infrared communication. Figure 9.2.4 shows the principle

Discrete modulation schemes (PCM) where the data information is represented by IR light pulses are more performant in data rate as well as from a power consumption point of view.



In the IrDA infrared communication standard the pulse duty cycle is 1/16.

Data words can be transmitted in a serial protocol as indicated in figure 9.2.

where:

r_d : required data rate (bits/sec)
 r_{max} : maximum data rate (bits/sec)
 k : IR power usage factor

another. This standard is currently adapted by most palmtop and laptop computers as well as peripheral devices.

9.2.8 Application example

The composition of the pen is illustrated in figure 9.2.9.

In the front, the SmartPenTM uses

A receiver which is embedded in the SmartInkWell captures the information and includes the interface circuitry for the connection to a standard IBM compatible PC. On the PC the application software can determine the specific use of the pen.

In portable applications the power consumption is very important and is determined by a combination of power users: sensors, actuators, wireless communication system, analog circuits (and accuracy) and digital processing. An easy switch between domains is required to make good balances. Tradeoffs can be made between the power usage in different parts of a design like:

- power consumed in sensors and power consumed in analog interface
- power consumed in analog versus power consumed in digital signal processing.
- power consumed in the wireless data communication and power consumed in signal processing to compress the data content.

9.2.9.3 CAD

Microelectronics CAD, especially in the digital domain, has matured very well in the last decades. Cell and module libraries as provided by many silicon foundries and synthesis tools starting from HDL's (VHDL and Verilog) have eased the design trajectory. It made possible that rather complex designs can be done in a reasonable time.

The behavior of global systems can be studied by means of algorithmic models built in algorithmic modeling tools such as MathCAD or MathLab.

3-D microstructures need to be designed in a 3-D CAD system (e.g. like AutoCAD). They have to be simulated for their performance (force, temperature, magnetic fields, electrical fields, humidity...) by means of FEM (Finite Element Model) simulators such as Systus, Ansys or Nastran. The integration with electronics CAD tools is non-existing or weak.

When these 3-D microstructures are realized by means of anisotropic etching [21] e.g. with EDP or KOH, it is not trivial how the structures will be etched starting from the original gdsII mask drawings. This is because these etchants have a different etching behavior depending of the crystal directions of the material. Etching modeling [21] and simulators need to be used here, to enable the appropriate design of compensation structures in the original mask drawings.

9.2.9.4 Design quality: Verification

Design quality is very important, as design iterations are too lengthy and as in some cases human lives can be in danger due to malfunctioning of systems. Verification of the

global system behavior is done in either custom made software models or in algorithmic modeling systems such as MathCAD or MathLab.

The behavior of the digital electronics [19, 20] and the software in embedded processors [29] will more and more require the help of formal verification. This verification method is much more thorough than simulation. By using symbolic values, it is possible to describe and verify global system behaviors. Currently first steps are made in the formal verification of mixed mode analog digital systems [28].

9.2.9.5 Production quality: Testability

Systems can be malfunctioning due to design errors as described in the previous paragraph. They can also fail due to errors in the production process. It is the goal of testing methods to determine appropriate strategies to allow for the testing of systems after production (and in operation). Design for Testability has gained good understanding in the area of digital electronic circuits and are very well adopted in digital design for testability (DfT) strategies such as scan-paths, built-in self test (BIST) and Iddq testing. In IMSD we not only have digital circuits, but also analog circuits as well as sensors and actuators. When they are integrated on micro-level or on one chip, it is not trivial to test the global systems anymore. Special strategies will have to be worked out to enable cost-effective testing of such integrated systems.

9.2.10 Conclusions

In this chapter design and low-power aspects in Integrated Micro Systems Design have been discussed. The technology evolution allows that complete systems can currently be integrated. This opens up a lot of new possibilities for novel applications employing microelectronics. Critical in IMSD is a global design approach combining several engineering disciplines: microelectronics, mechanical, computer science, chemical ...

CAD support for IMSD is still in its infancy. Much needs to be done for integrating different aspects: electronic, mechanical, etching. In order to get reliable and cost effective systems sufficient attention has to be paid to system verification and integrated test methodologies.

A global design approach avoids a waste of efforts in point-optimizations which often neglect the global optimization problem. This is especially true for the global power budgeting and power optimization of systems, which needs to take into account the available power sources (batteries) and power users (sensors, actuators, mixed-analog digital electronics, embedded processors and wireless interface).

9.2.11 References

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