ISSN: 1999-1630

SEU Journal of Science and Engineering, Vol. 12, No. 2, December 2018

RF Semiconductor Devices Technology: History and Evolution, Prospects and Opportunities, Current and the Future

Muhibul Haque Bhuyan[*]

Department of Electrical and Electronic Engineering
Southeast University, Tejgaon, Dhaka, Bangladesh

Abstract

The recent growth in application areas in civil and military telecommunication engineering and technology has generated bulk consumer marketplaces for systems based on radio frequency (RF)/microwave semiconductor devices. This paper describes a comprehensive review on RF/microwave semiconductor device technology. The principal aim is to trace its history and evolution stages, then to find out the present status and future prospects, potential civil and military application areas, limitations, opportunities and challenges of RF semiconductor devices as well as to explore its appropriateness for future RF device applications. While digging out, the device physics of various compound and hetero-junction semiconductors' characteristics are also described so that the important reasons for the technological challenges of RF semiconductor materials are well understood. Comparative pictures are also presented among various RF devices in tabular forms in terms of their Figure of Merits (FOM).

Keywords: RF Electronics, RF Technology, RF Communication, Semiconductor Device.

I. Introduction

Semiconductor electronic devices are playing a vital role in driving the global economy over the last few decades (M. H. Bhuyan, 2011). Therefore, it has become an important topic of discussion due to its increasing influence on human society as well as space explorations and military projects. There is a strong correlation between the world GDP and semiconductor market's revenue growth as shown in Fig. 1 (IHS 2018).

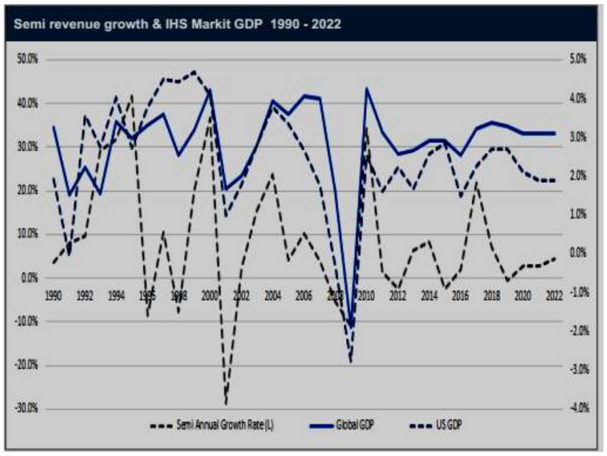

Figure 1: Correlation between global economy and revenue growth of semiconductor industry (IHS 2018)

The prime and crucial unit of the semiconductor electronics industry is the transistors, either MOS or bipolar devices. Approximately 70% of all semiconductor components are used in consumer related products worth of about US$350 billion. The number of transistors produced per year and the average cost with time as in Fig. 2, have been changing exponentially. In 2010, more than a billion transistors were produced for every person living on the Earth (MI, 2018)!

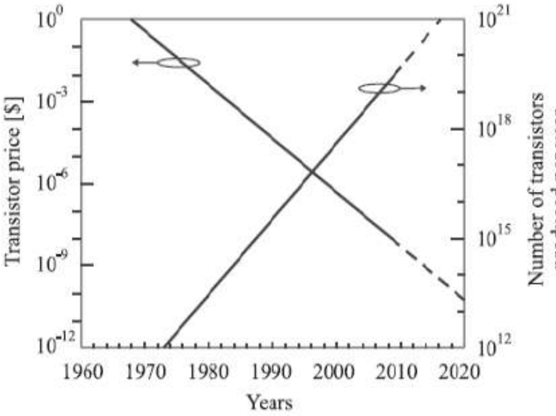

Figure 2: Number of transistors produced per year and transistor price with time (G. L. Arsov, 2013)

---

[*] **Corresponding Author:** Prof. Dr. Engr. Muhibul Haque Bhuyan, Professor and Chairman, Department of Electrical and Electronic Engineering, Southeast University, 251/A and 252, Tejgaon I/A, Dhaka 1208, Email: *muhibulhb@gmail.com*

There are various streams of semiconductor devices. The mainstream devices are mainly used in microprocessors and memories. Only the memory suppliers generated more than 28% of the total industry revenue in 2018 (IHS 2018).

The device that operate frequency above 1 GHz are called RF electronic device where RF transistor is the basic unit of construction. So, this is called the heart of information technology era. With the expansion of the smartphone use and evolution of 5G technology (Fig. 3), devices are using the nano scaled RF power semiconductor devices to get higher speed. With the increase in the need for higher data rates and greater spectral efficiency to be used for ever increasing high-speed mobile broadband internet connectivity. This has also led to the implementation of Long Term Evolution (LTE), which is supposed to enhance the growth of the RF electronics market.

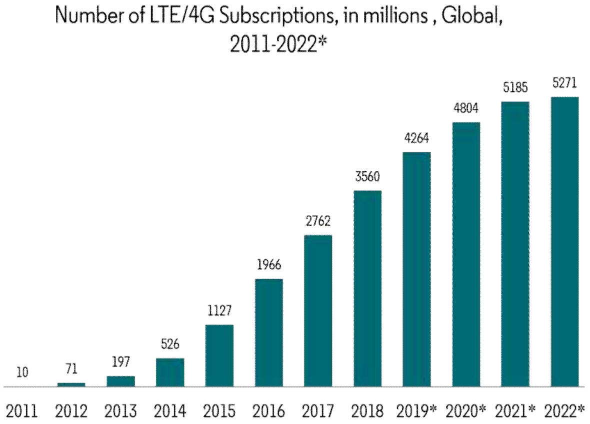

Figure 3: Growth of subscribers for LTE (MI: 2018)

The total market size of GaN-based RF devices will almost double within the next four years as shown in Fig. 4 (Yole, 2016).

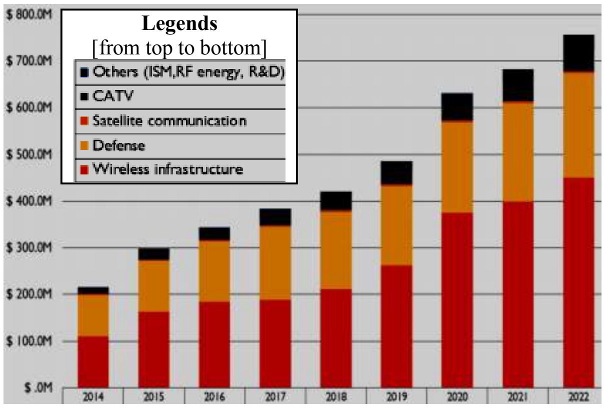

Figure 4: Forecast of GaN's RF market (Yole, 2016)

In this review paper, it is discussed about the history, evolution, types, structures, materials, modifications for performance improvement, construction, operation, current and future research trends on RF semiconductor devices. Different RF device performance parameters found from the literatures will also be presented. Finally, few application areas of RF electronics technology have been mentioned and then concluding remarks on this device are given.

II. History, Evolution, Research and Industry of RF Semiconductor Devices

Julius Edgar Lilienfeld (J. E. Lilienfeld, 1933), a physicist and electronic engineer, is credited with the first patents on the field-effect transistor (FET). He set out to find a solid-state replacement for the expensive and unreliable thermionic triode that consumed large power and space. Two years later, he presented the idea of the depletion mode MOSFET. Metal Oxide Silicon Transistors (MOST), which are built around field-effect principles, dominate semiconductor electronics, today after around 100 years. But the name MOSFET, originated from the Fairchild marketing department in October 1962 (C. H-T. Sah, 1988).

The notion of the inversion-mode MOSFET was proposed by Oscar Heil in 1935. Using the ideas of the 'point-contact transistor', Shockley completed the description of the BJT on 23 January 1948 and filed a patent on 26 June 1948. Shockley and his Bell Lab colleagues, Brattain and Bardeen, received the Nobel Prize in Physics in 1956 for this great invention. Soon the BJT became the dominating device in semiconductor electronics (C. H-T. Sah, 1988). Since then device engineers were trying to develop faster transistor. The first RF transistor with operating frequency at GHz range was introduced in the late 1950s using Ge-BJT. Later Si-BJTs became popular for RF transistor during 1960-70s (C. Hu, 1999).

The concept of the hetero-junction bipolar transistor (HBT) was first proposed by W. Shockley in 1948 and then patented by him in 1951 (W. Shockley, 1951). But H. Kromer (H. Kromer, 1957) developed the detailed theory and analysis of HBTs. He found that it is possible to raise the emitter injection efficiency (γ) by using an emitter material with a wider band gap than that of the base material to get higher operating speed.

In 1956, M. M. Atalla and Dawon Kahng prepared a p-type inversion-channel Si MOSFET using thermally grown oxide for the gate insulator. In 1958, the first integrated circuit was built at Texas Instruments using two transistors made of Ge using gold wires for interconnections by Jack Kilby who received the Nobel Prize in Physics in 2000 for it. But the first patent is awarded to Robert Noyce for a monolithic silicon integrated circuit in April 25, 1961. The MOSFET dramatically increased its importance in 1963 when Wanlass and Sah of Fairchild Semiconductor first invented the CMOS (Complementary MOS) circuit that reduces power consumption and dissipation with less space due to which MOSFETs have been the most widely used semiconductor device since then. The first two commercial MOSFETs were announced in late 1964, one by Fairchild and a second by Radio Corporation of America (C. H-T. Sah, 1988). In 1958, the first transistor that was operated at RF frequency (1 GHz) was Ge BJT.

The major breakthrough in RF electronics came when GaAs MESFET was introduced in 1965. Within the five years, the operating frequency of RF transistor was possible to enhance up to 30 GHz in 1970 (F. Cooke, 1971). During 1970-80s, Si BJTs and GaAs MESFET were mainly used for RF electronic devices for operating frequency less than 4 GHz and 4-18 GHz respectively. In 1973, the first transistor with maximum operating frequency, f_{max} with around 100 GHz was introduced.

In the late 1970s, high quality mono-crystalline hetero-structures using compound semiconductors were introduced. Such as, AlGaAs/GaAs hetero-structures were developed at Bell Labs with very high electron mobility (R. Dingle *et al.*, 1978). The first device, using AlGaAs/GaAs hetero-structure, introduced by any commercial manufacturer was Fujitsu, Japan in 1980 and they named it High Electron Mobility Transistor (HEMT) (T. Mimura *et al.*, 1980).

The first gallium nitride metal semiconductor field-effect transistors (GaN MESFET) were experimentally demonstrated in 1993 and they are being actively developed (M. A. Khan *et al*, 1993).

In 2010, the first enhancement-mode n-channel GaN transistors became generally available (S. Davis, 2010). These devices were designed to replace the power MOSFETs in applications where switching speed or power conversion efficiency is critical. The cost of these transistors are similar to Si power MOSFETs but with the superior electrical performance of GaN.

While most integrated circuits fabricated during the 1960s and 1970s were based on bipolar transistors, MOSFET-based circuits gained importance and took over the leading role in the early 1980s. RF electronics technology becomes a part of the semiconductor electronics industry during 1970s and 80s because of its military applications. After that its first civil applications were introduced in 1980s when satellite TV channels started to use GaAs based devices around the 12 GHz frequency band. This created a market economy for the RF electronics. But actual mass volume market economy was created in the early 1990s when cellular telecommunication systems started. This market is still growing upward.

In the past, Si-MOSFET-based devices were used in RF applications but these devices were slow due to low mobility (~650 $cm^2/V.s$) and surface roughness scattering of free electrons in the inversion channel. But today's semiconductor devices use compound materials which has higher mobility (e.g., mobility of GaAs is ~4700 $cm^2/V.s$ and that of GaN is ~1500 $cm^2/V.s$).

Consequently, RF transistors are based on III-V compound semiconductors, mainly based on GaAs and InP. However, Si and SiGe based transistors are also used along with the wide band gap materials based RF transistors, such as, SiC and III-Nitrides, (e.g. GaN). Transistors manufactured using these technologies are called MOSFET, MESFET, HEMT, HBT, BJT etc. Though in the last decade, III-V based technology dominates in the RF transistors' markets, but very recently RF MOS has become a strong competitor in this regard. Only the GaN based RF semiconductor device market was valued at US$460.93 million in 2018 and is expected to reach a value of US$1597.36 million by 2024, at a CAGR of 23.20% during the forecast period 2019-2024. The RF power amplifier sub-segment is also expected to capture the largest market share, about 40% of the global RF power semiconductor market and is expected to create an incremental opportunity of US$10,817.6 million between 2018 and 2027. This is ascribed to the growth of the

Internet of Things (IoT), the advent of high speed telecommunication network and widespread applications across various industries. Statuses of different semiconductor technologies for RF transistors are shown in Table 1.

Table 1 Status of different semiconductor technologies for RF transistors

Technology	Maximum Operating Frequency, f_{op} (GHz)	Status	Preferred Applications
Si CMOS	5	R&D, P	D/A, A/D
Si LDMOS	3	P	PA
Si BJT	5	P	LN, PA
SiGe HBT	50	P, R&D	LN, PA (?)
GaAs MESFET	20	P	LN, PA
GaAs HEMT	60	P	LN, PA
GaAs HBT	30	P	LN, PA (?)
InP HEMT	200	R&D, P	LN, PA
InP HBT	150	R&D, P	PA
SiC MESFET	10	R&D, P	PA
AlGaN/GaN HEMT	20	R&D	PA, LN (?)

* A/D=Analog to Digital, D/A=Digital to Analog, LN=Low Noise, P=Planning, PA=Power Amplifier, R&D=Research and Development,

III. Performance Measurement Parameters of RF Semiconductor Devices

Performance evaluation is done by using few parameters called Figures of Merit (FOM), which is the number or quantities of those parameters that enable a device engineer to appraise the performance of a particular device and also to compare its performance with that of the other devices. An important measure of RF transistor is the cutoff frequency, f_T. At this frequency, the short circuit forward current gain of the device becomes unity. Figure 5 shows the cutoff frequency vs. gate length of n-channel MOSFETs. From 50-100-nm channel length MOSFETs, the cutoff frequency reached up to 200 GHz (H. S. Momose *et al*., 2001). Applying a frequently used rule of thumb that the cutoff frequency should be around 10 times the transistor's operating frequency, one could use these devices to design integrated circuits operating up to 20 GHz, which is higher than that for the great majority of modern RF electronic devices.

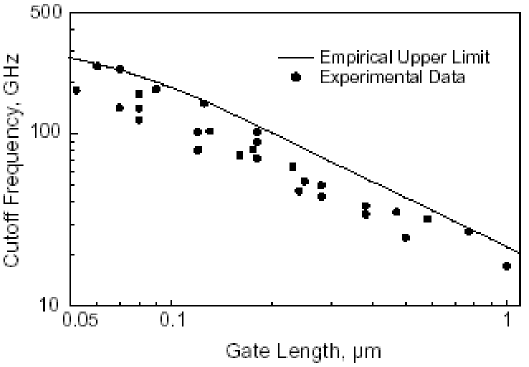

Figure 5: Reported cutoff frequency versus gate length of MOSFETs (J. J. Liou *et al*., 2003)

However, only a high cut-off frequency is not the only requirement for a good RF transistor. Another figure of merit (FOM) of RF device is the maximum frequency of oscillation, f_{max}, at which the unilateral power gain roll-offs to unity. Both of these frequency parameters (f_{max} and f_T) should be as high as possible for proper operation of the device. A conservative rule of thumb is that f_T should be equal to at least 10 times of the maximum operating frequency f_{max}.

Another important parameter of FOM is the minimum noise figure, NF_{min}, which is the minimum amount of noise generated inside the transistor. It should be as small as possible.

Another critical parameter of FOM is the output power, P_{out}, which is the RF power that can be delivered to the load. Sometimes, this parameter is defined in terms of per unit area of the device. It should be as high as possible. Therefore, all these four parameters of FOM should be considered for RF applications. In 1980, the reported output power of Si-BJT was 60W at 2GHz and that of GaAs-MESFET was 10W at 10GHz.

Properly designed III–V RF Field Effect Transistors (MESFET and HEMT) show comparable f_{max} and f_T, but typically with $f_{max} > f_T$. The situation is different for Si MOSFETs for which one could either realize short-channel transistors for high f_T with substantially lower f_{max} or long-channel transistors for rather low f_T with higher f_{max}. Hence, trade-off is needed while using Si MOSFETs. It is reported that the tradeoff resulted from the fact that a very high f_{max} can only be achieved with transistors having a high f_T and a low gate resistance, R_G.

To minimize the gate resistance, R_G, metal gates with multi-finger mushroom structures are frequently used in III–V FETs. The gates of Si MOSFETs are made of poly-silicon, which has a much higher resistivity than a metal. Reducing R_G is imperative for RF MOSFETs because R_G not only limits the power gain attainable at a certain frequency (and thus f_{max}), but also sets a lower limit to the minimum noise figure. There are several means to minimize the gate resistance of Si MOSFETs, such as,

1. Deposition of silicide on top of the poly-silicon gate,
2. Metal over gates on top of the poly-silicon gates,
3. Multi-finger gates with small finger width.

Recently, considerable progress on increasing the maximum frequency of oscillation of Si MOSFETs has been made. In 1980, the reported maximum frequency of oscillations of Si-BJT was 35GHz and that of GaAs-MESFET was up to 100GHz. But later reported maximum frequencies of oscillation are: f_{max} of 193 GHz (f_T of 178 GHz) for the 50-nm SOI-MOSFET (S. Narashima *et al.*, 2001) and f_{max} of 185 GHz (f_T of 120 GHz) of the 80-nm SOI-MOSFET (T. Hirose *et al.*, 2001). Because of the presence of Si/SiO$_2$ interface, MOSFETs are noisier than other RF transistors. Reported minimum noise figures NF_{min} of experimental Si MOSFETs were found around 1.5 dB at about 15 GHz (F. Schwierz *et al.*, 2003), and MOSFETs become too noisy at even higher frequency for practical microwave applications.

High-power microwave amplifiers used in the base stations for mobile communication systems, however, are designed for maximum operating (and thus breakdown) voltage to deliver maximum output power. For such kind of applications, very often, a different type of MOS device structure, called Laterally Diffused (LD) MOSFET, is used. Depending on the specific designs, typical f_T of LDMOSFETs is around 5-15 GHz, and the approximate drain-to-source breakdown voltage (BV_{DS}) is 20-40 V.

In the past, the preferred RF MOSFET structures were conventional single-gate bulk or single-gate SOI MOSFETs. Technical progress in bringing SiGe HBT technology to reality has been exceptionally rapid. The first functional SiGe HBT was demonstrated in December 1987 (S. S. Iyer *et al.*, 1987; G. L. Patton *et al.*, 1988). Worldwide attention was directed toward the technology in mid-1990 by the demonstration of a non-self-aligned SiGe HBT with a cut-off frequency of 75 GHz (G. L. Patton *et al.*, 1990). Recent progress on the SiGe HBT will help to expand the market share of MOSFETs in RF electronics. SiGe HBTs offer excellent RF properties (high speed, i.e. both high f_T and f_{max} and low noise figure), as evidenced by the noise margin (NF_{min}) given in Table 2 (M. H. Bhuyan, 2017).

Table 2 State of the art noise figures of SiGe HBTs

Cut-off Frequency, f_T (GHz)	**Noise Margin, NF_{min} (dB)**	**Reference**
2	0.14	H. Schumacher *et al.*, 1997
4	0.18	H. Schumacher *et al.*, 1997
10	0.20	D. R. Greenberg *et al.*, 2002
26	1.50	D. R. Greenberg *et al.*, 2002
278	1.748	O. Esame *et al.*, 2004

During the last few years, considerable reports have been devoted to realize SiGe HBTs from standard CMOS processes. This makes pure Si-based RF ICs possible, where SiGe HBTs are used in the critical parts which demand RF performance (such as frequency and noise performance) while Si MOSFETs are employed in other components. An interesting feature of SiGe HBTs is the fact that both f_T and f_{max} between 50 and 100 GHz can be realized with an emitter width larger than 0.4 μm (J. J. Liou *et al.*, 2003). This is different from the RF Si MOSFET, which requires a much smaller gate length to reach such high frequency limits.

For evaluating RF devices, its performance characteristics parameters, such as, the cutoff frequency (f_T), the maximum oscillation frequency (f_{max}), the minimum noise figure (NF_{min}), gate length, gate width, break down voltage, output power, power gain, power added efficiency (PAE), etc. are usually employed. Table 3 and Table 4 provide a summary of the reported f_T and f_{max} values respectively obtained for the different III-V HEMT devices in various literatures.

GaAs HBTs are commercially available in the market and generally used in RF power amplifiers while InP HBTs are still not matured enough. Table 5 provides state-of-the-art GaAs and InP based HBTs in terms of cut-off frequency and maximum operating frequency. Both of these devices can exihibit both frequency parameters above 200 GHz. However, InP substrate is expensive than that of GaAs.

Table 3 Record cutoff frequencies with gate length for different HEMT devices

Device Name	Cut-off Frequency, f_T (GHz)	Gate Length, L_G (nm)	Reference
AlGaAs/GaAs HEMT	113	100	A. N. Leopre *et al.*, 1988
p-HEMT on GaAs	152	100	L. D. Nguyen *et al.*, 1989
mm-HEMT on GaAs	200	120	D. L. Edgar *et al.*, 1999
mm-HEMT on InP	350	30	T. Suemitsu *et al.*, 1998
p-HEMT on InP	340	50	S. E. Rosenbaum *et al.*, 1995

Table 4 Record maximum frequencies with gate length for different HEMT devices

Device Name	Maximum Frequency, f_{max} (GHz)	Gate Length, L_G (nm)	Reference
AlGaAs/GaAs HEMT	151	240	I. Hanyu *et al.*, 1988
p-HEMT on GaAs	290	100	K. L. Tan *et al.*, 1990
mm-HEMT on GaAs	400	100	M. Zaknoune *et al.*, 1999
mm-HEMT on InP	455	150	P. Ho *et al.*, 1991
p-HEMT on InP	600	100	P. M. Smith *et al.*, 1995

Table 5 Record cut-off and maximum frequencies of GaAs and InP HBT devices

Device Name	Cut-off Frequency, f_T (GHz)	Maximum Frequency, f_{max} (GHz)	Reference
GaAs	156	255	T. Oka *et al.*, 1998
GaAs	138	275	T. Oka *et al.*, 1997
InP	144	267	S. Yamahata *et al.*, 1994
InP	228	227	S. Yamahata *et al.*, 1995

The prominent use of III-V HBT devices is in RF power amplifiers due to its high power densities, good impedance matching and tiny chip dimension. Table 6 provides a comparative picture of output power (P_{out}), power density (P_D), power gain (G_P) and power-added efficiency (*PAE*) found from various literatures for III-V HBT devices.

Table 6 Record power related parameter values of GaAs and InP HBT devices

Device Name	Frequency, f (GHz)	P_{out} (W)	P_D (mW/μm^2)	G_P (dB)	*PAE* (%)	Reference
GaAs	10	0.6	10	7.1	60	B. Bayraktaroglu *et al.*, 1993
InP	18	1.17	2.44	7.3	54	R. S. Virk *et al.*, 1997

From the beginning of the 90's decade, SiC, GaN and InN started to fascinate the device designers to use in high power RF applications due to their higher break-down potentials, carrier concentrations and saturation velocities. Besides, these are available in several types of crystal structures. Their two important parameters with gate length are summarized in Table 7. It is observed that as the gate length is reduced the maximum and cut-off frequencies are increased.

Table 7 Record maximum and cut-off frequencies with gate length for different wide band gap FET devices

Device Name	Gate Length, L_G (nm)	Maximum Frequency, f_{max} (GHz)	Cut-off Frequency, f_T (GHz)	Reference
SiC	0.45	50	22	S. T. Allen *et al.*, 1998
AlGaN/GaN	0.45	114	28	S. T. Sheppard *et al.*, 1991
AlGaN/GaN	0.05	140	110	M. Micovic *et al.*, 2000

IV. Construction and Characteristics of a typical RF Semiconductor Device

A. Construction of LDMOSFET

A wide variety of semiconductor transistor technologies are used for RF power applications. These include Laterally Doped Metal Oxide Semiconductor Field Effect Transistors (LDMOSFETs), Bipolar Junction Transistors (BJTs) and Heterojuction Bipolar Transistors (HBTs) on Si substrates; Metal-Semiconductor Field Effect Transistors (MESFETs), High Electron Mobility Transistors (HEMTs) and HBTs on gallium arsenide (GaAs), and on indium phosphide (InP), and HEMTs on gallium nitride (GaN) and MESFETs on silicon carbide SiC. The choice of technology used for a particular application is dictated primarily by three criteria: cost, output power, and frequency (J. G. Fiorenza, 2002). From the start of the 21st century, LDMOS transistors are being used for cellular base stations power amplifiers due to tremendous development of its architecture with an improvement in output power, power gain, power added efficiency, linearity, hot carrier reliability and thermal resistance (F. van Rijs, *et al*., 2006; P. J. van der Wel, *et al*., 2006; J. R. Gajadharsing, *et al*., 2004).

The advancement of RF LDMOSFETs over the last few decades was primarily enabled by three design improvements: gate length scaling, gate resistance reduction, and process and layout optimization. The gate lengths were scaled from about 1.2 µm to 0.35 µm. The gate resistance was reduced by the use of tungsten silicide and metal runners. The process and layout were optimized to reduce the pad loss and optimize the finger length and number of fingers. (J. G. Fiorenza, 2002).

The cross-section of a typical high-power LDMOSFET structure is shown in Fig. 6 (P. C. A. Hammes *et al*., 2004). It consists of a p^+-Si substrate on top of a lightly doped p^--layer grown epitaxially. While the n^+-source region extends to the gate, the n^+-drain region is spatially separated from the gate. The conductive connection between the n^+-drain and the channel region underneath the gate is realized by an n^--LDD (lightly doped drain) region which is frequently called the drift region. This is the main region contributing to a high breakdown voltage. Typically, the gate length of LDMOSFETs is in the range of 0.3–1.0 µm and the gate oxide is several nm thick. As such, the technology, especially the lithography and the gate oxide deposition of LDMOSFET is much relaxed than that of the small signal microwave MOSFET.

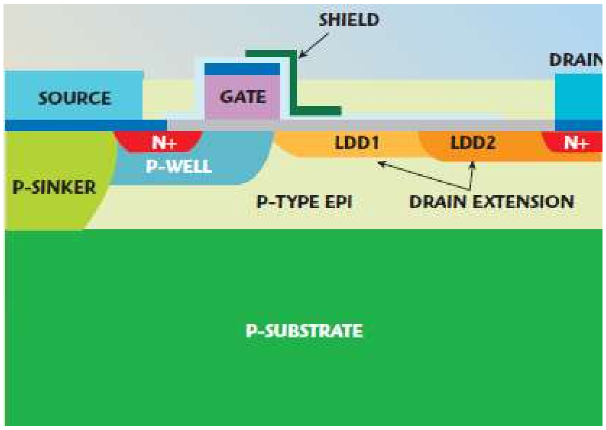

Figure 6: Typical cross-section of a state-of-the-art LDMOS structure (P. C. A. Hammes *et al*., 2004)

Gate materials used in RF devices are shown in Table 8. Of course, HfO_2 and its nitrides are being used in mainstream R&D industries.

Table 8 Use of gate materials in RG devices

Gate Materials	Dielectric Permittivity
NO stack	5-6
Al_2O_3	8-9
$HfSi_xO_y$	10-15
$HfAl_xO_y$	10-15
$HfSi_xO_yN_z$	10-15
ZrO_2, HfO_2	20-30
La_2O_3	15-30

B. Characteristics of GaAs MESFET

Some of the key characteristics include:

i) *High electron mobility:* The use of Gallium Arsenide or other high performance semiconductor materials gives high electron mobility required for high performance RF applications. MESFET semiconductor technology has enabled amplifiers using these devices that can operate up to 50 GHz and more frequencies up to 100 GHz.

ii) *Low capacitance levels:* The use of Schottky diode gate structure in RF MESFET provides very low stray capacitance which lends high frequency operation.

iii) *High input impedance:* The use of high-k dielectric at the gate of MESFET gives very high input impedance as compared to bipolar transistors thus results in the non-conducting diode junction.

iv) *Negative temperature coefficient:* The MESFET/GaAs FET has negative temperature co-efficient which inhibits some of the thermal problems experienced with other transistors.

v) *Lack of oxide traps:* When compared to the more common silicon MOSFET, the GaAs FET/ MESFET does not have the problems associated with oxide traps.

vi) *High level of geometry control:* The MESFET has better channel length control than a JFET. Because, JFET requires a diffusion process to create the gate The more exact geometries of the GaAS FET/ MESFET provide a much better and more repeatable product, and this enables very small geometries suited to RF microwave frequencies to catered for.

V. Applications of RF Semiconductors

There are many technologies available in the RF semiconductor industry, each adapted to one or several applications. RF devices are used as RF filters, RF switches, RF power amplifiers, other RF devices that are used in various industries, which include telecommunication, automotive, consumer electronics, aerospace and defense.

RF modules are electronic devices that enable designers to transmit and receive radio signals between two devices. They enable wireless signal transmission and are used in wireless alarm systems, remote controls, automation systems and smart sensor applications. Typical RF modules are Bluetooth module, GPS module, RFID module, Zigbee module, WLAN module, UHF module, cellular module, proprietary RF modules etc.

LDMOSFET technologies have been in the dominant position in the wireless base station applications for frequencies ranging from 450 MHz to 2.7 GHz for more than 20 years due to performance, cost, reliability, and power capability advantages (G. Ma *et al.*, 1996; H. Brech *et al.*, 2003). The operating frequencies of civil RF applications can range from a few hundreds MHz to 100 GHz, but most systems having mass markets operated at frequencies below 6 GHz. As third and fourth generations (3G and 4G) cellular systems, such as, W-CDMA are emerging, the demand for transistors with increased output power has escalated in support of the RF power amplifier designs required for base station infrastructure (C. P. Dragon *et al.*, 2000). The number of units sold in these markets is of the order of billions per year.

The GaN RF semiconductor devices market is segmented by application (defense and aerospace, communication, consumer electronics, automotive, industrial, data centers, renewable energy, and geography. Owing to the growth of the Internet of Things (IoT), the advent of 5G network and widespread applications across various industry verticals will offer immense growth opportunities to the RF GaN semiconductors market (MI, 2018).

The successful implementation of IoT needs data transfer over a network without human-to-computer interaction. Increasing implementation of IoT will result in signal congestion and will demand the use of GaN technology that can amplify power, capacity, and the bandwidth required for communicating with all interconnected devices (MI, 2018).

Development of MEMS technology is an integral part of IoT devices, and will also have a positive impact on the GaN RF semiconductor devices market (MI, 2018).

Furthermore, the rising trend of digitalization and increase in the number of *smart city* projects in various countries around the world is also creating potential opportunities for the growth of the RF power semiconductor market.

GaN with a high crystalline quality can be obtained by depositing a buffer layer at low temperatures (H. Amano, 1986). Such high-quality GaN led to the discovery of p-type GaN and p-n junction blue/UV-LEDs (H. Amano, 1989) and room-temperature stimulated emission (H. Amano, 1990) (essential for LASER action) (I. Akasaki, 1995). This has led to the commercialization of high-performance blue LEDs and long-lifetime violet-laser diodes, and to the development of nitride-based devices, such as, UV detectors and high-speed field-effect transistors. Increasing demand for smartphones, gaming devices, laptops, tablets and TVs is expected to drive the GaN semiconductor devices market in the consumer electronics sector (MI, 2018).

When doped with a suitable transition metal, such as, manganese (Mn), GaN is a promising Spintronics material (H. Morkoc, 1994).

Cellular phones are no doubt the most popular wireless communication system currently in use. In wireless communications, the noise produced intrinsically in the RF devices is somewhat negligible comparing to that from the noisy environment. GaAs MESFETs and Si bipolar transistors as the traditional low-noise transistors used in wireless communications, but the use of MOSFETs, possibly merged with SiGe HBTs using a low-cost BiCMOS process, has become a realistic option. Another requirement for the handset is the reduction of power consumption. At present, a supply voltage of 3V has been established as a standard. To deliver a high output power combined with a high efficiency at a limited supply voltage of 3V, RF power transistors possessing a large on-current and a low on-resistance are required in the transmit section of the handset. MOSFETs are not the best devices for this application due to the relatively low output power density. GaAs transistors (especially GaAs HBT) dominate this application. To date, the dominant power RF transistor used in base stations of wireless communications systems with operating frequencies up to 2.8 GHz is the Si LDMOSFET, which in the last several years has replaced all other competing Si and GaAs transistors. Si LDMOSFETs combine the advantages of moderate cost, high reliability and extremely high output power (A. Wood *et al.*, 1996). Aside from cellular phones, several other civil RF systems with operating frequencies below 20 GHz are potential fields for the application of RF MOSFETs as well. For example, Bluetooth, in which the requirements on transistor's RF performance are quite moderate, is predestinated for RF MOSFETs. In fact, all-MOS Bluetooth products are commercially available. For other applications below 20 GHz but with more stringent requirements concerning RF performance, the combination of SiGe HBTs and CMOS (SiGe BiCMOS) is currently a heavily discussed possibility in industry. Table 9 summarizes various RF applications and their frequency spectrums (J. J. Liou *et al.*, 2003).

Table 9 Civil RF systems operating below 6 GHz

Application	Operating Frequency (GHz)
Pagers	0.2-0.9
Cellular phone (1G)	0.8-0.9
Cellular phone (2G, 2.5 G)	0.9-1.9
Cellular phone (2.5 G)	2.5
Cellular phone (3G)	3.0
GPS	1.8
WLAN	2.4
Bluetooth	2.4
Microwave Oven	2.4
GPRS	2,5
HiperLAN2	5.0
802.11a LAN (Wi-Fi)	5.15-5.825
Collision avoidance RADAR in automobiles	77

Although RF MOSFETs seem to fulfill the most of the performance requirements for civil RF systems with operating frequencies from several 100 MHz up to 6 GHz, debates still existed as to whether such devices will find widespread applications in the market. Nevertheless, the importance of MOSFETs in RF applications is increasing day by day and it will continue to rise in the future.

Four Gate SOI transistor's multiple gate inputs give rise to exciting circuit opportunities for analog, digital, RF, and mixed-signal applications.

Vacuum channel transistors could be used for THz frequency operation, such as, sensing hazardous chemicals, noninvasive medical diagnostics, high-speed telecommunications, as well as in extreme environments having high temperature and various radiations, military and space applications etc.

VI. Conclusions

Prior to 1980, only two RF transistor types (Si BJT and GaAs MESFET) existed. In 2001, a large variety of different devices became available, including Si-CMOS, SiGe HBT, GaAs HBT, GaAs HEMT, InP HBT, InP HEMT, and wide band gap FETs. Of them Si-CMOS devices have a clear cost advantage and are typically used for frequencies up to 2.5 GHz. However, applications above 2.5 GHz use GaAs-based RF transistors. But high frequency applications above 40 GHz utilize mainly InP-based RF transistors. Because, InP-based HBTs and HEMTs possess the highest cutoff frequency (f_T) and maximum operating frequency (f_{max}) though InP-based devices suffer from poor power performance. On the other hand, GaAs-based HBT had been the most widely used HBT in RF design, but SiGe HBT has gained popularity recently due to its superior noise performance and its compatibility with the existing Si-CMOS technology. Wide band gap RF devices have huge potential due to its relatively high maximum operating frequency (f_{max}) and superior power performance, but the difficulties with their processing are hindering its growth of becoming the mainstream RF devices

RF semiconductor devices are still escalating its fields in the RF semiconductor industry. There is no doubt that MOSFETs are progressing quickly and becoming a strong contender in the RF applications traditionally dominated by III–V devices. Today's RF MOSFETs already fulfilled most of the performance requirements for civil RF systems. Rapid technology advancement, cost and size reduction are expanding the numerous applications of the RF MOS devices in residential, industrial, commercial, aerospace, military, transportation and utility systems.

RF electronics has now become the heart of the modern telecommunication and information technology based hardware system. As long as the performance needed is reached, RF-MOS will continue to be the choice of technology, but the time is coming where RF-MOS is difficult to downscale further without affecting the performance and other solutions are being sought after. However, new device structures are bringing other intangible benefits. Model is very useful for circuit simulation of MOS devices having channel length in the nano scale regime. So, modeling of new RF semiconductor devices requires knowledge on RF device geometry and RF device physics insights.

References

A. N. Leopre, H. M. Levy, R. C. Tiberio, P. J. Tasker, H. Lee, E. D. Wolf, L. F. Eastman and E. Kohn, "0.1 μm gate length MODFETs with unitycurrent gain cutoff frequency above 110 GHz," Electron Device Letters, vol. 24, 1988, pp. 364-366.

A. Wood, C. Dragon, and W. Burger, "High Performance Silicon LDMOS Technology for 2 GHz RF Power Amplifier Applications," IEDM Technical Digest, 1996, pp. 87-90.

B. Bayraktaroglu, J. Barette, L. Kehias, C. I. Huang, R Fitch, R. Neidhard and R. Scherer, "Very high power density CW operation of GaAs/AlGaAs microwave heterojunction bipolar transistors," IEEE Electron Device Letters, vol. 14, 1993, pp. 493-495.

C. H-T. Sah, "Evolution of the MOS Transistor-from Conception to VLSI," Proceedings of the IEEE, Vol. 76, No. 10, October 1988, pp. 1280-1326.

C. Hu, "Silicon Nanoelectronics for the 21st Century," Nanotechnology, vol. 10,p. 113, 1999.

C. P. Dragon, W. R. Burger, B. Davidson, E. Krvavac, N. Dixit and D. Joersz, "High Power RF-LDMOS Transistors for Base Station Applications," RF Semiconductors, March 2000, pp. 20-26.

D. L. Edgar, N. I. Cameron, H. McLelland, M. C. Holland, M. R. S. Taylor, C. R. Stanley and S. P. Beaumont, "Metamorphic GaAs HEMTs with fT of 200 GHz," Electronics Letters, vol. 35. 1999, pp. 1114-1115.

D. R. Greenberg, B. Jagannathan, S. Sweeney, G. Freeman and D. Ahlgreen, "Noise Performance of a Low Base Resistance 200 GHz SiGe Technology," IEDM Technical Digest, 2002, pp. 787-790

F. Cooke, "Microwave Transistors: Theory and Design," Proceedings of IEEE, vol. 59, p. 1163, 1971.

F. Schwierz and J. J. Liou, "Modern Microwave Transistors: Design, Modeling and Performance," Hoboken, Wiley, 2003.

F. van Rijs and S. J. C. H. Theeuwen, "Efficiency improvement of LDMOS transistors for base stations: towards the theoretical limit," IEDM Technical Digest, pp. 205-208, December 2006.

G. L. Arsov, "Celebrating 65th Anniversary of the Transistor," Electronics, Vol. 17, No. 2, December 2013, pp. 63-70.

G. L. Patton, J. H. Comfort, B. S. Meyerson, E. F. Crabb´e, G. J. Scilla, E. de Fresart, J. M. C. Stork, J. Y.-C. Sun, D. L. Harame, and J. Burghartz, "75 GHz fT SiGe Base Heterojunction Bipolar Transistors," IEEE Electron Device Letter, vol. 11, pp. 171-173, Apr. 1990.

G. L. Patton, S. S. Iyer, S. L. Delage, S. Tiwari, and J. M. C. Stork, "Silicon–Germanium-Base Heterojunction Bipolar Transistors by Molecular Beam Epitaxy," IEEE Electron Device Letter, vol. 9, pp. 165-167, Apr. 1988.

G. Ma, W. Burger, C. Dragon and T. Gillenwater, "High Efficiency LDMOS Power FET for Low Voltage Wireless Communications," IEEE IEDM Technical Digest, 1996, pp. 91-94.

H. Amano, M. Kito, K. Hiramatsu, and I. Akasaki, "P-Type Conduction in Mg-Doped GaN Treated with Low-Energy Electron Beam Irradiation (LEEBI)," Japanese Journal of Applied Physics, vol. 28, no. 12, p. L2112, 1989.

H. Amano, N. Sawaki, I. Akasaki and Y. Toyoda, "Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer," Applied Physics Letters, vol. 48, no. 5, p. 353, 1986.

H. Amano, T. Asahi and I. Akasaki, "Stimulated Emission Near Ultraviolet at Room Temperature from a GaN Film Grown on Sapphire by MOVPE Using an AlN Buffer Layer," Japanese Journal of Applied Physics, vol. 29, no. 2, p. L205, 1990.

H. Brech, W. Brakensiek, D. Burdeaux, W. Berger, C. Dragon, G. Formicone and B. Pryor, D. Rice, "Record Efficiency and Gain at 2.1 GHz of High Power RF Transistors for Cellular and 3G Base Station," IEEE IEDM Technical Digest, 2003, pp. 359-602.

H. Kromer, “Theory of a Wide-Gap Emitter for Transistors,” Proceedings of the IRE, 45, 1957, pp. 1535-1537.

H. Morkoc, S. Strite, G. B. Gao, M. E. Lin, B. Sverdlov, M. Burns, “Large-band-gap SiC, III-V nitride, and II-VI ZnSe-based semiconductor device technologies,” Journal of Applied Physics, vol. 76, no. 3, p. 1363, 1994.

H. S. Momose, E. Morifuji , T. Yoshitomi , T. Ohguro, M. Saito and H. Iwai, “Cutoff frequency and propagation delay time of 1.5-nm gate oxide CMOS,” IEEE Transactions on Electron Devices, Vol. 48, No. 6, pp. 1165-1174, June 2001.

H. Schumacher, U. D. Erben and W. Durr, “SiGe Heterojunction Bipolar Transistors—The Noise Perspective,” Solid-State Electronics, vol. 41, 1997, pp. 1485-1492.

I. Akasaki, H. Amano, S. Sota, H. Sakai, T. Tanaka and Masayoshikoike, “Stimulated Emission by Current Injection from an AlGaN/GaN/GaInN Quantum Well Device,” Japanese Journal of Applied Physics, vol. 34, no. 11B, p. L1517, 1995.

I. Hanyu, S. Asai, M. Nukokawa, K. Joshin, Y. Hirachi, S. Ohmura, Y. Aoki and T. Aigo, "Super low-noise HEMTs with a T-shaped WSi gate," Electron Device Letters, vol. 24, 1988, pp. 1327-1328.

IHS: Global Semiconductor Market Trends, IHS Markit, May 2018. http://theconfab.com/wp-content/uploads/P-18-Len-Jelinek.pdf, Accessed on 28 November 2018.

J. E. Lilienfeld, “Device for controlling electric current,” U.S. Patent 1900018. Application filed March 28, 1928, granted March 7, 1933.

J. G. Fiorenza, “Design and Fabrication of an RF Power LDMOSFET on SOI,” PhD Thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, September 2002, p. 28.

J. J. Liou and F. Schwierz, “RF MOSFET: Recent Advances, Current Status and Future Trends,” Solid-State Electronics, vol. 47, pp. 1881-1895, May 2003.

J. R. Gajadharsing, O. Bosma, P. van Westen, “Analysis and design of a 200 W LDMOS based Doherty amplifier for 3G base stations,” IEEE MTT-S International Microwave Symposium Digest, TX, USA pp. 529-532, 6-11 June 2004.

K. L. Tan, R. M. Dia, D. C. Streit, T. Liu, T. Q. Trinh, A. C. Han, P. H. Liu, P-M. D. Chow, H. C. Yun, "94 GHz 0.1 □m T-gate low-noise pseudomorphic InGaAs HEMTs, IEEE Electron Device Letters, vol. 11. 1990, pp. 585-587.

L. D. Nguyen, P. J. Tasker, D. C. Radulescu and L. F. Eastman, "Characterization of ultra-high-speed pseudomorphic AlGaAs/InGaAs (on GaAs) MODFETs," IEEE Transactions on Electron Devices, vol. 36. 1989, pp. 2243-2248.

M. A. Khan, J. N. Kuznia, A. R. Bhattarai, D. T. Olson, “Metal semiconductor field effect transistor based on single crystal GaN,” Applied Physics Letters. vol. 62, no. 15, p. 1786, 1993. doi: 10.1063/1.109549.

M. H. Bhuyan, “Analytical Modeling of the Pocket Implanted Nano Scale n-MOSFETs,” PhD Thesis, EEE Dept, BUET, Dhaka, Bangladesh, 2011.

M. H. Bhuyan, “History and Evolution of CMOS Technology and its Application in Semiconductor Industry,” Southeast University Journal of Science and Engineering (SEUJSE), 1999-1630, vol. 11, no. 1, June 2017, pp. 28-42.

M. Micovic, N. X. Nguyen, P. Janke, W-S. Wong, P. Hishamoto, L-M. McCray and C. Nguyen, "GaN/AlGaN high electron mobility transistors with fT of 110 GHz, Electronics Letters, vol. 36, 2000, pp. 358-359.

M. Zaknoune, Y. Cordier, S. Bollaert, D. Ferre, D. Theron and Y. Crosnier, "0.1 □m high performance metamorphic In0.32Ga0.68As/In0.33Ga0.67As HEMT on GaAs using inverse step InAlAs buffer, Electronics Letters, vol. 35, 1999, pp. 1670-1671.

MI: Mordor Intelligence, https://www.mordorintelligence.com/industry-reports/gan-rf-semiconductor-devices-market. Accessed on 28 November 2018.

O. Esame, Y. Gurbuz, I. Tekin and A. Bozkurt, “Performance Comparison of State-of-the-Art Heterojunction Bipolar Devices (HBT) based on AlGaAs/GaAs, Si/SiGe and InGaAs/InP,” Microelectronics Journal, Elsevier, vol. 35, 2004, pp. 901-908.

P. C. A. Hammes, R. Jos, F. V. Rijs, S. J. C. H. Theeuwen and K. Vennema, “High Efficiency, High Power WCDMA LDMOS Transistors for Base Stations,” Microwave Journal, April 2004.

P. Ho, N. Y. Kao, P. C. Chao, K. H. G. Duh, J. M. Ballingall, S. T. Allen, A. J. Tessmer and P. M. Smith, "Extremely high gain gate length 0.15 □m InAlAs/InGaAs/InP HEMTs, Electronics Letters, vol. 27, 1991, pp. 325-326.

P. J. van der Wel, S. J. C. H. Theeuwen, J. A. Bielen, Yaxin Li, R. A. van den Heuvel, J. G. Gommans, F. van Rijs, P. Bron and H. J. F. Peuscher, "Wear out failure mechanisms in aluminium and gold based LDMOS RF power applications," Microelectronics Reliability, vol. 46, pp. 1279-1284, 2006.

P. M. Smith, S-M. J. Liu, M-Y. Kao, P. Ho, S. C. Wang, K. H. G. Duh, S. T. Pu and P. C. Chao, "W-band high efficiency InP-based power HEMT with 600 GHz fmax," IEEE Microwave and Guided Wave Letters, vol. 5, 1995, pp. 230-232.

R. Dingle, H. L. Storner, A. C. Gossard and W. Wiemann, "Electron Mobilities inModulation-Doped Semiconductor Heterojunction Superlattices, Applied Physics Letter, vol. 33, p. 665, 1978.

R. S. Virk, M. Y. Chen, C. Nguyen, T. Liu, M. Matloubian and D. B. Rensch, "A high-performance AlInAs/InGaAs/InP DHBT K-Band power cell," IEEE Microwave Guided Wave Letters, vol. 7, 1997, pp. 323-325.

S. Davis, "Enhancement Mode GaN MOSFET Delivers Impressive Performance," Power Electronic Technology. Vol. 36, no. 3, March 2010.

S. E. Rosenbaum, B. K. Kormanyos, L. M. Jelloian, M. Matloubian, A. S. Brown, L. E. Larson, L. D. Nguyen. M. A. Thompson, L. P. B. Katehi and G. M. Rebeiz, "155 and 213 GHz AlInAs/GaInAs/InP HEMTs MMIC oscilllators, IEEE Transactions on Microwave Theory and Techniques, vol. 43, 1995, pp. 927-932.

S. Narashima, A. Ajmera, H. Park, D. Schepis, N. Zamdmer, K. A. Jenkins, et al., "High performance sub-40 nm CMOS devices on SOI for the 70 nm technology node," IEEE IEDM Technical Digest, 2001, pp. 625–628.

S. S. Iyer, G. L. Patton, S. L. Delage, S. Tiwari, and J. M. C. Stork, "Silicon-Germanium Base Heterojunction Bipolar Transistors by Molecular Beam Epitaxy," Tech. Dig. Int. Electron Device Meeting, 1987, pp. 874-876.

S. T. Allen, R. A. Sadler, T. S. Alcorn, J. Sumakeris, R. C. Glass, C. H. Carter Jr. and J. W. Palmour, "Silicon Carbide MESFETs for high-power S-band applications," Materials Science Forum, 1998, 953-956.

S. T. Sheppard, K. Doverspike, W. L. Pribble, S. T. Allen, J. W. Palmour, L. T. Kehias and T. J. Jenkins, "High-power microwave GaN/AlGaN HEMTs on semi-insulating silicon substrates, IEEE Electron Device Letters, vol. 20, 1991, pp. 161-163.

S. Yamahata, K. Kurishima, H. Ito and Y. Matsuoka, "Over 200 GHz fT and fmax InP/InGaAs double-heterojunction bipolar transistors with a new hexagonal-shaped emitter," GaAs IC Symposium Digest, 1995, pp. 163-166.

S. Yamahata, K. Kurishima, H. Nakajima, T. Kobayashi and Y. Matsuoka, "Ultra-high fmax and fT InP/InGaAs double-heterojunction bipolar transistors with step graded InGaAsP collector," GaAs IC Symposium Digest, 1994, pp. 354-358.

T. Hirose, Y, Momiyama, M. Kosugi, H. Kano, Y. Watanabe, T. Sugii, "A 185 GHz fmax SOI DTMOS with a new metallic overlay-gate for low-power RF applications," IEEE IEDM Technical Digest, 2001, pp. 943–945.

T. Mimura, S. Hiyamizu, T. Fujii and K. Nanbu, "A new Field Feffect Transistdor with Selectively Doped GaAs/n-AlxGa1-xAs Heterounctions, Japan Journal of Applied Physics, vol. 19, p. 1225, 1980.

T. Oka, K. Hirata, K. Ouchi, H. Uchiyama, K. Mochizuki and T. Nakamura, "InGaP/GaP HBT's uwith high-speed and low-current operation fabricated using WSi/Ti as the base electronic and burying SiO2 in the extrinsic collector," IEEE IEDM Technical Digest, 1997, pp. 739-742.

T. Oka, K. Hirata, K. Ouchi, H. Uchiyama, T. Taniguchi, K. Mochizuki and T. Nakamura, "Advanced performance of small-scaled InGaP/GaAs HBTs with fT over 150 GHz and fmax over 250 GHz," IEEE IEDM Technical Digest, 1998, pp. 653-656.

T. Suemitsu, T. Ishii, H. Yokoyama, Y. Umeda, T. Enoki, Y. Ishii and T. Tamamura, "30-nm-gate InAlAs/InGaAs HEMTs lattice matched to InP substrates, IEEE IEDM Technical Digest, 1998, pp. 223-226.

W. Shockley, US Patent no. 2 569 347, 1951.

Yole Development, "GaN RF Market: Applications, Players, Technology and Substrates: 2016-2022, published in 2016 at www.yole.fr.