Invited paper

Evolution and recent advances in RF/microwave transistors

Juin J. Liou and Frank Schwierz

Abstract — Most applications for radio frequency/microwave (thereafter called RF) transistors had been military oriented in the early 1980s. Recently, this has been changed drastically due to the explosive growth of the markets for civil wireless communication systems. This paper gives an overview on the evolution, current status, and future trend of transistors used in RF electronic systems. Important background, development and major milestones leading to modern RF transistors are presented. The concept of heterostructure, a feature frequently used in RF transistors, is discussed. The different transistor types and their figures of merit are then addressed. Finally an outlook of expected future developments and applications of RF transistors is given.

Keywords — microwave devices, RF devices, heterostructures, HEMT, HBT, frequency limits, RF CMOS.

1. Introduction

Currently RF electronics is most likely the fastest growing segment of semiconductor industry. This is due to the explosive growth in the wireless communications market during the past 10 years. Currently, there is a string of further applications which are either already commercially available or are expected to come to market in the near future. Examples are the 3rd generation cellular phones with extended functionality (e.g. mobile internet access), satellite communication services such as direct broadcast satellite (DBS) and local multipoint distribution system (LMDS), and local area networks such as wireless local area network (WLAN) and wireless personal area network (WPAN), also known as Bluetooth.

About 20 years ago, the situation was much different. During that time, RF electronics was somewhat mysterious, and their applications had been mainly military (e.g. secure communications, electronic warfare systems, missile guidance, control electronics for smart ammunition, radars) and the funding for their development came mainly from government agencies. In the first half of the 1980s, satellite television using low-noise transistors operating at 12 GHz in the receiver front-ends emerged as the first civil application of RF transistors with a market volume worth mentioning.

The backbone of RF systems is high-speed transistors with the capability of operating at GHz frequencies. In the following sections we will introduce important figures of merit (FOMs) of RF transistors and cover the evolution of these devices. This will be followed by the discussions of different types of RF transistors and major milestones of their development. Finally, the year 2003 state of the art of RF transistors will be highlighted, and an outlook of expected future development will be given.

2. RF transistor FOMs

The term RF stands for radio frequency and is commonly designated as electromagnetic waves with frequencies around and above 1 GHz. Thus RF transistors are devices with the capability to operate and amplify signals at GHz frequencies.

RF transistors are used in a large number of different circuits, such as low-noise and power amplifiers, mixers, oscillators, frequency converters, etc. Although the requirements on transistor performance differ from application to application, RF transistors in general can be divided into two groups: small-signal low-noise transistors and power transistors. For low-noise transistors, very low noise in the transistor and high operating frequency are desired, while power transistors are designed for high output power at high operating frequency.

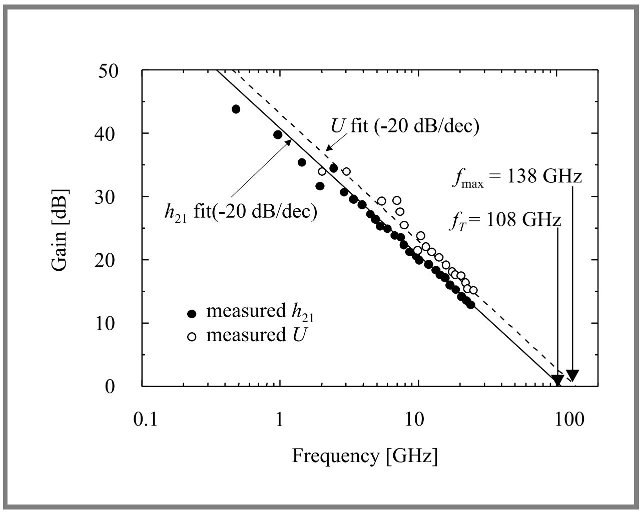

Fig. 1. Current gain, unilateral power gain, and extrapolated f_T and $f_{\max}$ of a GaAs MESFET. Data taken from [4].

RF engineers use several different FOMs to characterize transistors. These FOMs are the characteristic frequencies including the cutoff frequency f_T and maximum frequency for oscillation $f_{\max}$, the minimum noise figure $NF_{\min}$, and the RF output power P_{out} [1, 2]. The cutoff frequency is the frequency at which the small signal current gain of the transistor, h_{21}, becomes unity (i.e., 0 dB). The maximum frequency of oscillation, on the other hand, is the frequency at which the unilateral power gain of the transistor, U, becomes unity. Both h_{21} and U are frequency dependent and roll off with a slope of −20 dB/dec at high frequencies. Figure 1 shows the measured h_{21} and U of a typical RF transistor. As can be seen, f_T and $f_{\max}$ can be estimated by extrapolation of the lower frequency data to the frequency axis using the known −20 dB/dec slope. This practice is not only convenient but in some cases inevitable because of the frequency limit of the measurement equipment. P. Greiling [3] stated in his review of the history of GaAs field-effect transistor (FET): "For those of us associated with this technology, this measurement problem always seems to exist. We are in a catch 22 situation in which we are developing circuits for instruments that are needed to measure the circuits we are developing".

3. Period between 1960 and 1980

Since the invention of the bipolar junction transistor (BJT) in 1947, device engineers have devoted a lot of efforts to increase the speed and operating frequency of transistors. The first transistors capable of amplifying signals in the frequency range around 1 GHz were Ge BJTs developed in the late 1950s. Soon after that, Si and GaAs BJTs had been exploited for high-frequency applications, and the Si BJT became the dominating transistor type in RF electronics [5]. In 1970, the state of the art Si BJTs showed minimum noise figures of 1.3, 2.6 and 4 dB at frequencies of 1, 2, and 4 GHz, respectively, and output powers of 100, 20, and 5 W at frequencies of 1.2, 2, and 4 GHz, respectively [5].

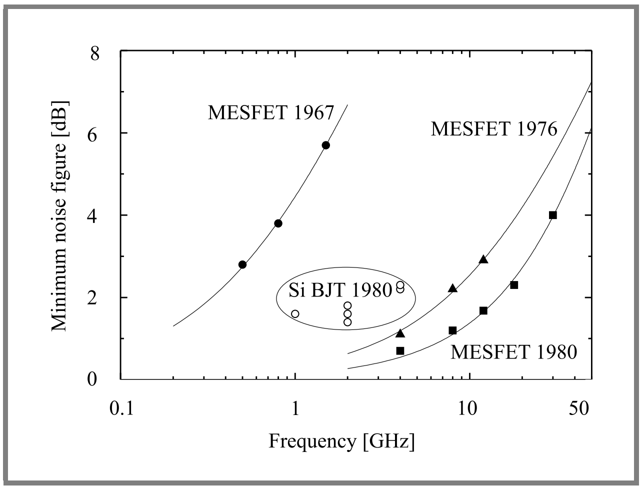

Fig. 2. State of the art Si BJTs and GaAs MESFETs in terms of the minimum noise figure reported in 1980.

The development of GaAs BJTs, however, had only limited success. By 1968, the interest in these transistors declined and the research activities stopped [6]. More success had achieved for GaAs FETs, however. In 1966, C. Mead presented the first GaAs metal-semiconductor FET (MESFET) and laid the foundation for a revolution in RF electronics [7]. One year later, a GaAs MESFET with $f_{\max}$ of 3 GHz was reported [8]. In 1970, a GaAs MESFET with a record $f_{\max}$ around 30 GHz was obtained [9], which clearly exceeded the performance of any other transistor type at that time, and in 1973 the 100 GHz $f_{\max}$ mark was reached [10]. Both low-noise and power GaAs MESFETs became commercially available in the mid 1970s.

Si BJTs and GaAs MESFETs were the only RF transistor types available in the late 1970s. Si BJTs were commonly used at frequencies below 4 GHz, whereas in the frequency range between 4 and 18 GHz the GaAs MESFET was the device of choice. Figure 2 shows the minimum noise figures of Si BJTs and GaAs MESFETs developed in this period.

4. Period between 1980 and 2000

4.1. Development of III-V HEMTs

In the late 1970s experiments at Bell Labs revealed the existence of a two-dimensional electron gas (2DEG) in epitaxially grown heterostructures consisting of undoped GaAs and n-doped AlGaAs. Both materials have the same lattice constant, thus resulting in a lattice matched heterostructure. The measured electron mobility in the 2DEGs was much higher than that in bulk GaAs [11]. The underlying physics is shown in Fig. 3. Electrons transfer from the conduction band of the doped AlGaAs to the energetically lower conduction band of the undoped GaAs. This transfer creates an electric field and band bendings at the heterointerface. The transferred electrons are confined in a narrow potential well on the GaAs side and are spatially separated from the donor ions. Thus ionized impurity scattering is largely suppressed, a mechanism leading to a high electron mobility.

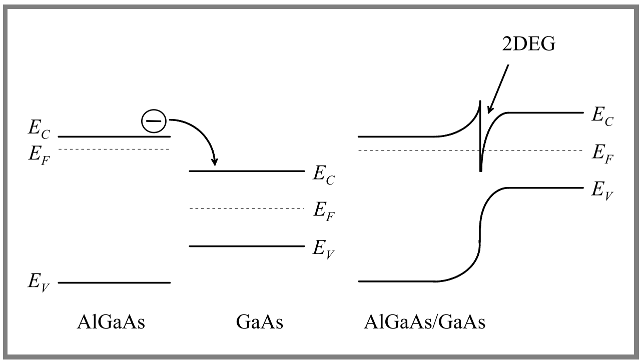

Fig. 3. Band diagram of the AlGaAs/GaAs heterostructure in HEMTs.

Engineers were interested in developing a transistor structure taking the advantage of high 2DEG mobility. The basic idea came again from Bell Labs [12], but the first successful realization of such a device was reported by researchers at Fujitsu [13]. The Bell group called their device selectively doped heterostructure transistor (SDHT), while the name of the Fujitsu device was high electron mobility transistor (HEMT). The naming of this transistor became even more confusing because other groups reporting experimental transistors of the same kind called their devices modulation doped FET (MODFET, University of Illinois, Rockwell) and two-dimensional electron gas FET (TEGFET, Thomson). The name HEMT prevails and is widely used by the RF community.

Early HEMTs consisted of the AlGaAs/GaAs material system. They showed better RF performance compared to GaAs MESFETs, especially in terms of minimum noise figure and output power, but the performance improvement was less than anticipated. One of the targets in HEMT design is the combination of a high electron mobility μ_0 with a high 2DEG electron sheet density n_s. It was found later that, by replacing the GaAs layer with an InGaAs layer, the product $\mu_0 \times n_s$ can be considerably increased. Thus, in the mid 1980s, the AlGaAs/InGaAs heterostructure was introduced in HEMTs, and the most prominent types are the AlGaAs/InGaAs/GaAs and InAlAs/InGaAs/InP HEMTs.

The lattice constant of InGaAs is larger than that of AlGaAs and GaAs. When grown on GaAs substrate, the atoms of the InGaAs layer can be adjusted to accommodate the GaAs lattice, thus resulting in a strained layer (frequently called pseudomorphic layer), provided the InGaAs layer is thinner than the so-called critical thickness t_c. For $In_{0.2}Ga_{0.8}As$ layers, which are typical for the GaAs pseudomorphic HEMT (PHEMT), t_c is about 20 nm. The heterostructure system $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ grown on InP substrate is lattice matched for $x = 0.53$. A further increase in the In content, i.e. $x > 0.53$, results in a strained layer as well. Figure 4 shows the reported $\mu_0 \times n_s$ products for various heterostructures, which clearly demonstrates the advantage of high In-content layers [14].

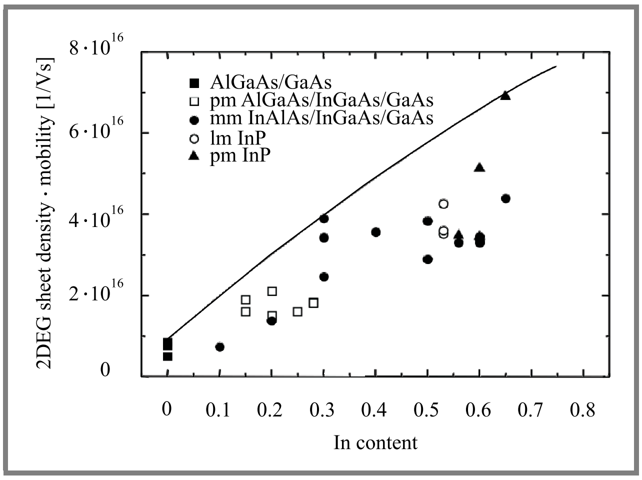

Fig. 4. Product $\mu_0 \times n_s$ versus In content in different HEMTs: lm – lattice matched, pm – pseudomorphic, mm – metamorphic.

GaAs PHEMT became commercially available in the early 1990s and are now in widespread use for both low-noise and power amplifications. Figure 5 shows the reported f_T and f_{max} of GaAs PHEMTs [14].

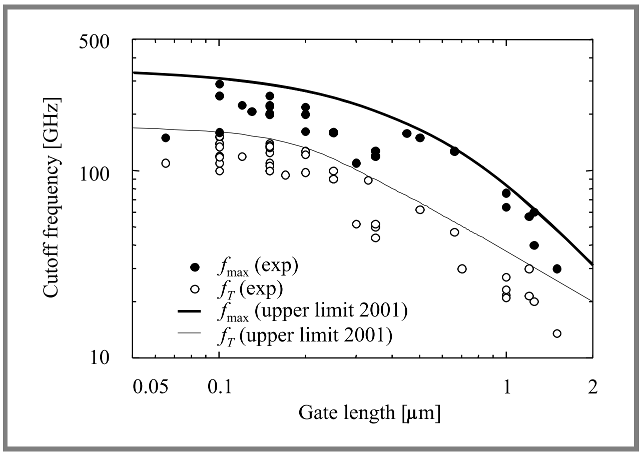

Fig. 5. Reported f_T and f_{max} versus gate length for different GaAs PHEMTs.

Although InP HEMTs show even better RF performance compared to GaAs PHEMTs, these transistors still await for commercialization. The main reasons are the low degree of maturity of InP technology and the InP substrates, which are expensive and available only in small diameters. Nevertheless, InP HEMTs possess the lowest noise figures and the highest operating frequencies among all field-effect transistors.

4.2. Development of III-V HBTs

The basic idea to use a heterostructure in bipolar transistors is almost as old as the bipolar transistor itself. In 1948, W. Shockley described the advantage of a bipolar transistor consisting of a wide bandgap emitter and a narrow bandgap base [15]. The physical effect exploited in a heterostructure bipolar transistor (HBT) is shown in Fig. 6. Because of the bandgap difference at the emitter-base heterjunction, electrons moving from the emitter to the base encounter a smaller energy barrier to be surmounted compared to that to be surmounted by holes moving from the base to the emitter. Thus, hole injection into the emitter is effectively reduced. This effect allows for the realization of a very thin and highly doped base layer, thereby leading to a short base transit time and low base resistance. As a consequence, HBTs with extremely high f_T and f_{max} values are possible.

It took more than 30 years to materialize Shockley's idea in practical devices, as the advance in epitaxial growth technology, especially the development of molecular beam epitaxy (MBE), allowed for the growth of high-quality heterostructures and the realization of GaAs HBTs in the early 1980s. To date, GaAs HBTs with AlGaAs and InGaP emitters are commercially available and used mostly

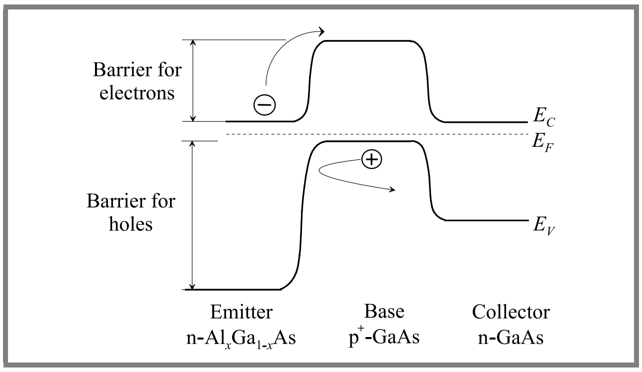

Fig. 6. Band diagram of the AlGaAs/GaAs heterostructure in HBTs.

for power amplification in wireless communication systems.

Much effort has also been spent on the development of the InP HBT, which consists of an InAlAs emitter, InGaAs base, and either InGaAs or InP collector. InP HBTs show higher f_T's and $f_{\max}'$s than GaAs HBTs but are not yet commercially available. Recently an interesting and novel InP HBT utilizing the substrate transfer has been reported [16]. This concept dramatically reduces the size of the extrinsic transistor, which minimizes the collector-base capacitance, and results in an extremely high $f_{\max}$. A transferred substrate HBT with an extrapolated $f_{\max}$ of more than 1 THz has been reported [17]. This is the highest $f_{\max}$ ever obtained from a three-terminal semiconductor device.

Because of economical reasons, it is always desirable to use Si-based devices instead of III-V devices, provided that the performance of the Si-based devices is adequate. A major step to use Si-based transistors at frequencies above 4 GHz was the development of SiGe HBTs. These transistors consist of a strained SiGe base layer embedded between the Si emitter and collector. The first SiGe HBT was reported in 1987 [18], and the RF performance of SiGe HBTs has improved continuously since. Currently SiGe HBTs are commercially available, and both f_T and $f_{\max}$ of advanced laboratory SiGe HBTs are exceeding the 300 GHz mark.

4.3. Further developments

Three directions in RF transistor research during the 1990s are worth mentioning. The first is the availability of the Si MOSFET as an RF device. Despite the fact that the Si MOSFET had not been considered seriously in the past for RF applications due to its relatively low speed, the continuous scaling and increasing maturity of short-gate Si MOS technology in recent years has led the MOSFET to become a strong candidate for applications in the lower GHz range. In fact, the topic RF CMOS was frequently discussed at all major device conferences around the world since the mid-1990s. Meanwhile Si laterally diffused MOSFET (LDMOSFET) for high-power applications up to 2.5 GHz and small-signal RF CMOS circuits are commercially available.

The second direction is the investigation of wide bandgap semiconductors, such as SiC and III-nitrides, for use in RF power transistors with large output powers in the GHz range. The wide bandgaps of these materials (3.2 eV for SiC and 3.4 eV for GaN compared to 1.1 eV for Si and 1.4 eV for GaAs) result in high breakdown fields and high operating temperatures for wide bandgap transistors. Most prominent devices are SiC MESFETs and AlGaN/GaN HEMTs. SiC MESFETs became commercially available in 1999, and AlGaN/GaN HEMTs with f_T and $f_{\max}$ exceeding 100 GHz and extremely high output power densities (output power per mm gate width) have been reported.

Finally, the so-called GaAs metamorphic HEMT (MHEMT) should be mentioned [19]. The key feature of this transistor is an InGaAs channel layer grown on GaAs substrates with an In content higher than that used in GaAs PHEMTs. This is done using a thick relaxed InGaAs buffer layer serving as a relaxed pseudosubstrate for the actual device layer grown on top of the buffer. The main advantage of the metamorphic approach is that inexpensive GaAs substrates can be used to obtain InP HEMT like performance.

Furthermore, the conventional Si BJTs and GaAs MESFETs have been improved in terms of RF performance and maturity.

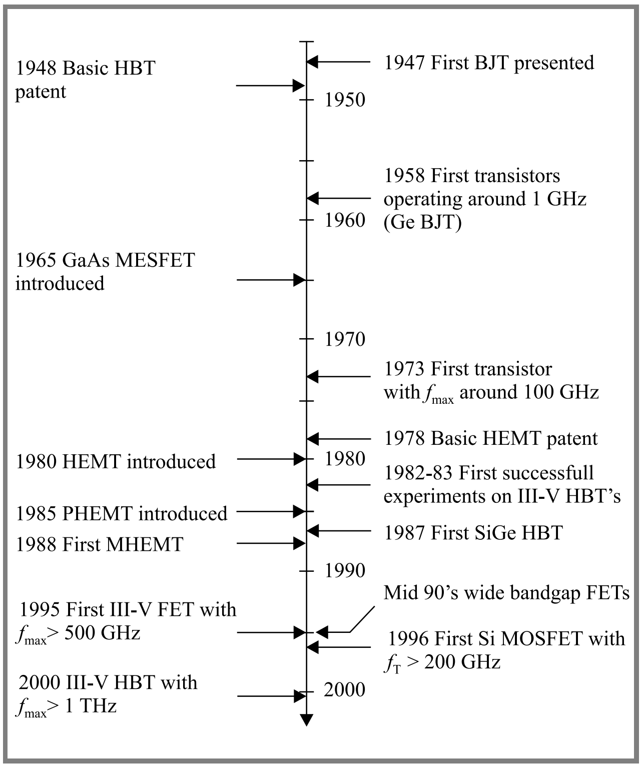

Fig. 7. Major milestones for the evolution of RF transistors.

Figure 7 summaries the major milestones of the evolution of RF transistors during the past four decades.

5. State of the art of RF transistors – 2003

During the more than 40 years of RF transistor development, the operating frequency has been increased continuously. This became possible by shrinking the critical device dimensions, introducing heterostructures, and exploiting the properties of new semiconductor materials.

Table 1 lists the state of the art performance in terms of f_T and $f_{\max}$ for different types of RF transistors. Two remarks should be made in regard to the values in Table 1. First, the $f_T - f_{\max}$ pairs do not necessarily belong to the same transistor. Second, the values represent the performance of laboratory test devices. Commercial devices possess lower f_T and $f_{\max}$ values, because for these devices not only high performance but also cost, yield, and reproducibility are of concern.

Table 1
State of the art of RF transistors in terms of f_T and $f_{\max}$

Transistor type	f_T [GHz]	Ref.	$f_{\max}$ [GHz]	Ref.
GaAs MESFET	168	20	177	21
AlGaAs/GaAs HEMT	113	22	151	23
GaAs PHEMT	152	24	290	25
InP HEMT	562	26	600	27
SiC MESFET	22	28	50	28
AlGaN/GaN HEMT	121	29	195	30
Si MOSFET	245	31	193	32
SiGe HBT	350	33	338	34
GaAs HBT	156	35	350	36
InP HBT	377	37	478	38
InP HBT (TS)	300	39	1080	17
TS – transferred substrate.				

To date, InP transistors possess the highest $f_T's$, the highest $f_{\max}'s$, and thus the highest operating frequencies of all transistor types. InP HEMTs show the lowest noise figure among all RF transistors. Minimum noise figures below 1 dB at 60 GHz and of 1.2 dB at 94 GHz have been reported for InP HEMTs having a 0.1 μm gate length [40]. GaAs MHEMTs show only slightly higher noise figures than InP HEMTs. State of the art GaAs PHEMTs with noise figures less than 1 dB up to 30 GHz have been reported [41]. In general, FETs are less noisy compared to bipolar transistors. On the other hand, bipolar transistors possess higher output power densities (both per unit chip area and per mm device width) than field effect transistors. For example, output power densities of 10 mW per μm^2 emitter area and 30 W per mm emitter length have been achieved in a GaAs HBT [42]. In the case of power FETs, wide bandgap FETs demonstrate the highest output power densities up to 20 GHz. An AlGaN/GaN HEMT with 11.2 W/mm at 10 GHz has been realized [43]. Currently the total output power of AlGaN/GaN HEMTs is, however, still lower compared to SiC MESFETs and III-V power HEMTs. Work is under way to realize large area AlGaN/GaN HEMTs with high output powers. The only transistor types delivering useful output power above 60 GHz are GaAs PHEMTs and InP HEMTs. A main drawback of InP HEMTs is the low breakdown voltage stemmed from the narrow bandgap of the In-rich InGaAs layers.

6. Future outlook and developments

During the 1970s and 1980s, military applications dominated RF electronics, and the device performance was the major concern while the economical factor played only a secondary role. The situation has changed dramatically recently, as the new global political situation in the 1990s has led to considerable cuttings in the military budgets. Furthermore, a strong shift to consumer applications is taking place. Thus, the design philosophy for most RF systems has changed from “performance at any price” to “sufficient performance at lowest cost”.

Prior to 1980, only two transistor types (Si BJT and GaAs MESFET) existed. In 2003, a large variety of different competing devices and technologies is available, including Si CMOS, Si BJT, SiGe HBT, GaAs MESFET, GaAs HEMT, GaAs HBT, InP HEMT, InP HBT, and wide bandgap FETs. Each of the different transistor types has certain advantages and disadvantages in terms of maturity, cost, and performance. The situation of the circuit designer can be described by “the wider the choice, the greater the difficulty”. In the mass consumer markets (operating frequencies up to 2.5 GHz), all technologies can compete, but Si-based technologies have a clear cost advantage. Most applications above 2.5 GHz belong to GaAs-based transistors (MESFET, HEMT, HBT). High-performance applications above 40 GHz are dominated by InP-based transistors. The role of RF CMOS is expected to grow in the future. The upper frequency limits of Si-based technologies will increase, due to the MOSFET scaling and the use of SiGe HBTs. The importance of GaAs PHEMTs and HBTs will continue to grow as well. For some specific applications, the commercial use of InP devices can be expected. On the other hand, the market share of the GaAs MESFET is shrinking, and this trend will continue for many years to come.

We conclude with two simple statements. First, in the foreseeable future, the dynamic growth of RF electronics will continue and new applications will emerge. Second, RF transistors are no longer exotic but becoming more and more mainstream devices.

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Juin J. Liou received the B.Sc. (honors), M.Sc., and Ph.D. degrees in electrical engineering from the University of Florida, Gainesville, in 1982, 1983, and 1987, respectively. In 1987, he joined the Department of Electrical and Computer Engineering at the University of Central Florida, Orlando, Florida, where he is now a Professor. Dr. Liou has published six textbooks (another in progress), more than 180 journal papers (including 11 invited articles), and more than 130 papers (including 35 keynote or invited papers) in international and national conference proceedings. He has been awarded more than $4.0 million of research grants, and he is an associate editor for the *Simulation Journal* and a regional editor for the *Microelectronics Reliability.* Dr. Liou received ten different awards on excellence in teaching and research from the University of Central Florida and two different awards from the IEEE Electron Device Society. Dr. Liou is an IEEE EDS Distinguished Lecturer, an IEEE EDS Administrative Committee Member, and a Senior Member of the IEEE.

e-mail: liou@pegasus.cc.ucf.edu
School of Electrical Engineering and Computer Science
University of Central Florida
Orlando, FL 32186, USA
Department of Electronics Science and Technology
Huazhong University of Science and Technology
Wuhan, P. R. China

Frank Schwierz received his Ph.D. degree in electrical engineering from the Technical University Ilmenau, Ilmenau, Germany, in 1983. He is currently Head of the RF and Nanoelectronic Device Group at Technical University Ilmenau, Germany. Dr. Schwierz's research interests include semiconductor device physics, simulation, and modeling. Dr. Schwierz has published 1 book and more than 60 journal and conference papers. He is a member of the Council of the Center of Micro- and Nanotechnology, Germany, and a Senior Member of the IEEE.

e-mail: frank.schwierz@tu-ilmenau.de
Fachgebiet Festkörperelektronik
Technische Universität Ilmenau
P.O. Box 100565, 98684 Ilmenau, Germany