Allen A. Sweet

DESIGNING BIPOLAR TRANSISTOR RADIO FREQUENCY INTEGRATED CIRCUITS

Designing Bipolar Transistor Radio Frequency Integrated Circuits

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FUNDAMENTAL PHYSICAL CONSTANTS

1. Speed of light in a vacuum: $c=3x10^{10}$ cm/s
2. Permittivity of a vacuum: $\varepsilon_0=8.89x10^{-14}$ F/cm
3. Permeability of a vacuum: $\mu_0=1260$ nH/meter
4. Planck's constant: $h=6.63x10^{-34}$ J-seconds
5. Boltzmann's constant: $k=1.38x10^{-23}$ J/degrees Kelvin
6. Charge of an electron: $q=1.6x10^{-19}$ C
7. Rest mass of an electron: $m_e=9.11x10^{-31}$ Kg
8. Thermal voltage: $VT=kT/q=0.0259$ volts at $T=300$ degrees Kelvin
9. Bandgap energy of Silicon= 1.12 eV
10. Bandgap energy of GaAs = 1.42 eV
11. Dielectric constant of Silicon: 11.7
12. Dielectric constant of GaAs: 12.5

IMPORTANT UNIT CONVERSIONS

1. Angstrom (Å): $1Å=1x10^{-8}$ cm
2. Nanometer (nm): 1 nm $=1x10^{-7}$ cm
3. Micron (μm): 1 $\mu m=1x10^{-4}$ cm
4. Electron-Volt (eV): 1 $eV=1.6x10^{-19}$ J

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CHAPTER 1

Introduction

Over the past three decades, radio frequency (RF) and microwave circuits have come through a period of rapid evolution and growth. Until the early 1960s, most RF and microwave circuits made use of vacuum tubes such as "lighthouse" tubes, klystrons, magnetrons, backward wave oscillators (BWOs), and traveling-wave tubes (TWTs) [1]. By the mid-1960s, all this was beginning to change as even more dramatic changes were rapidly approaching on the horizon in the form of new solid-state devices capable of working at RF and microwave frequency ranges. The first of these new technologies to present itself was the silicon (Si) bipolar transistor, which had been scaled to operate up to a frequency of about 1 GHz. And that was only the beginning of a wave of development during which time such unique solid-state devices as Gunn diodes, Impatt diodes, PIN diodes, and varactor diodes became available [2]. These two-terminal solid-state devices had the ability to push the upper frequency limit of solid-state electronics from under 1 GHz to well over 10 GHz. The rush was on. All eyes were watching to see whose efforts would deliver the next highest operating frequency, the highest power output, the lowest noise, and the best temperature stability. As the Vietnam War came to an end, this process accelerated even more because of the availability of federal research money. Because much of the basic RF and microwave research was funded by the federal government, a sharp focus was placed on military applications. RF and microwave technology had become a very important element in the cold war strategy of the time.

Since then, the RF and microwave field has evolved over four distinct periods. Figure 1.1 provides a map of the way these developing technologies emerged over time. The first period, from the mid-1960s to the mid-1970s, is characterized by the use of diode-active devices and waveguide transmission lines and resonators. The great technology push during this period provided a replacement for vacuum tubes in both military and commercial communications systems. Reliability was a major motivating factor. Vacuum tube systems were famous for failing at the worst possible time, and it was widely felt in the 1960s that a switch to solid state, even with reduced performance, would significantly improve system reliability [3]. The question of the day became, what vacuum tubes can realistically be replaced by solid-state devices? Since solid-state devices could not generate the RF power of the magnitude that vacuum tubes were capable of, the first targets were applications not requiring high RF power levels. Examples of these include receiver local oscillators and low power transmitters. Most mixers in this period were already using solid-state designs employing point contact diodes, or Schottky diodes, as the active devices. It was therefore very natural to include a solid-state local oscillator as an

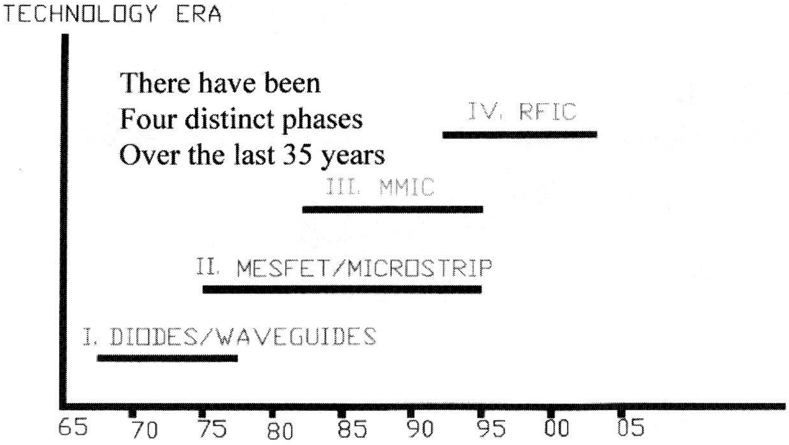

Figure 1.1 A timeline showing how the RF and microwave electronics field has evolved through four distinct phases during the last forty years.

integral part of these mixers, forming a nearly complete solid-state receiver. This need was filled by replacing klystron vacuum tubes with Gunn diode oscillators. The exception to the trend toward solid state within receiver systems was the low-noise amplifier, which remained a TWT until gallium arsenide (GaAs) metal-semiconductor field-effect transistors (MESFETs) became more widely available. Low- and medium-power transmitters evolved into solid-state designs; Impatt diode oscillators were used as replacements for klystron, TWT, and magnetron vacuum tubes in these applications. Along with reliability, the new solid-state hardware offered the systems designer further advantages of lower power dissipation (no vacuum tube filaments needing heater power) and lower operating voltages, eliminating complex high-voltage power supplies. The RF/microwave industry very rapidly became sold on the virtues of solid-state hardware. We were ready for the next important period of development.

The second major period is characterized by the availability of GaAs MESFET devices [4]. With the arrival of GaAs MESFET devices, three terminal devices were at long last available to the RF/microwave circuit designer. Microstrip transmission lines were introduced during this period [5]. Microstrip transmission lines are usually patterned on thin film ceramic substrates. Using photolithographic techniques [4], the circuit designer can fabricate an entire network of microstrip transmission lines on a single thin film ceramic substrate, and using so-called hybrid assembly techniques, circuits may be assembled by connecting active devices such as GaAs MESFETs and diodes to the patterned ceramic substrates using wire-bonding techniques. The field was revolutionized with the development of these RF/microwave thin film hybrid circuits. It was now possible to construct an entire subsystem within a single small mechanical housing. When compared to the old technologies using vacuum tube equipment or even the diode/waveguide solid-state equipment from the recent past, the savings in terms of size, weight, and power consumption were dramatic.

During the cold war military buildup following the end of the Vietnam War, considerable research and development funding for this type of work became available from the U.S. government. For this reason, many of the applications addressed by the emerging solid-state RF/microwave technology were military in nature. In fact, RF/microwave technology development coincided with a major cold war arms buildup in both the United States and the Soviet Union. The compact hardware, made possible by the use of ceramic microstrip circuits and GaAs transistors and diodes, found ready application in newly designed radar, electronic warfare, and missile systems. This period extended from the mid-1970s to the mid-1990s. It was a very intense and exciting two decades of design progress. The domain of solid-state circuits was growing by leaps and bounds. With the advent of GaAs MESFET devices, both low-noise and medium-power TWTs were at last replaced by solid-state transistor amplifiers [7]. These ceramic microstrip hybrid circuits were capable of extremely wide bandwidth operation. This was a great advance for electronic warfare systems, which depend on the ability to acquire random signals over a wide range of possible input frequencies. TWT amplifiers were no longer needed in such systems. The elimination of TWTs created an opportunity for tremendous savings in terms of cost, power, and weight in many airborne systems. All of these technological advances worked in combination with advances in other areas, such as engine design, new materials, and life support, to make possible the high-performance military aircraft that became available toward the end of the cold war period.

The third significant period of RF/microwave technological development grew out of the desire to reduce the cost, size, and weight of RF/microwave solid-state circuits. The path to cost and size reduction followed the same route as that followed by both digital and low-frequency analog circuits: the implementation of integrated circuit (IC) techniques. Since GaAs MESFET devices had very quickly become the most important solid-state active device at these frequencies, an integrated circuit technology was needed that would build on GaAs MESFETs. Fabrication technology for GaAs integrated circuits became available in the mid-1980s [8].

At first, these so-called microwave monolithic integrated circuits (MMICs) were limited to perhaps two transistors and some matching elements, but over time MMICs grew to include enough components to make up entire amplifiers and even simple subsystems. MMICs made use of a particular property of undoped GaAs substrates: their high natural resistance. In fact, undoped GaAs, unlike undoped silicon, is an excellent insulator. This means that the undoped GaAs substrates used in MMIC circuits are excellent media for microstrip lines. Furthermore, since the dielectric constant of GaAs is 12.5, such transmission lines are physically short, reducing size, weight, and total cost. As cost depends heavily on total die area, this unique new MMIC technology held the promise of replacing much of the then existing ceramic microstrip hybrid hardware with low-cost, fully monolithic, MMIC-integrated circuits.

This promise has been only partially fulfilled because of two factors: First, there is the issue of tuning (or tweaking). Hybrid ceramic circuits had always required a moderate amount of expensive hand alignment. This alignment, known in the industry as "tweaking," accounted for much of the hardware's cost. However, in the case of MMIC circuits, it was no longer possible to tweak the circuit because it is an integrated circuit and too small for any hands-on alignment (even if the insulating passivation layer were to be left off in processing) to be practical. This means that either MMICs work or they don't. However, it's not quite that simple. Variations in the fabrication process occur from wafer to wafer, which can significantly affect the performance of an MMIC circuit. Wafer-to-wafer variations reduce the overall yield of MMIC devices, and depending on the degree of difficulty of the electrical specifications, the yield may be quite low, which tends to cancel out the cost advantages of using an MMIC approach in the first place.

Two possible solutions to these problems were attempted. The first was more exact modeling, and the second was improved process uniformity. The first solution made use of models that allowed the simulation of a wide range of electrical parameters, not just the small-signal S-parameters, which were customarily used in hybrid ceramic circuit simulations. The new models created for MMIC applications had to be able to function over a large range of signal levels, including dc behavior. These models, generically called large-signal models, were far more complex than the small-signal S-parameter models that preceded them. Considerable effort and expense went into the development of these large-signal models, with the hope that if the new MMIC circuits could be modeled accurately and completely, their yields would increase. The effort was only partially successful because of a second major issue: wafer-to-wafer variations during fabrication. All the modeling precision in the world won't increase yield if the model parameters keep changing in unpredictable ways. To improve this situation, the foundries (fabrication facilities) attempted to use more repeatable processes. The most significant change was a switch from wet etch processing (involving placing the wafers into chemical baths) to a dry etch process (which makes use of a plasma that impinges very uniformly onto the wafer in a specially designed vacuum chamber). However, not all etching processes could be switched to dry etch. In particular, the gate recess etch step in fabricating the MESFET device's gates could not be done by dry etch and had to remain a wet etch process step. A lot of device variation is experienced in this one step, and it is a challenge to model developers and circuit designers alike to deal with this variation. This situation has never been totally resolved. MESFET circuits today still experience significant process variations that affect yield, sometimes profoundly. By necessity, designers have developed ways of optimizing their circuits for process variations so that yield number can be increased. However, to date no universal solution to this problem has been identified.

History intervened at this point to create a shift in emphasis and application. In 1991, the Soviet Union ceased to exist, and the cold war ended. As a result, the ongoing demand for improved military hardware came to an abrupt end, and government-sponsored research and development funding sharply declined. This global political change created temporary hard times for companies and individuals working in RF and microwaves throughout the 1990s. However, just as the RF/microwave electronics field descended into decline with the end of the cold war, the technology quickly came back to life with the arrival of the wireless revolution, which began gaining energy in the second part of the 1990s.

The emergence of wireless technology signaled the beginning of a fourth period of technology development, and work in wireless research and development continues today. This period signaled the emergence of radio frequency integrated circuits (RFICs) as a major driver of progress in RF and microwaves. The timeline presented in Figure 1.2 focuses on the applications in each time period. Wireless applications

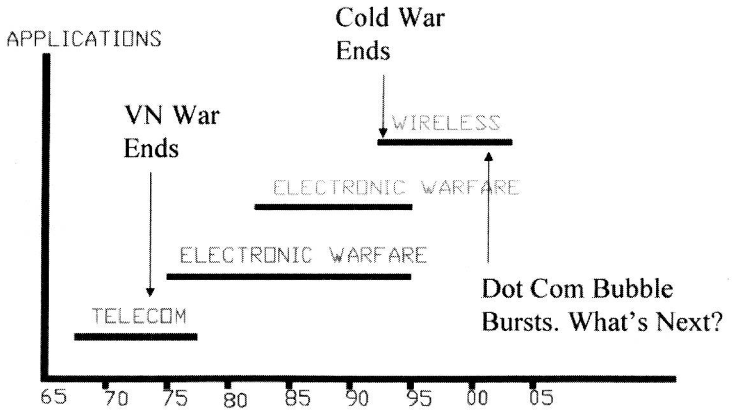

Figure 1.2 A timeline showing the most important application associated with each phase in the development of the RF and microwave electronics field.

are the latest period. In many ways, wireless applications feel like "back to the future." The focus is changing to narrowband applications at relatively low frequencies (1 to 4 GHz). This is a dramatic shift from ceramic/hybrid and MMIC technologies, where the focus was on very broadband applications at high frequencies (up to 25 GHz). However, the concept of RFIC was born out of the need to serve these applications.

New high-frequency fabrication technologies began to appear. All during the purely microwave–millimeter-wave period (late 1960s to mid-1990s), the dominant high-frequency fabrication technology was GaAs MESFET. However, by the late 1990s, GaAs MESFET was joined by the GaAs heterojunction bipolar transistor (HBT) [9] whose advantages relative to GaAs MESFET are discussed throughout the present book. MMIC designers were quick to perceive the advantages of GaAs HBT, and many designers changed technologies, especially for cellular infrastructure applications. Within a short period, designers began designing PAs for mobile handsets using GaAs HBT. During this largely III–V compound semiconductor design period of the late 1980s, MMIC designers gave considerable attention to cellular applications. Due to the low-frequency (0.80 to 1.9 GHz) operations associated with cellular applications, these new integrated circuits came to be called RFICs, rather than MMICs. RFICs have operating frequencies more in keeping with traditional RF frequencies than with the higher microwave frequencies associated with MMICs.

Then, the world changed again, in many ways, all at once. First, new silicon-based fabrication technologies [silicon germanium (SiGe), BiCMOS, and RFCMOS] became available [10]. Second, in order to reduce cost and size, there was a major push toward higher levels of integration. This trend toward high IC integration was the key ingredient responsible for morphing the "brick" cellular telephone of the 1990s into the palm-sized "clam shell" phone of today. Today, everyone, young children included, uses cell phones. This is true not only in the United States but worldwide. In terms of availability, cell phones are to this decade what personal computers were to the 1980s and 1990s. Mobile cellular phones have indeed changed the world, and these emerging IC technologies had a lot to do with it. These new product trends were driven by the availability of new and highly integrated RFICs. Transceiver designs moved away from realizations involving separate components attached to a common PCB, to one (or a few) RF chips based on one of the new silicon technologies. Currently, many low-frequency analog designers are entering the field in order to apply their craft of designing very large integrated circuits to the RF frequency range. Most of the GaAs technologies have been ignored by these analog designers (because of cost) when designing the new, highly integrated transceiver chips.

There are two exceptions to this trend. The first is infrastructure amplifiers and mixers, which remain mostly in GaAs. The second exception includes handset PAs and T/R switches, which also remain in GaAs. The scope of this book is chiefly those designs made in support of cellular infrastructure and instrument applications. So, the question remains, are these cellular infrastructure (and instrument) amplifiers, mixers, voltage-controlled oscillators (VCOs), and switches, strictly speaking, RFICs or MMICs? Good question. It all depends on how one defines MMIC and RFIC technologies.

In many ways, RFIC devices are replacements for discrete circuits. Their frequencies are low enough and their bandwidth is narrow enough that, in general, transmission line parasitic elements do not greatly affect performance. This is a big relief to the designer, who is not facing the difficult goals of wide-bandwidth, high-frequency operation where designs require modeling every transmission line like parasitic elements in order to succeed.

RFICs have always relied on the same circuit elements used in MMICs use, such as spiral inductors and metal insulator metal (MIM) capacitors. These elements naturally have complicated models, each of which must be carefully analyzed in a top-notch simulator in order to predict performance accurately. Like the MMIC before it, the RFIC cannot be tuned, or "tweaked." Once it is fabricated, "what you see is what you get." To avoid a costly series of design "spins," it is very important to model and simulate an RFIC accurately. However, these concerns can be mitigated to some degree by using feedback (both digital and analog) to control performance parameters. Some examples are variable bias circuits and automatic gain-control circuits.

Concurrent with the wireless revolution of the late 1980s and early 1990s, a similar revolution was happening in device and fabrication technology. For many years, the only transistor technologies available to the RFIC/MMIC designer had been silicon bipolar or GaAs MESFET. That situation changed drastically during this period for two important reasons. The first was the exploration and exploitation of heterojunctions, and the second was the availability of CMOS devices operating at RF/microwave frequencies. Heterojunction devices were first proposed in the late 1950s by Herb Kromer, who ultimately won a Nobel Prize for this work [11].

Heterojunctions significantly increase the degrees of freedom available to the device designer. No longer are device parameters adjustable only with doping gradients; with heterojunctions, the dissimilar material's energy band gap becomes a controlling aspect for determining performance The Ft performance of nonheterojunction transistors (i.e., homojunction transistors) is dependent on the ratio of the donor concentrated in the emitter to the acceptor concentration in the