Extended Abstracts of the 2001 International Conference on Solid State Devices and Materials, Tokyo, 2001, pp. 74–75

C-2-1 (Invited)

Evolution and Current Status of RF Semiconductor Devices

Juin J. Liou and Frank Schwierz [1]

School of Electrical Engineering and Computer Science, University of Central Florida, Orlando, FL 32186, USA
Phone: +1-407-823-5339; Fax: +1-407-823-5835; E-mail: liou@pegasus.cc.ucf.edu
[1]Fachgebiet Festkörperelektronik, Technische Universität Ilmenau, 98684 Ilmenau, Germany

Abstract

Prior to the early 1980s, most applications for RF transistors had been military oriented. Recently, this has been changed drastically due to the explosive growth of the markets for civil wireless communication systems. This paper covers the evolution and current status of transistors used in RF electronic systems. Important background, development and major milestones leading to modern RF transistors are presented. 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.

1. Introduction

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

Currently RF electronics is most likely the fastest growing segment of semiconductor industry. The reason is the explosion of the markets for wireless communication systems during the last 10 years. Most prominent are cellular phones, but there is a whole 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 DBS (Direct Broadcast Satellite) and LMDS (Local Multipoint Distribution System), and local area networks such as WLAN (Wireless Local Area Network) and WPAN (Wireless Personal Area Network, also known as Bluetooth).

The backbone of RF systems is high-speed transistors with the capability of operating at GHz frequencies. In the following sections we introduce important figures of merit (FOMs) of RF transistors and trace the evolution of these devices. The different types of RF transistors and major milestones of their development are discussed. Finally, the year 2001 state of the art of RF transistors is highlighted, and an outlook of expected future developments is given.

2. RF Transistor FOMs

RF engineers use several different FOMs to characterize transistors. They include the characteristic frequencies f_T and f_{max}, the minimum noise figure NF_{min} at a given frequency, and the RF output power P_{out} at a given frequency [1]. The cutoff frequency is the frequency at which the small signal current gain of the transistor, h_{21}, becomes unity or 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.

3. Evolution and Current Status

In the late 1970s experiments at Bell Labs revealed the existence of 2DEGs (Two-Dimensional Electron Gas) 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 2DEGs was much higher compared to that in bulk GaAs [2]. Engineers were interested in developing a transistor structure taking advantage of the high 2DEG mobility. The basic idea came again from Bell Labs [3], but the first successful realization of such a device was reported by researchers at Fujitsu [4]. The Bell group called their device SDHT (Selectively Doped Heterostructure Transistor) while the name of the Fujitsu device was HEMT (High Electron Mobility Transistor).

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 mobility, μ_0, with a high 2DEG electron sheet density, n_s. It turned out that by introducing an InGaAs layer, the product $\mu_0 \times n_s$ can be considerably increased compared to the conventional AlGaAs/GaAs structure. Thus, in the mid 1980s, AlGaAs/InGaAs heterostructures was introduced in HEMTs, and 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 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. During the 1990s GaAs pHEMT became commercially available and are now in widespread use for both low-noise and power amplifications. Figure 1 shows the reported f_T and f_{max} of 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.

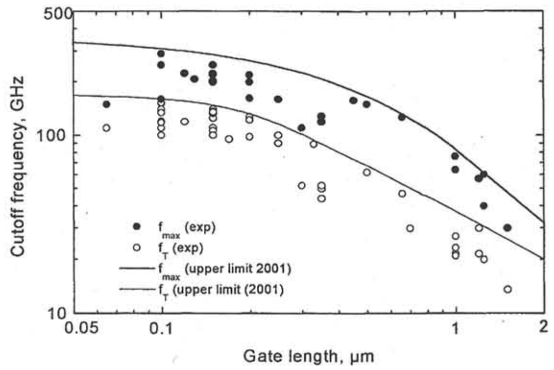

Fig. 1 Reported f_T and f_{max} vs. gate length for different GaAs pHEMTs.

The basic idea of heterojunction bipolar transistors (HBTs) is almost as old as the bipolar transistor itself. Already in 1948 W. Shockley described the advantage of a bipolar transistor consisting of a wide bandgap emitter and a narrow bandgap base [5]. It took more than 30 years to materialize Shockley's idea in practical devices, as the progress in epitaxial growth, especially the development of MBE (Molecular Beam Epitaxy), 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. Their preferred application is power amplification in wireless communication systems.

Much effort has also been devoted to the development of InP HBTs. These transistors consist of InAlAs emitters, InGaAs base layers, and either InGaAs or InP collectors. InP HBTs show higher f_T's and f_{max}'s compared to GaAs HBTs but are not yet commercially available. Recently an interesting and novel InP HBT realized by a substrate transfer has been reported [6]. This concept dramatically reduces the size of the extrinsic transistor, which minimizes the collector-base capacitance, and extremely high f_{max} can be obtained. A transferred substrate HBT with an extrapolated f_{max} of more than 1 THz has been reported [7]. This is the highest f_{max} ever obtained from a three-terminal device.

Because of economical reasons it is always desirable to use Si-based devices for a specific application instead of III-V devices, provided the performance of the Si-based device is satisfactory. 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 narrow bandgap SiGe base embedded between the Si emitter and collector. The first SiGe HBT was reported in 1987 [8]. Since then, the RF performance of SiGe HBTs has improved continuously. Currently SiGe HBTs are commercially available, and both f_T and f_{max} of advanced SiGe HBTs are approaching the 200 GHz mark.

Three directions in RF transistor research during the 1990s are worth mentioning. The first is the application of the standard device of Si VLSI, i.e. the Si MOSFET, as an RF device. Despite the fact that in the past the Si MOSFET had not been considered seriously for RF applications due to its relatively low speed, the continuous FET 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 on all major device conferences around the world in the second half of the 1990s. Meanwhile Si LDMOSFET (Laterally Diffused MOSFET) 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 at the GHz range. The wide bandgap 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) results in high breakdown fields and high operating temperatures for wide bandgap transistors. Most prominent 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 metamorphic GaAs HEMT (GaAs mHEMT) should be mentioned [9]. The key feature of this transistor is an InGaAs 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 transistors with InP-like performance.

References

[1] F. Schwierz and J. J. Liou, *Microelectron. Reliab.*, **41**, 145 (2001).

[2] R. Dingle, H. L. Störmer, A. C. Gossard, and W. Wiegman, *Appl. Phys. Lett.*, **33**, 665 (1978).

[3] R. Dingle, A. C. Gossard, H. L. and Stormer, U.S. Patent 4,163,237, Filed Apr. 24, 1978, Issued Jul. 31, 1979.

[4] T. Mimura, S. Hiyamizu, T. Fujii, and K. Nanbu, *Jpn. J. Appl. Phys.*, **19**, L225 (1980).

[5] W. Shockley, U.S. Patent 2,569,347, Filed Jun. 26, 1948, Issued Sep. 25, 1951.

[6] Q. Lee, B. Agarwal, D. Mensa, R. Pullela, J. Guthrie, L. Samoska, and M. J. W. Rodwell, *IEEE Electron Device Lett.*, **19**, 77 (1998).

[7] M. Rodwell, Keynote Speech, *IEEE BCTM* 2000.

[8] S. S. Iyer, G. L. Patton, S. L. Delage, S. Tiwari, and J. M. C. Storck, *Tech. Dig. IEDM* 2000, p. 847.

[9] W. E. Hoke, et al., *J. Vac. Sci. Technol.*, **B17**, 1131 (1999).