Introduction

Since the invention of the transistor in 1947, followed by the concept of integrated circuits in 1958 by Jack Kilby, Nobel Prize laureate in 2000, progress in the field of microelectronics has been tremendous. Huge advances have been achieved in the packing density of transistors thanks to a continuous improvement in fabrication processes, following the downscaling principle of devices developed by R. H. Dennard in 1972 and generalized in 1984. The result has been a chip complexity increase at a rate of roughly a factor of 2 every 1.5 years since 1975, less than the initial observation of Gordon E. Moore in 1965, but impressive for its steadiness over more than 40 years. Although this is not a real law, this prediction of technology integration is popularly known as "Moore's law". Whereas in 1971 the first microprocessor, a 4-bit model, had only about 2300 transistors, in 2008 Intel reported the world's first two-billion transistor processor, a quad-core implemented in 65 nm CMOS (complementary metal oxide semiconductor), within an area of 700 mm^2 [STA 08]. It should also be mentioned that the first microprocessor was designed with a 10 µm minimum feature size, whereas today, major companies are on track to ramp 32 nm logic technology in 2009. The same trend is observed with regard to memories. The DRAM (dynamic random access memory) capacity has been raised from only 1 kb in 1970 to 2 Gb at present. For flash NAND, the increase is still more impressive at a pace which doubles the capacity every year, leading to a record of 64 Gb. This increase in transistor count and memory capacity has been strongly beneficial to the processing power, measured in millions of instructions per second (MIPS). But Moore's law also means decreasing cost per function, due to productivity gains, since more transistors are packed within a given area, while increasing wafer size and throughput and keeping a high yield level. Historically, the transistor price has dropped at an average rate of about 1.54 per year. According to the International Technology Roadmap for Semiconductors, ITRS [ITR 08], there are big challenges to overcome in order to continue progress in the same direction, but nonetheless there are promising solutions. Further, the worldwide research effort is so intense, and the societal and industrial stakes are so high, that we can be quite optimistic, at least for the next decade.

As a result of the miniaturization of transistors, there has been a dramatic increase in their performance, measured as the ON to OFF ratio of drain current in DC mode, while lowering the supply voltage. In AC mode, progress has also been spectacular, due to the reduction of capacitances and propagation delay along the channel, and better optimization. A cut-off frequency close to 500 GHz has been measured on a 45 nm SOI (silicon on insulator) CMOS leading edge technology [LEE 07] and many system-on-chip (SOC) radio frequency CMOS circuits have been demonstrated at 60 GHz. In addition to the drop in transistor price, these features contribute greatly to the broadening of the range of electronic products, in particular to those related to computing, storage and transmission of data and information. As an example, there has been a strong transition from analog electronics to a digitized world, such as in the case of cellular phones, especially for video and TV broadcasting, implying more computing power for data processing, compression, decompression and particularly for high definition. Also, evanescent and cheap electronics will boost the development of new mobile applications and will make possible the emergence of ambient intelligence, where the environment will adapt to people through improved user–system interaction, leading to what is known as pervasive/ubiquitous computing. Technology-driven and user-driven viewpoints are complementary. Their synergy will have a strong impact on our daily life.

This book is focused on the most important electronic devices which are embedded in integrated circuits or SOCs, from MOSFETs (metal oxide semiconductor field effect transistors) and bipolar transistors to non-volatile memory devices. It gives physical insight into their operation and comments on directions of evolution, including updated characteristics and discussions of the challenges to face for the future. It also provides the physical background on semiconductor materials needed to understand the concepts which are at the basis of electronic devices. Equations and theoretical developments are limited to what is really useful to the reader.

The six chapters of this book have been written by scientists, from university, research institutes and industry, strongly involved in teaching or research programs related to microelectronic devices. Because of their international commitment or level of responsibility, they are very well informed on the state-of-the-art of technologies and their evolution.

The first chapter explains what a semiconductor material is, focusing on silicon because of its great importance for integrated circuits. Of neither an insulating nor a metallic nature, semiconductors have specific properties which are advantageously exploited in microelectronic devices; this is why it is useful to acquire the minimum amount of knowledge needed to understand the operation of these devices. This is the purpose of this chapter and of the following one. After a general presentation of the crystal structure, the formation of energy bands is developed from two kinds of approaches introduced in a comprehensive way. Then the important concepts of "hole" and of "effective mass" are defined, powerful abstractions for efficiently dealing with semiconductors and calculating their electronic properties. Next, introducing impurities in a perfect crystal is presented as a way of doping materials, i.e. modifying their characteristics, through a change in the electron–hole balance.

The second chapter is mainly related to the physics of electron transport in a semiconductor put out of thermal equilibrium by a perturbation. The resulting carrier diffusion or electrical conduction is at the basis of the operation of electronic devices. How to take into account the different scattering mechanisms that carriers undergo is discussed. The notions of electron mobility, saturation velocity and electromotive force are presented as well as expressions for current calculation. Generation and recombination phenomena of carriers are also introduced, because of their strong role in the physics of devices. Finally, the case of a simple device, the diode, is treated here, exemplifying the way in which to deal with the equations previously established.

In the following chapter, the principle of operation of MOSFET devices is explained. In a first step, the case of an ideal transistor is considered, then parasitic effects existing in real devices are introduced, especially those related to quantum confinement, effective mobility, series resistances, subthreshold conduction and channel dimensions, namely short and narrow channel effects for the latter. Based on a model taking all of these effects into account, performance projections for future technology nodes are established. Then the behavior of ultimately scaled MOSFETs is discussed.

Chapter 4 is focused on transistors fabricated on an insulator, motivated by the definite advantages that arise thanks to the full dielectric isolation of the channel, in comparison with the bulk approach. This is decisive in particular in the highly competitive field of low-power and low-voltage circuits. The main methods for synthesizing SOI (silicon on insulator) materials are reviewed, then the operation of partially depleted and fully depleted SOI transistors is discussed, with emphasis on features specific to SOI. In the final part, different emerging device architectures leading towards ultimate SOI MOSFETs are presented.

In addition to MOSFETs, bipolar transistors are important devices for some applications, especially for analog and RF functions. Chapter 5 deals with the physics of these transistors and discusses their integration in CMOS technology. As for the MOSFET, the principle of operation is first explained in the case of an ideal transistor before introducing non-ideal mechanisms, followed by a discussion of small signal operation and trade-offs for performance optimization. In a second part, it is shown how the use of SiGe extends the limits for high-frequency operation. Integration in a BiCMOS (bipolar CMOS) technology is reviewed and extended with some prospects.

The last chapter addresses the theme of solid-state non-volatile memories (NVM). The long-term storage of information and data is an essential function for numerous applications. This is why an important research effort is dedicated to this subject. In this chapter the different types and evolutions of non-volatile memories are presented, particularly those based on charge storage in a MOS structure embedding traps or a floating gate. Physical phenomena involved in their operation are also explained. Scaling limits of current NVM technologies are discussed as well as solutions for further pushing their miniaturization. The last part introduces the most important alternative technology candidates: phase-change memories, magnetoresistive memories, ferroelectric memories, conductive bridging RAM and OxRAM (oxide resistive RAM).

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[ITR 08] http://www.itrs.net/.

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