Branko L. Dokić
Tatjana Pešić-Brđanin

ANALOG INTEGRATED CIRCUITS

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Reviewers
Ninoslav Stojadinović
Academician of SASA

Vančo Litovski
Full Professor – Faculty of Electronic Engineering Niš

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To grandchildren: Nađa, Rastko, Hristina, Luka, Gabriela, Katarina, Ivan

Branko L. Dokić

To Lena and Dražen

Tatjana Pešić-Brđanin

Preface

Based on the operating mode of transistor as a basic active element, monolithic integrated circuits are divided into digital, analog (linear) and mixed-signal circuits. In digital circuits transistors operate in switching mode, so they are in either ON or OFF mode. Those modes represent bits. For practical reasons, bits are marked as "0" or "1". In the early years of digital electronics, a bit sequence mostly represented numerical information, usually in binary code. Binary vocabulary is considerably enriched by digitalization of analog signals like audio or video signals. To digitalize a signal means to obtain its samples in discrete time intervals which, if close enough, can be used as its perfect replica.

Digital integrated circuits process a digital signal, and analog process an analog signal. Analog signal is continuous over time and space. While digital signal modes are very stable and mostly independent of parameters of integrated circuit elements, analog signal is highly dependent of physical and electrical parameters of semiconductor devices. It is why the analog design is much more complex than digital one and requires intuition, rigor and creativity. Furthermore, analog integrated circuits use larger area active devices than digital designs and are usually less dense in circuitry.

These are only a few reasons why the development and production of digital integrated circuits were much faster than analog. The explosive growth of digital electronics is based on computers and other digital systems widely used today in very different areas of technology such as: automation, radio and telecommunications, robotics, measuring techniques, entertainment electronics, automobile industry etc. The development and application of digital integrated circuits have a huge influence not only on development of economy, science and technology but on human civilization in general. Today we often say how everything is digitalized, and we even speak of digital intelligence.

So where does the analog electronics belong? In the early 1980s many experts predicted the demise of analog circuits. However, the world as we experience it is not digital at all, but continuous. Everything we hear, see and feel in life is analog, from our voice, music, seismic movements, visual and biological perception, to the energy exchange. Since the physical world consists of signals in the continuous time domain, analog integrated circuits will be needed in the foreseeable future. All digitalized electrical systems must possess an interface over the analog circuits. It is simply impossible to imagine any life practical engineering solution without the help of high-performance analog integrated circuits. That is the reason why the market for analog integrated circuits is expanding every year.

The digitalization also enabled faster development of analog integrated circuits, at least in two ways. Before the emergence of microprocessors in the 1970s and the corresponding software for circuit analysis and synthesis, the analog integrated circuits were designed using manual calculations. That is why the complexity of those circuits, at the time, was limited to around dozen transistors (operational amplifiers, comparators, analog multipliers and so on). In the early 1970s, the computer programs were written to simulate analog integrated circuits designs with greater accuracy than practical by manual calculation. The first circuit simulator was called SPICE (**S**imulation **P**rogram with **I**ntegrated **C**ircuits **E**mphasis).

On the other hand, the more the digitalization entered the *real* world, the need for various high-performance analog integrated circuits was increasing. For example, when digitalizing physical signals, an analog-to-digital (ADC) and a digital-to-analog (DAC) converters are always needed. That is how monolithic integrated circuits with mixed signal appeared. They are integrated circuits with processing of both analog and digital signals (ADC, DAC, smart sensors, digital signal processors DSP etc.) Modern devices of consumer electronics are inconceivable without the mixed-signal integrated circuits. Interface and processing of analog signals includes the following three groups of analog circuits or mixed-signal circuits and systems: power management (bias circuits, regulators, references, protection circuits), front-end interface (sensors, amplifiers, ADC, filters) and back-end interface (DAC, amplifiers, filters, power drivers).

The analog (linear) courses on many faculties, although addressing the microelectronic technologies, are conceptually more based on discrete analog circuits. Luckily, the basic principles that govern the analysis and designing of electronic circuits, are not nearly as prone to changes as technologies of their implementation. It the opinion of authors of this book, it is much more rational that these principles should be illustrated on examples of actual technologies, and only to address the specifics of nonstandard techniques. This book is the result of efforts to include the analog integrated circuits technology in general electronics course in the early phase of academic process. Numerous solved examples inside each chapter will help the students to grasp more easily the principles and laws behind the content of those chapters. Unsolved problems and questions at the end of each chapter should help the students to verify acquired knowledge.

The analysis of a circuit is based on manual calculations, therefore simplified small-signal transistor models are used. It is our objective that students understand the influence of key elements parameters on basic circuit characteristics. We assume that the students are previously trained to use SPICE simulator so detailed analysis of more complex circuits is planned for practical classes.

Development of analog integrated circuits from the beginning until today has passed several phases. Initially, these circuits were designed and manufactured in bipolar technology that was followed by a rapid development of analog circuits realized in MOS technology. Afterward, a BiCMOS technology, which combines bipolar and CMOS components on a single chip, emerged as a serious competitor and, recently, as a leader in analog integrated circuits production. In order to reduce the costs and power dissipation of the electronic systems, analog and digital circuits are often technologically integrated, which provides strong economic motivation for usage of CMOS compatible circuits. Although in some cases the production of linear BiCMOS circuits is more expensive, it allows the designer of analog integrated circuits to utilize the best features of bipolar and MOS components in various innovative combinations of their characteristics. Also, BiCMOS technology enables the reduction of design time, since it allows the direct use of a large number of existing cells for realization of the given analog functions.

In this book, both bipolar and MOS devices and circuits were described in a way that is suitable for combining them later in BiCMOS technologies chapter. For engineers that will deal with the design of analog integrated circuits, the knowledge of bipolar and MOS devices similarities and differences is of a great importance, which determines the selection of suitable devices and topologies for the required circuit performance.

In the first chapter, a classification of integrated circuits with respect to characteristic parameters was described. Considering the fact that the application of integrated circuits became very complex in the last few decades, we outlined classifications with respect to technology and technique of production, scale of integration, operation mode, design methodology, and application of integrated circuits.

The second chapter is dedicated to the planar technology used for production of monolithic integrated circuits. All phases are explained in detail, and, in addition, modern processes that are found in individual phases were given.

Relationship between production technologies of integrated circuits and basic devices was described in the third and fourth chapter. In the book, the basic and advanced techniques for production of bipolar and MOS transistors in silicon technology were given as well. The existence of parasitic elements and structures was pointed out. It was shown how technological parameters and polarizations may affect the static and dynamic characteristics of bipolar and MOS devices. The second-order effects, which occur while bipolar and MOS transistor operating, were specially treated. Small-signal models that are used in SPICE were given.

The fifth chapter is dedicated to the description of the development of modern bipolar and MOS transistors structures that emerge in nanometer technologies and are used in RF electronics and telecommunications. The comparative characteristics of the technologies that are developed on substrates of different materials, as well as the characteristics of the transistors (MESFET, HEMT, HBT) that are developed in these technologies were given.

Topology and characteristics of basic circuits, which are used for design of more complex analog integrated circuits, were described in the sixth chapter. Special attention was paid to constant current sources, differential amplifiers, voltage amplifiers, voltage sources, voltage reference sources and output stages of integrated circuits. Peculiarities of each group of analog integrated circuits mentioned above, as well as their possibilities and limitations, were pointed out. The topologies of these circuits in bipolar and MOS technology were analyzed in parallel.

RF elementary circuits are described in Chapter 7.

Operational amplifier is the most popular analog integrated circuit. Considering the variety of applications it is justly regarded as a device. In Chapter 8, general characteristics of operational amplifiers, with emphasis on the specifics of particular types, were considered. The most commonly used operational amplifier 741 was analyzed separately, and its static and dynamic parameters were calculated and given in this chapter. CMOS two stage opamps and CMOS transconductance amplifiers are also analyzed.

In Chapter 9, standard applications of operational amplifiers are described. Here, the op-amp is regarded not as circuit but as device. Also described are different configurations of op-amps as voltage or current amplifiers, voltage-to-current and current-to-voltage converters, analog arithmetic circuits, linear and pulse oscillators, active filters and comparators.

In the Chapter 10, the basic principles of the voltage regulation and stabilization were explained, and then, general-purpose, three-terminal and dual-tracking integrated regulators were described. Special attention was paid to current and thermal protection of regulators. Methods of application of regulators in various configuration of supply blocks.

There are often problems of comprehension of a text when authors are not from the English speaking regions. Dr. Zoran Jakšić has made effort to diminish this problem. The authors owe him sincere gratitude.

Banja Luka, March 2018 *Authors*

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Chapter 1

Introduction to integrated circuits

Development of integrated circuits – IC (**I**ntegrated **C**ircuits) can be considered within the context of microelectronics. Microelectronics, as a science discipline, is a branch of science, engineering and technology that investigates transport phenomena of charge carriers through semiconductors, conductors, gases and vacuum, as well as the consequences and effects of these phenomena used for applicative purposes.

The role of microelectronics is crucial for the development of computers, telecommunications, industrial equipment, military industry, consumer appliances, automotive industry, etc. In a more general sense, microelectronics includes not only microelectronic technologies, but also the products of these technologies. All these products are jointly denoted as integrated circuits.

Compared to discrete circuits, integrated circuits have the following advantages:

- Smaller dimensions of circuit elements,
- Improved performance,
- Larger chip surface,
- Larger number of transistors per chip,
- Higher operating speed of transistors and circuits,
- Lower dissipation of elements,
- Higher allowed dissipation per unit surface,
- Lower weight,
- Better reliability and stability in different operating conditions,

- Simpler system design,
- Standard packaging,
- Lower cost, etc.

1.1. Different technologies

There is a vast number of various integrated circuits that differ in complexity, purpose, fabrication technology, etc. Integrated circuits are fabricated on two types of substrates: semiconductor and passive. There are three basic technologies for the fabrication of integrated circuits: planar (semiconductor) technology, thick film technology and thin film technology (Fig. 1.1). Thick film and thin film integrated circuits are most often fabricated combined with the semiconductor ones, and in that case these are thick and thin film hybrid integrated circuits.

The planar processes represent the foundation of the semiconductor technology. Initially it was intended for the fabrication of discrete transistors, and then the first integrated circuits were produced by this process. Although the devices fabricated by planar technology extend into all three dimensions, the planar structure is dominant. This technology ensures a very large degree of miniaturization, higher reliability, low cost, high operating speeds and very low power consumption.

Thick and thin film technologies are most convenient for small series of specialized circuits, complex, mostly passive matrices and applications that demand mid or high powers of dissipation, large voltage variations or stable

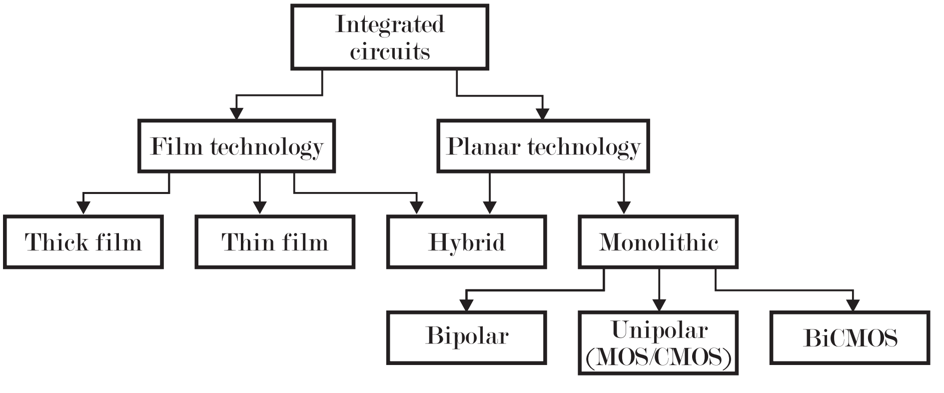

Figure 1.1. Different technologies