Device Technologies for RF Front-End Circuits in Next-Generation Wireless Communications

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Invited Paper

Next-generation high data rate wireless communication systems offer completely new ways to access information and services. To provide higher data speed and data bandwidth, RF transceivers in next-generation communications are expected to offer higher RF performance in both transmitting and receiving circuitry to meet quality of service. Chosen semiconductor device technologies will depend greatly on the tradeoffs between manufacturing cost and circuit performance requirements as well as the variations in system architecture. Hardly did we find a single semiconductor device technology that offers a total solution to RF transceiver building blocks in terms of system-on-a-chip integration. The choices of device technologies for each constituent component are then important and complicated issues. In this paper, we will review the general performance requirement of key components for RF transceivers for next-generation wireless communications. The state-of-the-art high-speed transistor technologies will be presented to assess the capabilities and limitations of each technology in the arena of high data rate wireless communications. The pros and cons of each technology will be presented and the feasible semiconductor device technologies for next-generation RF transceivers can be chosen upon the discretion of system integrators.

Keywords**—***Bipolar junction transistor (BJT), device technology, field-effect transistor (FET), heterojunction bipolar transistor (HBT), metal semiconductor field-effect transistor (MESFET), pseudomorphic high electron mobility transistor (p-HEMT), radio frequency (RF) front-end circuits, RF microelectromechanical systems (RF MEMS), third generation (3G), wireless communications.*

I. INTRODUCTION

The evolution of wireless networks involves enormous complexity and rapid changes between different generations as well as different applications. Take mobile communications as an example. It is one of the fastest growing areas over the past decade. The first-generation mobile communication systems are analog systems designed to carry the voice traffic. The rapid growth in the number of subscribers and the proliferation of incompatible first-generation systems drove the evolution toward second-generation (2G) cellular systems. Multiple access techniques such as time division multiple access (TDMA), code division multiple access (CDMA), and global system for mobile communications (GSM) are used in the 2G systems. Again, the spectrum shortage of current 2G communication systems results in a revolutionary instead of evolutionary approach to increase system capacity and support innovative broadband multimedia services. Third–generation (3G) mobile communication systems, which GSM and CDMA converge into a single, official, globally roamable system, provide not only voice service but also data delivery.

The system for 3G wireless communications is also referred as International Mobile Telecommunications 2000 (IMT-2000). Several terms are also used to describe networks that use the 3G specification: Universal Mobile Telecommunication System (UMTS) in Europe, Freedom of Mobile Multimedia Access (FOMA) in Japan, or UMTS Terrestrial Radio Access Network (UTRAN). Multiple radio technology options have been included in the IMT-2000 standard to allow seamless service evolution from the various 2G mobile standards that have been extensively deployed around the world. In Europe and Japan, for example, the wide-band CDMA (W-CDMA) was adopted. W-CDMA offers much higher data speed and data bandwidth. W-CDMA can support mobile voice, images, data and video communications at up to 2 Mb/s for local-area access and 384 kb/s for wide-area access,

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respectively. The input signals are digitalized and transmitted in a coded, spread-spectrum mode over a range of frequencies with 5-MHz channel bandwidth. In the United States, CDMA-2000 is employed for backward compatible with CDMA (IS-95). The CDMA-2000 standard will be deployed in all cellular spectra with high-voice capacity and high-speed packet data capabilities. It was devised to have high spectral efficiency and better power control scheme through an open loop power control mechanism.

Due to high cost in upgrading currently available infrastructure and physical limitation in device technology, some interim technologies, or 2.5G mobile communications, were introduced in the roadmap to 3G communications. For example, general packet radio service (GPRS) was introduced to provide nonvoice value-added service that allows information to be sent and received across a mobile telephone network at a theoretical maximum data rate of 171.2 kb/s. It supplements today's circuit switched data (9.6 kb/s) and short message service (160 characters). Current GSM standard are expecting to be replaced with an Enhanced Data rate through GSM Evolution (EDGE) modulation format. The EDGE signal offers greater date rates while occupying the same bandwidth as the older GSM format. This means that operators can create base station transmission sites that offer both GSM and EDGE radio interfaces and use the same switch and site controllers for both applications. The deployment of EDGE triples the capacity of GPRS as well as enables smooth evolution to 3G mobile services. EDGE is expected to be a complementary technology to W-CDMA that allows an operator to deploy a single 3G network and to deliver optimum performance, coverage, and long-term flexibility at lowest cost.

Similarly, in the short-distance wireless data communications, the wireless local access network (WLAN) per IEEE 802.11 specifications has become the mainstream technology. The WLAN operates at the 2.4- and 5.8-GHz frequency bands with maximum network range of 150 ft and maximum theoretical data transmission rate of 54 Mb/s. Several standard versions coexists in IEEE 802.11 standard representing different generations of technological evolution. IEEE 802.11b specifies radios transmitting at 2.4 GHz and at speeds up to 11 Mb/s using direct sequence spread spectrum (DSSS) technology. Different carrier modulation methods ranging from BPSK, QPSK, 16QAM, to 64QAM were implemented in IEEE 802.11a using an orthogonal frequency division multiplexing (OFDM) technique. OFDM allows close-packed signal transmission for better channel utilization. The IEEE 802.11g standard is a high-speed standard at 2.4 GHz and is backward compatible with 802.11b. Other LAN or personal access networking (PAN) standards such as Bluetooth, HyperLAN, and IEEE 802.15 are among the wireless standards that are expected to be deployed and will use the unlicensed national information infrastructure (UNII) frequency band.

In the radio physical (PHY) layer, several hardware components are crucial to the system implementation: media access controller (MAC), baseband processor, and RF front-ends. Among these components, RF front-end circuits were considered the most challenging area and the successful development in these RF front-end components is the most critical path in the deployment of next-generation wireless communications. For example, EDGE signals, unlike conventional GSM which uses constant-envelope GMSK modulation, employ $3\pi/8$-shifted 8-PSK modulation. In order to provide sufficient quality of service (QoS) to meet the required error vector magnitude (EVM) tolerance, one will need highly linear and low-phase-noise power amplifiers (PAs) and modulators to maintain signal quality in radio transmission. This issue is complicated by some other factors in reality such as power consumption, chip cost, and technology availability. Common approaches such as nonlinear modulation technique or output power backoff PA operation lead to high-cost design cycle and inefficient power utilization. Thermal buildup in wireless communication RF front-ends degrades the system performance as the power efficiency degrades at higher operating temperature. Similar requirement is desired in short-distance WLAN such as OFDM with 64-QAM modulation schemes. WLAN transceivers, for example, face challenges in stringent EVM requirement in order to provide a high-quality in-phase and quadrature (I/O) modulation constellation. More power backoff in PA operation and low phase noise components are then required.

New modulation formats for next-generation wireless communications keep placing higher RF performance requirements on transceiver circuits. Looking further ahead, fourth–generation (4G) wireless communications are the term of concepts beyond 3G wireless systems. It will include technologies with innovations in system architectures and spectrum allocation as well as utilization in radio communication, networking, services and applications. It will improve and revolutionize wireless/wireline data and voice networks. Gigabit wireless communications will be among one of them. The communication between mobile stations will not only contain voice but also involve with real-time multimedia and data exchanges. The higher carrier frequency of possibly 2–8 GHz, wider bandwidth, and better channel utilization will be required for large data transmissions. The RF transceiver will remain one of the research hot spots in the development of high-speed wireless communications, and the successful development of innovative wireless components will be based on the success in innovative semiconductor device technology development. An innovative and useful semiconductor technology accelerates the implementation of new wireless communication systems and effectively addresses issues that technologists faced in current wireless communications.

In this paper, we will focus on semiconductor device technologies that constitute the RF front-end circuit components. Several competing semiconductor device technologies serve as the backbones in the making of RF transceivers in current wireless systems. They range from silicon-based to compound-semiconductor-based devices. Silicon RF CMOS, BiCMOS, silicon germanium (SiGe) heterojunction bipolar transistors (HBTs), and laterally double-diffused metal–oxide semiconductors (LDMOSs)

Table 1
Handset Specs of Different Mobile Phone Systems

Standard	**GSM (DCS 900)**	**GSM (DCS 1800)**	**CDMA (IS-95)**	**PHS**	**CDMA-2000**	**W-CDMA**
Multiple Access	TDMA /FDMA	TDMA /FDMA	CDMA /FDMA	TDMA /FDMA	CDMA	CDMA
Modulation	GMSK	GMSK	BPSK /QPSK	QPSK	QPSK/ BPSK	QPSK
UE Receive Frequency (MHz)	935-960	1805-1880	869-894	1895-1917 (77 channels)	-	2110-2170
UE Transmit Frequency (MHz)	890-915	1710-1785	824-849	1895-1907	-	1920-1980
Transmission rate (kbps)	270	270	14.4	64/384	384	8-384 (outdoors) 2000 (indoors)
Channel Spacing(kHz)	200	200	1250	300	3.75	5000

are contending candidates for the RF transceiver blocks from silicon world. In III-V compound semiconductor, GaAs-based metal semiconductor field-effect transistor (MESFET), heterostructure field-effect transistor (HFET), pseudomorphic high electron mobility transistor (p-HEMT), and HBT are commonly discussed technologies of choice with higher RF performance. New emerging technologies, such as InP-based HBT and p-HEMT, GaN HFETs, and RF MEMS switches also show great potential for wireless RF transceiver applications. Different semiconductor device technologies can always find their own niche applications in certain circuit components but hardly did we see any device technology that readily provide a universal solution to all the circuit blocks in transceiver modules so far.

In the course of our discussion, we will start with a simplified transceiver block diagram as an exemplary instance of RF transceivers. General requirements in each component will be identified to achieve efficient delivery of signal streams per specifications. Existing semiconductor device technologies will be discussed from the aspects of intrinsic properties of the material as well as the pros and cons in terms of fabrication and circuit applications. The emerging semiconductor device technologies with great potential for the future wireless communications will also be presented. They are developed in a hope to complement the shortfalls of currently available semiconductor device technology and promisingly hold the keys to future gigabit wireless communications. Major components in the transceiver and possible choices of semiconductor device technologies will be discussed as well.

II. RF TRANSCEIVERS

Transceivers, by definition, consist of transmitters and receivers in wireless systems to exchange data and voice messages through free space. Since the specifications and frequency allocations for every class of wireless communications predetermine the system topology and feasible semiconductor technologies in RF transceiver design, each semiconductor device technology has its own unique cost/performance proposition in different frequency bands and applications.

Take a 3G mobile communication as an example. Table 1 shows a summary of different handset standards that can be deployed in a 3G system. Each standard has different combination of frequency band, modulation scheme, and data/voice rate. For instance, the W-CDMA system allocates its upload and download frequency band at 1.92–1.98 GHz and 2.11–2.17 GHz, respectively. It allows a maximum data transmission rate of 2 Mb/s (indoor) with a channel spacing of 5 MHz. Operating at a new frequency band may require new upgrade and additional capital expenditure in the operator's infrastructure. In contrast, CDMA–2000 can be deployed in essentially all cellular, PCS, or the new IMT-2000 spectrum. Its high spectral efficiency enables high traffic deployment in any 1.25-MHz channel of spectrum. The difference in modulation schemes between GSM and W-CDMA also result in different performance requirement in terms of device linearity. Usually, Gaussian minimum shift keying (GMSK) modulation is less susceptive to the device linearity than other phase shift keying (PSK) modulations are.

A simplified transceiver block diagram for W-CDMA mobile communications is shown in Fig. 1 [1], [2]. In a transmitter, the carrier signals are modulated using particular modulation schemes and are delivered through an antenna. The receiver recovers the information from the received signal from the antenna. A transmitter usually consists of an oscillator, a modulator, an up-converter, filters, and PA. It can also include a phase-locked oscillator or synthesizer along with the above-mentioned components. Signals are modulated by an oscillator through amplitude modulation (AM), frequency modulation (FM), phase modulation (PM), or other digital modulation schemes such as PSK, frequency shift keying (FSK), etc. In W-CDMA, the quadrature PSK (QPSK) modulation scheme is used. The data stream from baseband processor is split into "odd" and "even" streams. These signals are separately modulated before combining into a QPSK signal. The signals are then up-converted to a higher frequency carrier by a mixer. The carriers along

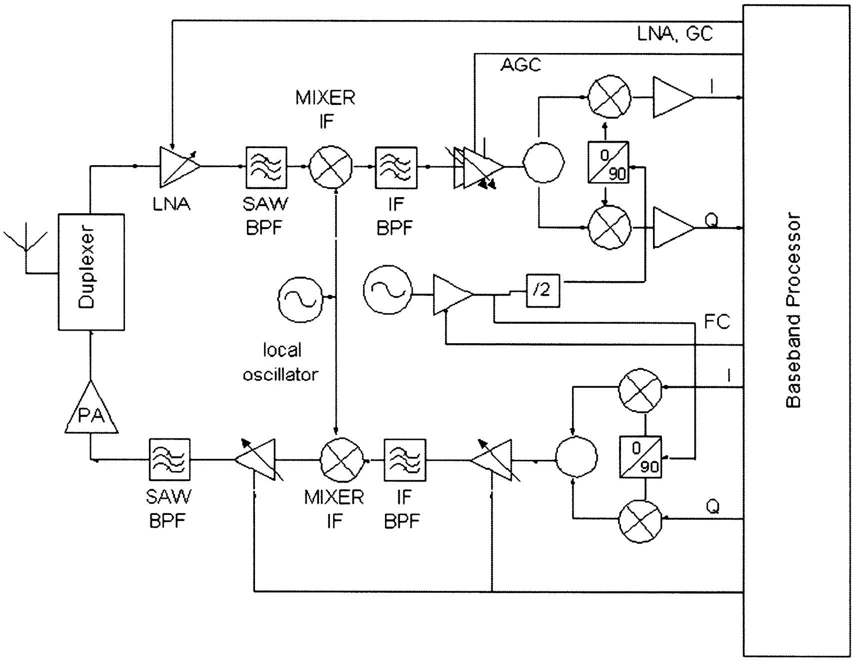


Fig. 1. A simple transceiver block diagram for 3G wireless communications.

with the signals are amplified by a PA and are transmitted by an antenna. To get a lower phase noise operation, the oscillator can be phase-locked by a low-frequency crystal oscillator or be replaced by a frequency synthesizer that derives frequencies from an accurate high-stability crystal oscillator source.

Each wireless communication standard specifies different transmitting characteristics to qualify the applications of a transmitter [3]. W-CDMA, for example, specifies a 5-MHz channel bandwidth and 4.997-MHz spread spectrum bandwidth. The maximum output power ranges from 29 to 33 dBm. The output power is controllable over a dynamic range of 70 dB. The minimum output power is from -41 to -37 dBm. It also specifies 60 channels within the frequency range. The power density of adjacent channel must not interfere the detection of the main channel. The spectrum emission mask within a channel bandwidth is clearly specified in each standard. The minimum adjacent channel leakage power ratio for W-CDMA shall be greater than 33 and 43 dB for adjacent channel frequency relative to assigned channel frequency at ± 5 and ± 10 MHz, respectively. To achieve system specification, PAs, in particular, will be required to have higher linearity, higher output power and higher adjacent channel power ratio (ACPR) with lower phase noise than those that were used in the 2G telecommunications.

A receiver is used to transfer the carrier signals into useful information. Receiver block in an RF transceiver may consist of a low-noise amplifier (LNA), mixers, oscillators, and band-pass filters (BPFs). The performance of the receiver depends on system architecture, circuit design and communication protocols. Acceptable levels of distortion or noise vary with standards. In a 3G system, a suitable receiver structure using coherent reception in both channel impulse response estimation and code-tracking procedures is assumed. Three forms of diversity, i.e., time diversity, multipath diversity, and antenna diversity, are considered to be available in the UMTS terrestrial radio access—frequency division duplexing (UTRA-FDD) uplink. The receiver shall perform the signal amplification and filtering functionality to meet the system sensitivity, adjacent channel selectivity, spurious response, and power control requirements. The signal power must be larger than the noise power by a specified minimum signal-to-noise (S/N) ratio in a system. The receiver sensitivity of W-CDMA is -106 dBm with a nominal receiver noise figure of 9 dB. The spurious response needs to be a least 60 dB at 10 MHz from the center and intermodulation response 60 dB or more at 10 and 20 MHz from the center. LNAs with low noise figures and high RF gains are preferred in receiving blocks. Passive components such as the BPF are also crucial for accurate bandwidth selection. In a transceiver, the duplexer is an array of switches that may provide diversity switching functionality in the selection of signal paths. Switching technologies with low-loss, low-noise, and high-power-handling capabilities are also preferred.

Several viable semiconductor device technologies are used in RF transceiver circuit blocks. GaAs HBTs and LDMOS have been extensively used in the PA for current wireless communication systems. GaAs p-HEMTs are among the best choices for RF Tx/Rx switches and LNAs. Recently, SiGe HBTs and RF CMOS have also been contenders for low-cost transceiver circuits in low-to-medium RF power amplifications. The race of being the dominant device technology in next-generation RF transceivers has just begun. The prevailing device technologies will be required to successfully resolve intricate issues on device performance, fabrication complexity, time to market, and cost. In the next section, we will investigate the state-of-the-art semiconductor device technologies that can potentially make future high-speed wireless communications real.

III. DEVICE TECHNOLOGIES FOR WIRELESS COMMUNICATION SYSTEMS

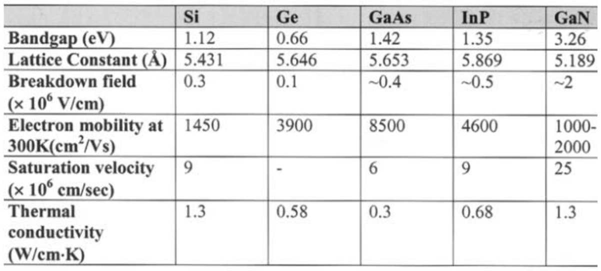
There are wide varieties of solid-state device technologies available for the implementation of wireless communication systems. In terms of semiconductor material systems, they can be categorized into silicon-based and III-V-compound-semiconductor-based devices. Silicon-based semiconductor devices, with its low-cost, high-volume production, have improved frequency response significantly over the past few years. In contrast, compound semiconductor-based devices take advantages of their intrinsic material properties and offer superior device performance in high-frequency applications such as monolithic millimeter-wave integrated circuits (MMIC). The III-V semiconductor industries have also increased their production yield and integration scale in response to the increasing demand of RF circuits in terrestrial and mobile wireless communications.

Current battlefields for silicon-based and III-V-based devices are those applications within the frequency band from sub-1 GHz to 10 GHz. Silicon-based devices provide competitive RF performance and are backed up by well-established manufacturing infrastructures. III-V devices, on the other hand, offer superior performance and reasonable scale of economy in manufacturing for certain types of applications. Many components in RF transceivers today have been implemented using semiconductor technologies from both groups to address different market subsectors. Each device technology is striving to maintain its niche market share and is trying to gain dominance over others through intensive research and development efforts and device performance break-through.

In terms of transistor operation principles, semiconductor transistor technologies can be categorized into two major types depending on their physical carrier transportation mechanisms: FETs and bipolar junction transistors (BJTs). FET devices are also referred as unipolar devices because the majority carriers are in principle responsible for the transport characteristics. Drain current in an FET is modulated by gate voltage through channel width modulation scheme. The amplification process in FET is characterized by a transconductance (g_m) to assess the controllability of the gate voltage modulation over the output drain current. On the other hand, carrier transportation mechanisms in bipolar transistors involve both electrons and holes. The collector current is modulated by the minority current injection from the base. BJT is equivalent to a current amplifier as the input base current is "amplified" by a factor of β (current gain) through the transistor and the output current is "collected" at the collector end.

Transistor technologies associated with BJTs and FETs were developed on almost all kinds of semiconductor material systems today. Many of them have become indispensable technologies in modern microelectronics. In silicon world, homojunction BJTs, silicon metal–oxide semiconductor FETs (MOSFETs), LDMOS transistors, and SiGe- heterojunction bipolar transistors (HBTs) are among the most viable technologies for wireless communications. In III-V semiconductor materials, GaAs MESFETs, GaAs-based high electron mobility transistors (HEMTs), InP-PHEMTs, GaAs-based HBTs, and InP-based HBTs are classical devices of choice in RF circuit/MMIC applications.

Table 2
Electron Properties of Several Materials and Their Impact on the Device Performance



	Si	Ge	GaAs	InP	GaN
Bandgap (eV)	1.12	0.66	1.42	1.35	3.26
Lattice Constant (Å)	5.431	5.646	5.653	5.869	5.189
Breakdown field ($\times 10^6$ V/cm)	0.3	0.1	~0.4	~0.5	~2
Electron mobility at 300K(cm^2/Vs)	1450	3900	8500	4600	1000-2000
Saturation velocity ($\times 10^6$ cm/sec)	9	-	6	9	25
Thermal conductivity (W/cm·K)	1.3	0.58	0.3	0.68	1.3

Each device technology has its own merits. The intended circuit applications depend not only on the constituent transistor performance but also on economical issues. However, we will focus on the physical properties and technical issues of each semiconductor device technology with less emphasis on the economic issues in the following subsections. First, we would like to compare different semiconductor material systems in order to select a suitable platform for the advanced RF device technologies. Currently available device technologies in both FET and BJT areas will then be discussed. Several novel and emerging technologies will also be included in our discussion in view of the shortfall of current device performance. The state-of-the-art device performances are promising for future ultrahigh-speed communications with proper device scaling. It is evident that wide range selections in semiconductor device technologies and diversified device characteristics will facilitate and expedite next-generation wireless technology development with great impacts in all aspects.

A. *Semiconductor Material Systems*

The intrinsic device characteristics are closely related to the constituent material systems and device physics behind a transistor's operation. Shown in Table 2 is an elective list of physical properties of major semiconductor materials. These properties of these materials set the fundamental limitation of every device technologies. The semiconductor bandgap along with breakdown field set the upper bound for maximum device operating voltage; the lattice constant decides whether high-quality single-crystal growth of certain materials can be done on a substrate without unintentional introduction of stain layers; the drift velocity as well as carrier mobility set intrinsic device speed limitation; and the thermal resistances of a semiconductor substrate undermine the device power handling capability. These factors altogether are used to determine which material system one should go with in the development of RF transceivers.

As we can see in the table, the material properties in each semiconductor are quite different and, unfortunately, none of them have been qualified as the sole choice of material systems for all constituent circuit blocks in RF transceiver technologies. Silicon has higher thermal conductivity but the electron drift velocity and mobility is slow. In addition, the lack of the semi-insulating substrates results in additional development effort and fabrication cost of silicon-based RF devices. On the contrary, semi-insulating substrates are easily prepared in most compound semiconductor. This property is beneficial in terms of providing RF applications with high device isolation and low dielectric loss. GaAs material has higher electron mobility compared with silicon. It has been a choice for MMIC applications for over decades. The drawback of this material system is the poor thermal dissipation capability. High thermal resistance value in RF power application is detrimental because special care must be taken to mitigate thermal-related system performance degradation.

GaN, on the other hand, seems to be a very promising material system. It has the fastest drift velocity among all other semiconductor materials. The wide bandgap in GaN translates to a higher breakdown field. Low thermal resistance and possible epitaxial growth on silicon carbide substrates make this material system perfect for high-power RF applications. However, this material system is in its infancy stage in terms of microelectronic applications. The innovation in processing technology and the availability of high quality epitaxial growth are two of the major issues for current GaN technology development.

InP material system has as long development history as that for GaAs. It has been extensively used in semiconductor-based optoelectronics for decades. The use of InP will ease the problematic thermal issues as we have seen in GaAs to some extent. The associated lattice-matched materials such as InGaAs or GaAsSb ternary compound semiconductors bring a boost to the RF performance of InP-based transistors. Researchers from many research groups have demonstrated that InP-based device can yield the fastest transistors among all the semiconductor devices on both FET and HBT devices. InP have been sought to become a technological alternative for GaAs-based material system due to their superior intrinsic electrical properties. The major issue of this material system is the unavailability of large wafer substrate. It is not only because of less intensive single-crystal technology development effort in this area but also because of other economical issues.

B. FET Devices

1) MOSFET: In FET device, silicon CMOS technology has been the major workhorse of the microelectronic world. Through intensive development effort in this field, CMOS technology has shown many impressive improvements in high-frequency performance over the past few years. The scaling of CMOS has increased f_T from 8 GHz at gate size 500 nm to greater than 60 GHz at gate size 180 nm [4], [5]. RF CMOS also showed excellent noise characteristic. A noise figure of 0.6 dB at 2 GHz was reported with 0.2-μm gate length [6]. Many silicon foundries have developed and offered commercialized RF CMOS processes. RF CMOS technology is expected to bring major impacts to future RF consumer electronic products. With the scaling of CMOS technology, lithography, reliability, and yield may become challenges for fulfilling Moore's law. The leakage currents, both through the gate and through source and drain, are unavoidable. Gate leakage becomes one of the impeding factors for smaller CMOS transistors. Proposed solutions for the leakage currents include the application of high-k dielectric material and double-gate structure [7]. Aside from the viewpoint of device technology development, the size of capital spending in acquiring critical equipments and the cost model for next-generation silicon technology node will be crucial in the technology advancement in silicon CMOS world when alternative technologies such as SiGe or III-V technologies have provided superior device RF performance and competitive cost structures.

Conventional CMOS is less likely to become the device of choice in wireless front-end circuits for medium to high-power ($>$ 1-W) applications. The LDMOS that is compatible with standard BiCMOS process becomes a more suitable choice. For example, a 0.15-μm short-channel LDMOS has been developed with f_T of 13 GHz for medium voltage RF and power applications [8]. A 6-W LDMOS distributed amplifier for a base station application was also reported in [9]. The typical breakdown voltages of LDMOS are greater than 30 V. The LDMOS has the flexibility in tailoring the breakdown voltage through device design in lateral dimensions to achieve desired power performance. They are replacing conventional bipolar devices at the BTS in 2G wireless systems. However, the improvement in RF power efficiency is, as always, major challenges for LDMOS in power amplification.

2) GaAs MESFET: In compound semiconductor, GaAs MESFET technology is the most widely used III-V semiconductor devices for high-frequency applications. A typical device cross-sectional view of a recessed-etched-gate n-channel MESFET is shown in Fig. 2(a). The gate Schottky barrier forms a depletion region in the channel under the gate area. When positive potential is applied to the drain, electrons flow from the source to the drain through the channel. The active channel can be formed either by ion implantation followed by anneal or by doped epitaxial growth. The drain current is modulated by the gate potential due to the modulation in the channel width with the gate voltage. Special care must be taken to prevent the gate from being turned on due to excessive forward gate bias. The turn-on voltage of the gate Schottky diode limits the dynamic range of the E-mode MESFET. Therefore, most of the MESFET are designed in D-mode for optimum performance. In practice, the nonlinear forward-biased Schottky gate characteristics along with normal MESFET operation are often used in the design of harmonic generation circuits such as voltage-controlled oscillators (VCOs) and mixers.

Compared with most of other III-V device technologies that require advanced epitaxial growth technologies, GaAs MESFET can be fabricated using a direct ion-implantation approach, which is a common practice in silicon technology. A planarized circuit fabrication was able to be implemented on the ion-implanted GaAs MESFET technology and high-speed VLSI was fabricated by advanced GaAs

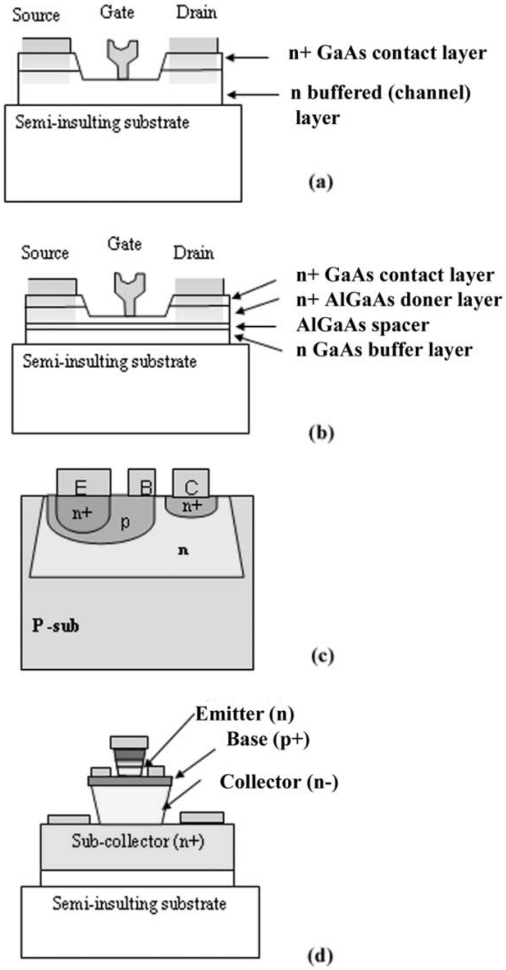


Fig. 2. Cross section view of: (a) GaAs MESFET; (b) AlGaAs/GaAs HFET; (c) InGaP/GaAs HBT; and (d) Si BJT.

MESFET manufacturers such as Vitesse Semiconductor, Inc. In analog circuit applications, recessed-etched gate are often employed in order to control the gate threshold voltages. One can also achieve an enhancement/depletion mode MESFETs implemented in a single chip through selective ion implantation or other proprietary etching techniques. The FET is, thus, a suitable technology for many high-performance small-signal and moderate power, as well as diversity switching applications.

Ion-implantation MESFET provides the most cost-effective solution among all the III-V technologies. A typical 0.12-μm gate length device is shown in Fig. 3. The MESFET has a two-fingered 50-μm-wide gate. By optimizing the implanted schedule and the gate process, the GaAs MESFET device achieved a cutoff frequency f_T of 121 GHz and $f_{\max}$ of 160 GHz with a breakdown voltage greater than 7 V [10]. The *I–V* characteristics of state-of-the-art 0.1-μm D-mode MESFET are also shown in Fig. 4 [11]. A good pinchoff behavior and no kink effects up to $V_{\rm ds} = 3$ V were achieved. The peak extrinsic transconductance is 580 mS/mm and the maximum drain-to-source current is 640 mA/mm with a pinchoff voltage of -0.85 V. A maximum f_T of 143 GHz at $V_{\rm ds} = 1.2$ V and $V_g = 0.5$ V and a maximum $f_{\max}$ of 197 GHz at $V_{\rm ds} = 2$ V and $V_g = 0.5$ V

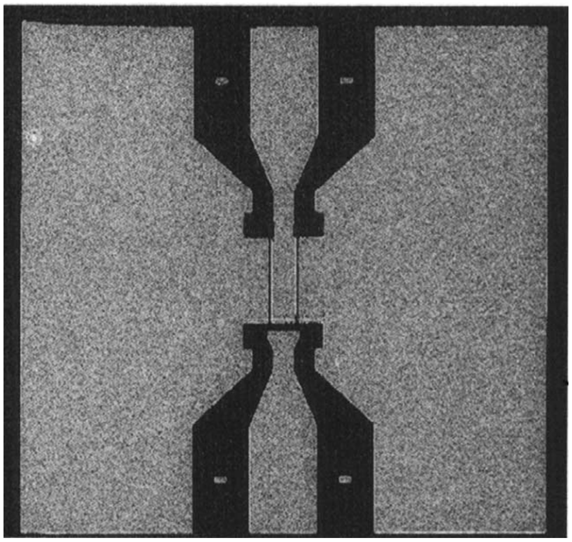
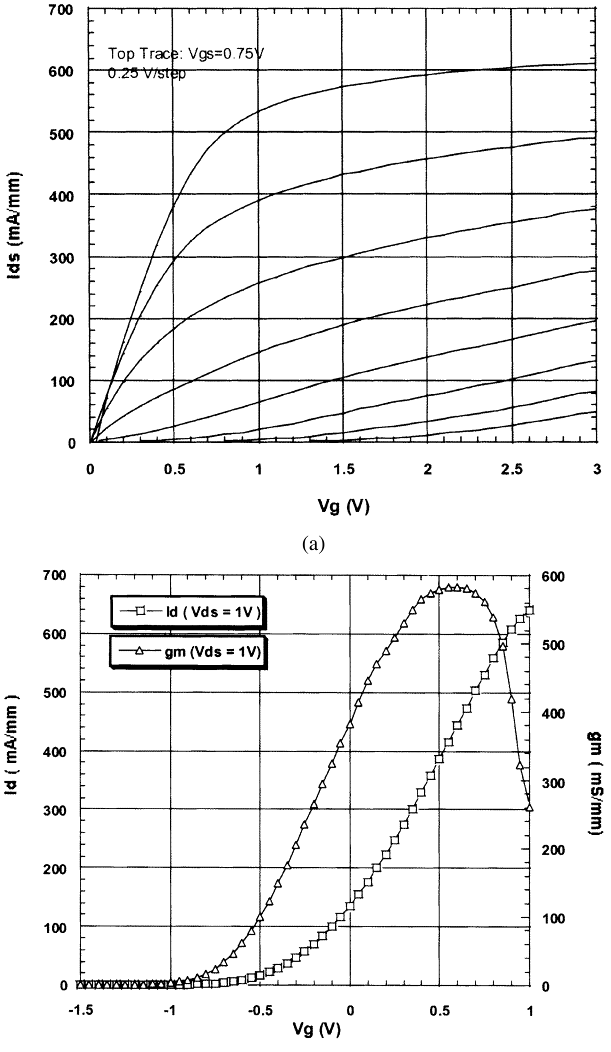


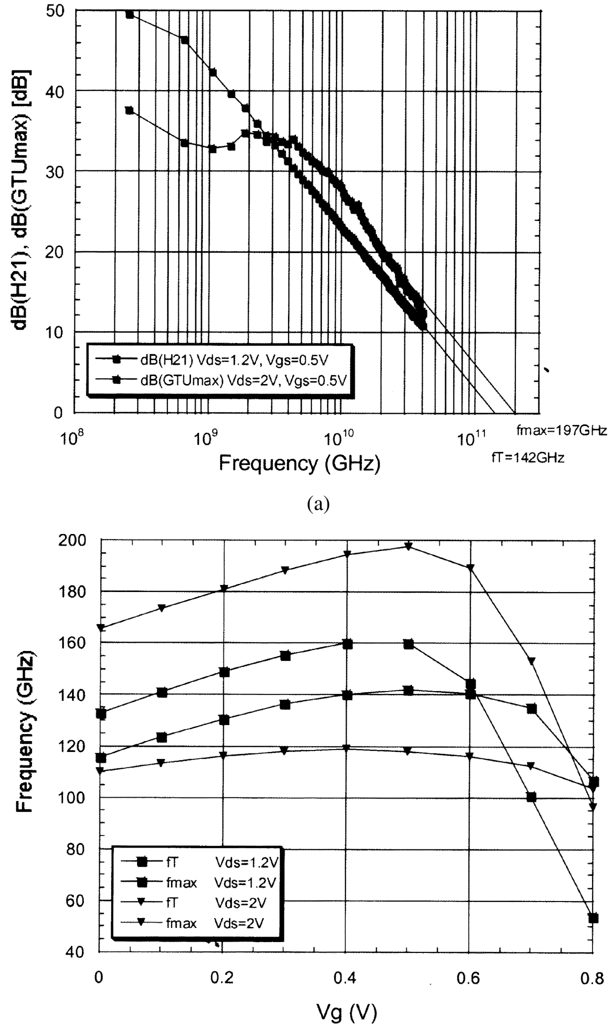
Fig. 3. SEM photograph of the fabricated 0.12-μm recessed-gate in an ion-implanted GaAs MESFET.



(a)

(b)

Fig. 4. (a) Atypical 2 × 50-μm D-mode MESFET *I–V* characteristics. (b) Typical drain-to-source current and extrinsic transconductance characteristics of a 2 × 50 D-mode GaAs MESFET.



(a)

(b)

Fig. 5. (a) High-frequency characteristics of a 2 × 50-μm MESFET. (b) Gate-voltage dependent RF characteristics of a 2 × 50-μm MESFET.

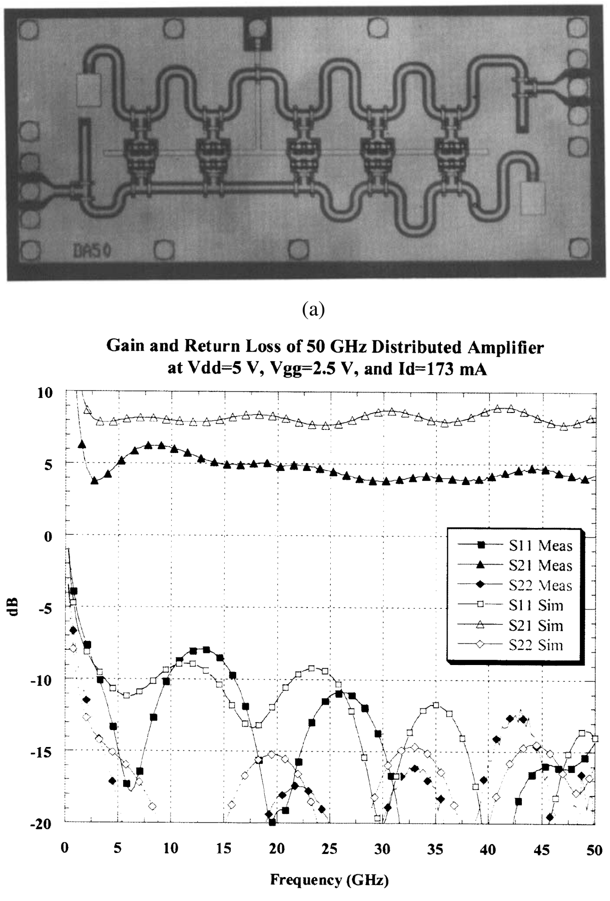
was obtained [Fig. 5(a)] with the f_T of greater than 100 GHz can be obtained at zero gate-bias as V_{ds} varies from 1 to 2 V [Fig. 5(b)].

A variety of circuits have also been demonstrated using an ion-implanted GaAs MESFET. These MMICs include 38- and 77-GHz LNAs and VCOs, a 50-GHz distributed amplifier, and 38.5- to 77-GHz diode and FET doublers [12]. For example, a 50-GHz distributed amplifier uses five cascode stages GaAs MESFETs is shown in Fig. 6(a). The distributed amplifier results in a wide bandwidth amplification operation and the measured gain and return loss is 5.0 ± 1.5 dB and less than 8 dB, respectively, over 50-GHz bandwidth [Fig. 6(b)]. Another example is the V-band VCO using GaAs MESFET technology [Fig. 7(a)]. The circuit delivers 3 dBm of output power at 72.2 GHz with −85-dBc/Hz phase noise at a 1-MHz offset [Fig. 7(b)]. These circuit results showed the feasibility of GaAs-based FETs for MMIC applications in Ka band and V band wireless communications.

3) GaAs HEMT, p-HEMT: The derivative device technologies of GaAs MESFETs are HFET, p-HEMT, and metamorphic HEMT (m-HEMT). These devices utilize advanced epitaxial material growth technology and bandgap engineering techniques to achieved high speed and low noise performance. HFETs have developed very rapidly in the last decade. The speed records of HFETs have been broken again and again. In this type of device [Fig. 2(b)], a large bandgap doped material (such as AlGaAs) is grown heteroepitaxially on an undoped lower bandgap material (such as GaAs). The undoped GaAs provides a high-mobility two-dimensional (2-D) channel for carriers supplied from AlGaAs. An undoped AlGaAs layer is used to avoid electronic interaction and to increase mobility. An HFET is also called a high electron mobility transistor (HEMT), modulation-doped FET (MODFET), or 2-D electron gas FET (TEGFET) due to its initial development by various groups.

To improve GaAs-HFET/HEMT performance, an InGaAs strained layer is used as the electron gas channel material instead of GaAs. The more indium percentage incorporated in InGaAs material, the higher the electron drift velocity is. The p-HEMT was then developed to enhance the electron mobility in 2-D electron gas (2DEG) layer. The lattice mismatched InGaAs layer can increase carrier mobility and improve carrier confinement in the conducting channel. The larger conduction bandgap difference at the AlGaAs/InGaAs heterointerface allows higher sheet charge density and hence higher current density and transconductance. Nevertheless, the fundamental speed limitation of an FET device is on the electron saturation velocity, rather than the mobility. Given the same semiconductor material in the FET's channel layer, the ultimate device speed is identical for both HFET and MESFET at given gate length. Fig. 8 shows a plot of state-of-the-art extrinsic f_T results for InGaAs channel HFETs and HEMTs [13]–[20]. The result clearly indicated that the high field electron saturation velocity determines the electron transport properties and the short-circuit unit current gain frequency, i.e., f_T, increases with the decrease in the gate length. Despite the nearly identical device speed performance between various GaAs-based FET technologies, the p-HEMT technology is still well suited for microwave and millimeter-wave power devices. They are advantageous for applications in LNAs and PAs because of their lower noise characteristics. A noise figure of 0.46 dB and associated gain of 13 dB on InGaP p-HEMT was reported in [21]. Noise parameter is critical for Rx circuits in an RF transceiver and FET-based device technologies historically have a better noise performance when compared with bipolar transistor devices.

4) GaAs m-HEMT and InP p-HEMT: The speed of a GaAs-based FET is enhanced by the incorporation of indium in the crystal lattice. The increase of indium composition was limited by the amount of lattice mismatch between GaAs and InGaAs layers. An alternative approach is to use amorphous buffer layers to relax the strain between GaAs substrate and the high indium content InGaAs layer. This type of device is referred as m-HEMT. The MBE-grown m-HEMTs have shown competitive performance with reported f_T and $f_{\max}$ as high as 204 and 188 GHz, respectively [22]. The technical issues with m-HEMT are



(a)

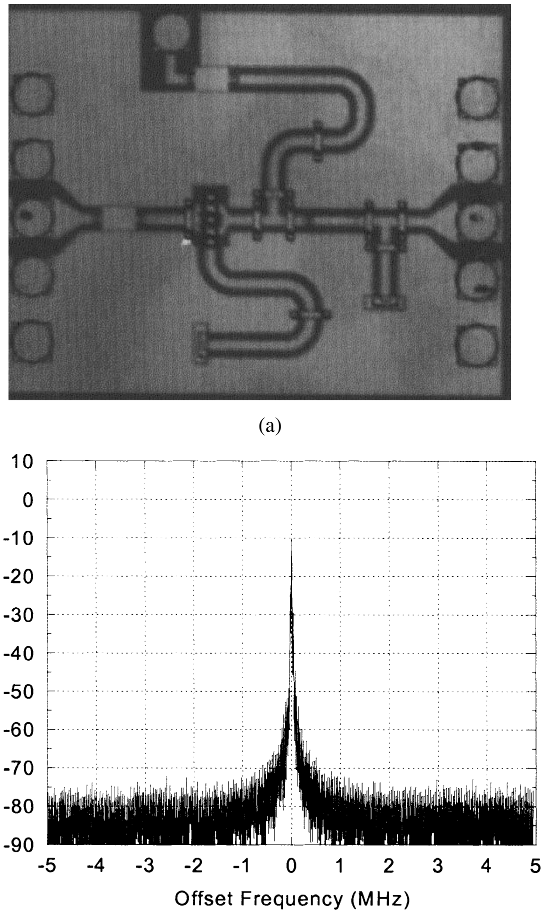
(b)

Fig. 6. Measured and simulated gain and return loss of 50-GHz distributed amplifier.

that the controllability of the strain-release buffer layer and the epitaxial material quality for circuit applications. The m-HEMT technology will be very promising in the future ultrahigh-speed applications provided that the crystal growth technology barriers can be successfully solved.

In contrast to the m-HEMT technology, InP substrates provide a perfect plateform to further increasing the In concentration and, hence, dramatically enhance the device RF performance. By optimizing the barrier thickness, the lattice-matched InP HEMT using an InGaAs channel can achieve an f_T of 500 GHz. The state-of-the-art highest f_T value of 562 GHz was reported on an InP p-HEMT with a gate length of 25 nm by researchers at Fujitsu Laboratory in Japan [23]. InP-based HEMT technology takes advantage of incorporating the InGaAs material system without much effort in crystal growth engineering compared with that for m-HEMT technology. Along with their well-known potentials in monolithic integration with next-generation high-speed long-haul optical links, InP-based FET technologies can be the enabling technologies for next-generation wireless communication systems.

5) GaN-Base HFET: As mentioned earlier, wireless communication systems usually require a high-power transmission capability at the BTS. The marginal power performance of LDMOS leads to the search of an alternative device technology for the transmitters in BTS. Gallium nitride is viewed as an excellent candidate for the fabrication of next-generation high-power and high-frequency transistors operating at elevated temperatures. Due to its wide bandgap, high electron saturation velocity, high critical breakdown field, and the potential to form lattice-matched heterojunctions with other group III-nitride materials, it has great potential to replace GaAs and Si for high power applications. The past decade has seen rapid progress toward the development of GaN-based transistors. GaN-based MESFETs,



(a)

(b)

Fig. 7. (a) Microscope photograph of a fabricated 72-GHz GaAs MESFET VCO. (b) Circuit result of 72-GHz VCO.

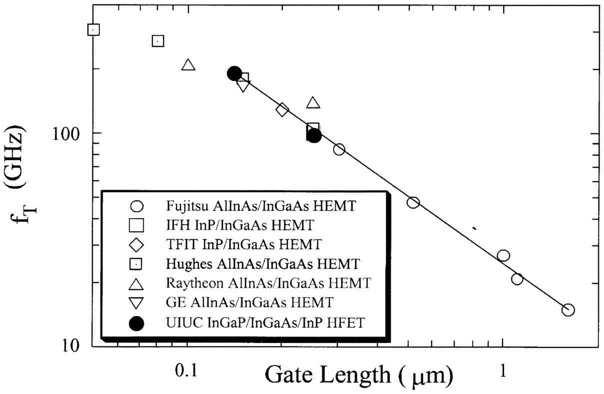
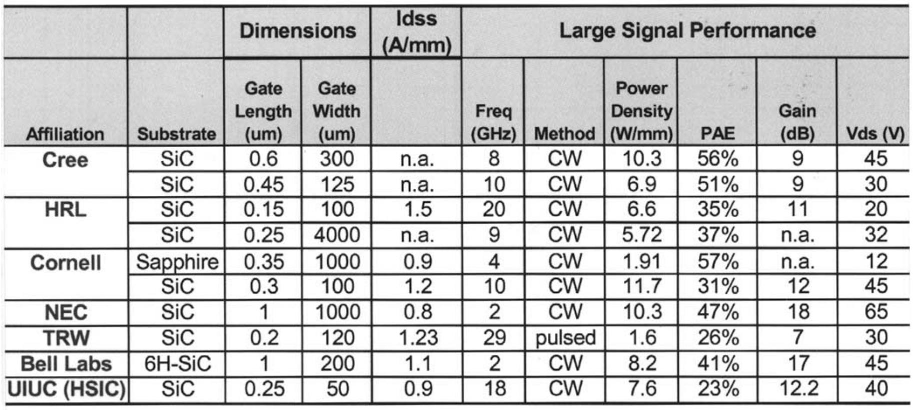


Fig. 8. A plot of f_T versus gate length in InGaP and InGaAs-channel HFET.

Table 3
A Performance Comparison Chart of GaN-Based FETs



		Dimensions		Idss (A/mm)	Large Signal Performance					
Affiliation	Substrate	Gate Length (um)	Gate Width (um)		Freq (GHz)	Method	Power Density (W/mm)	PAE	Gain (dB)	Vds (V)
Cree	SiC	0.6	300	n.a.	8	CW	10.3	56%	9	45
	SiC	0.45	125	n.a.	10	CW	6.9	51%	9	30
HRL	SiC	0.15	100	1.5	20	CW	6.6	35%	11	20
	SiC	0.25	4000	n.a.	9	CW	5.72	37%	n.a.	32
Cornell	Sapphire	0.35	1000	0.9	4	CW	1.91	57%	n.a.	12
	SiC	0.3	100	1.2	10	CW	11.7	31%	12	45
NEC	SiC	1	1000	0.8	2	CW	10.3	47%	18	65
TRW	SiC	0.2	120	1.23	29	pulsed	1.6	26%	7	30
Bell Labs	6H-SiC	1	200	1.1	2	CW	8.2	41%	17	45
UIUC (HSIC)	SiC	0.25	50	0.9	18	CW	7.6	23%	12.2	40

HEMTs, and HFETs were actively developed with a focus on their power performance. An incomplete list of research effort on GaN-based HFET is shown in Table 3 [24]–[31]. The development efforts on AlGaN/GaN HEMT continue showing the device improvement in both power-added efficiency (P.A.E.) and power density. Researchers at NEC demonstrated that a 1-mm-wide AlGaN/GaN HFET with a continuous wave (CW) saturated output power of 10.3 W, a linear gain of 18.0 dB, and a power-added efficiency of 47.3% at 2 GHz [24]. The fabricated device also showed a record gate-to-drain breakdown voltage of 160 V. A PAE of greater than 50% with a power density of 6.9 W/mm at 10 GHz was also demonstrated by researchers at Cree, Inc. on semi-insulating (S.I.) 4H-SiC substrates [25]. A PAE of 56% and output power density of 10.3 W/mm at 8 GHz was also demonstrated in the same group [28]. Similarly, Cornell University researchers demonstrated a record output power density of 11.2 W/mm with 45-V drain bias that delivered 10-W CW power on a 1.5-mm gate-width GaN HEMT at 10 GHz [26]. At higher frequency bands, researchers at the University of Illinois demonstrated an output power density of 7.8 W/mm with $V_{\mathrm{ds}} = 45$ V using 0.25-μm-gate AlGaN/GaN HFET at 18 GHz. TRW showed a pulsed power operation of AlGaN/GaN HFETs at 29 GHz [31]. These impressive power performance achieved in GaN devices will lead to a revolutionary PA design with higher output power with a smaller chip size. Despite of promising results reported in many research laboratories, extensive research effort will need to be conducted in material growth as well as device reliability issues.

C. Bipolar Devices

Historically, bipolar transistors were invented prior to the invention of the MOSFET. The era of modern microelectronics was brought to the world through the groundwork done by Bardeen and Brattain, who developed the minority carrier injection point-contact bipolar-transfer resistor, which was referred as the *bipolar transistor* [32]. The niche markets for bipolar transistors have been in analog and power applications as silicon CMOS technology dominates the digital IC arena.

1) BJT: Silicon BJTs [see Fig. 2(c)] offer a very cost-effective solution for transceiver design. The junctions are formed by ion-implantation and diffusion schedules with precise control. Below 4 GHz, microwave silicon BJTs used to provide a reliable and low-cost solution to many electronic designs. They are commonly used in small signal amplifiers, linear power amplifiers, LNAs, and oscillators. These BJTs, however, were often used in discrete transistor forms and the impedance matching was done externally on PCB boards partly due to the relatively large physical dimension requirement in RF matching networks.

In recent years, silicon BiCMOS technology was developed to combine the advantages of BJT and CMOS monolithically for mixed signal ICs. The advanced silicon processing technology also allows monolithic integration of high-Q inductor and capacitors into silicon chips at the expense of extra semiconductor estate cost. The highly integrated mixed-signal chips that include a variety of RF passive components become realizable in state-of-the-art silicon technologies. The BiCMOS technology will provide viable solutions to system-on-chip designs and will hopefully extend its reign to the future telecommunication markets by combining commonly used digital signal processing with baseband modulation circuit blocks and/or RF transceivers.

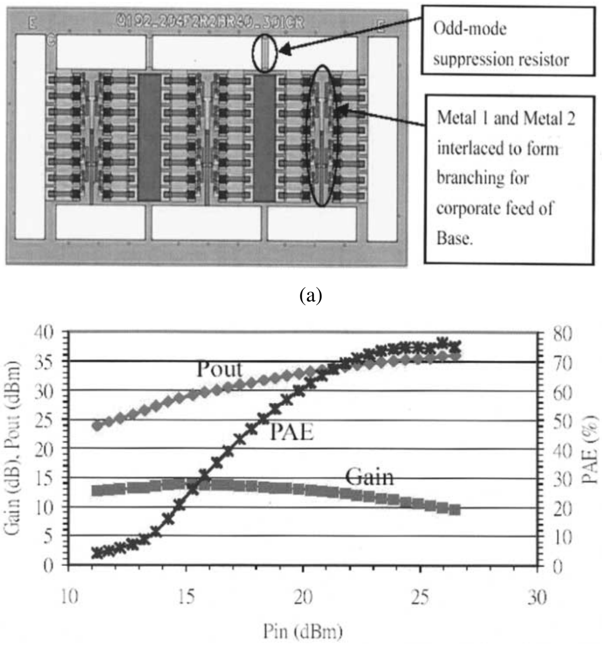
2) GaAs HBT: Despite the advantages in mixed signal circuit integration, the limitation of conventional silicon BJTs in microwave applications arises as the frequency goes higher. The insufficient power gain and high noise figure made silicon BJTs unsuitable for high power gain applications. The alternative device choice is HBT. The concept of HBT was first proposed by Shockley in light of his p–n junction theory [33], [34]. However, the progress of HBT development was limited by the availability in high-quality heterointerface single-crystal growth. The first high-quality AlGaAs/GaAs HBT was not built until 1972 by researchers at IBM using the liquid phase epitaxy (LPE) technique [35]. Later on, the successful development in metal organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) techniques greatly help the advancement and commercialization of HBT.

An HBT is a variation of a BJT with improved carrier injection efficiency, as stated in Shockley's patent. The bandgap difference in the emitter-base junction reduces the minority carrier recombination in the space charge region and results in a higher common-emitter current gain. Due to bandgap discontinuity in the emitter-base junction, emitter doping in HBTs can be lowered to reduce base-emitter capacitance and base doping can be set at higher doping level to decrease base contact and sheet resistance without degrading much of the current gain. The reduced resistance–capacitance (*RC*) transit time along with higher electron saturation velocity in an HBT results in a shorter total transistor delay. A higher transistor speed can, thus, be achieved in HBT than that in homojunction BJT.

In the compound semiconductor sector, GaAs HBT technologies have found wide acceptance in the marketplace. This acceptance is based on its technological merits that successfully address the need for high linearity, better power added efficiencies, low phase noise, good device ruggedness, and relatively low manufacturing cost in mobile communication sectors. The bipolar device allows circuit operation with single power supply while FET devices usually require a dual power supply (both positive and negative) in a circuit design. The dual supply requirement is often undesirable in mobile communication systems from the viewpoint of system simplicity. Depending on the target application, the collector thickness of HBTs can be adjusted for higher frequency response or higher breakdown voltage. A thinner collector design shortens carrier transport time across the collector and results in higher f_T. A thicker collector design increases the breakdown voltage at the cost of device speed. Since the carriers are transporting in the direction perpendicular to the wafer surface, the performance of HBTs are greatly dependent on the epitaxial technique maturity as well as material systems.

Two mainstream material systems dominate the current GaAs HBT market. They are the AlGaAs/GaAs HBT and the InGaP/GaAs HBT. Both manufacturing technologies have been extensively used in handset PA applications. The AlGaAs/GaAs HBT is considered as the 1G GaAs HBT. InGaP/GaAs HBT are the 2G GaAs HBT pioneered by Mondry and Kroemer in 1985 [36]. The InGaP/GaAs system has several performance advantages over the AlGaAs/GaAs HBT. These advantages of InGaP include a larger valence band discontinuity, smaller conduction band discontinuity, lower DX-center, higher electron saturation velocity, and etching selectivity [37]. The availability of the carbon-doped base in the InGaP/GaAs HBT also claims a better reliability than that in the AlGaAs/GaAs HBT.

InGaP/GaAs HBTs have become one of the major research topics in III-V HBTs. For example, the advanced performance of submicrometer InGaP/GaAs HBTs was demonstrated by researchers at Hitachi with f_T of 156 GHz and $f_{\max}$ of 255 GHz [38]. InGaP/GaAs HBTs are also suitable for an LNA at the 2- to 6-GHz range with minimal power consumption, high associated gain, low equivalent noise resistance, and variable optimum noise match coupled with an excellent degree of device linearity [39]. For power applications, an InGaP/GaAs HBT can achieve a f_T of 39 GHz and $f_{\max}$ of 139 GHz with a $\mathrm{BV_{CEO}}$ of 16 V [40]. Due to its outstanding device linearity and higher power gain for current wireless communications frequency bands, the GaAs HBT is currently the dominating device technology in the handset PA market. For example, a two-stage InGaP/GaAs PA with PAE of 63.2%, an ACP of -52 dBc at a 50-kHz offset frequency per 1.5-GHz Japan PDC standard, and P_{out} of 31 dBm was demonstrated [41]. The InGaP/GaAs HBT for handset applications can easily pass device ruggedness test with output mismatch voltage standing wave ratio (VSWR) of 10 : 1 [42]. The reliability of production-grade InGaP/GaAs HBT was also reported with mean time to failure (MTTF) of 3×10^9 h at T_j of 125 C and with an activation energy E_A of 1.8 eV [43].



(a)

(b)

Fig. 9. (a) Multifingered power InGaP/GaAs HBT. (b) Its RF power performance at 1.85 GHz. (Courtesy of WIN Semiconductor, Inc., Taiwan).

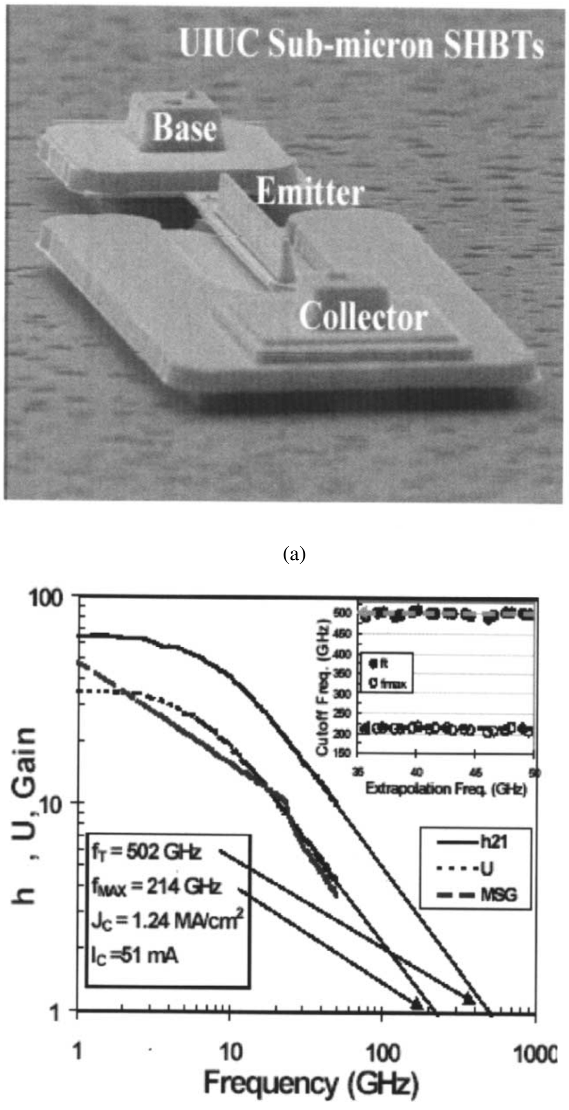
Six-inch GaAs HBT foundry services have been set up, mostly in Taiwan, to provide GaAs HBT and GaAs-based HEMT processes. Shown in Fig. 9(a) is a microscope photograph of multifingered GaAs power HBTs fabricated at WIN Semiconductor, Inc. [44]. It is a good example of a power transistor used in a handset PA. The standard power HBT cell has an array of 96 unit cells with four-fingered emitter configuration per cell. The multifinger configuration is essential for power applications in order to compromise the usage of semiconductor real estate and the production cost. The thermal dissipation issues set the limitation on the density of the power cells. To avoid the thermal runaway, emitter and base ballast resistors are often used for thermal stability. The specific device in Fig. 9(a) can deliver an output power of 36 dBm with a peak PAE of 75.2% and an associated gain of 9.52 dB at 1.85 GHz, as shown in Fig. 9(b). The integration level of the GaAs HBT has been increased as well. It is common nowadays that we see three-stage input-matched

PA with thermal feedback and power control circuitries integrated monolithically onto one GaAs HBT chip in commercial products.

3) SiGe HBT: The improvement of transistor performance, especially the operation speed, is an essential requirement for the increased capacity of network communication systems. Conventional silicon device technologies faced the fundamental speed performance limitation. The SiGe HBT, a Si processing-compatible technology, has drawn much attention recently for the applications in wireless transceivers. By using strained and composition-graded SiGe as the base layer in conventional Si BJTs, SiGe HBTs achieved RF performance comparable to GaAs technologies with fabrication cost and reliability similar to the Si process. A silicon-based device has intrinsically higher thermal conductivity than GaAs HBTs and the SiGe HBT offers the flexibility of bandgap engineering as well as base and emitter doping adjustment capabilities when compared with Si BJTs. The processing compatibility of SiGe technology and existing Si CMOS provide a powerful combination for future high-frequency mix-signal circuits.

In terms of speed performance, the most advanced SiGe HBT technology demonstrated a f_T of 350 GHz by IBM researchers [45]. SiGe HBTs also received a lot of attention as devices for PA of cellular phones. For examples, impressive results of SiGe HBT PAs were demonstrated for PCS CDMA and AMPS applications [46], [47]. Nevertheless, in next-generation wireless systems, for instance, a W-CDMA system, the device linearity is of crucial important in order to maintain low adjacent channel power rejection (ACPR) within the wide frequency spectrum and narrowly spaced adjacent channels. The reported SiGe HBT power devices may not be sufficiently compatible with GaAs HBTs in W-CDMA systems [48]. In addition, it is the opinion of the authors that the SiGe HBT may suffer from poorer device ruggedness in wireless applications due to its relatively low open-base collector-to-emitter breakdown voltage ($\mathrm{BV_{CEO}}$), which is one of the major parameters considered for power applications. These factors may hamper the dominance of SiGe technology in 3G wireless circuit blocks. Rather, highly integrated SiGe RF transceiver chips are commonly seen in lower power RF applications such as $802.11x$ ($x = a$, b, or g), WLAN, and Bluetooth. Despite these facts, considering the tremendous amount of research efforts invested in SiGe HBT technologies and the progress made through years of continuing technology advancement, one should remain optimistic that SiGe HBT will have the potential to become the competing device technologies in future PA markets where GaAs HBT dominates today.

4) InP-Based HBT: InP-base HBT technologies offer another device choices for next-generation wireless transceiver systems. The higher RF performance of InP-based HBT or FET devices stems from the superior intrinsic electronic properties of their constituent semiconductors. Over past decades, InP/InGaAs HBTs were extensively studied in the laboratory environment and many millimeter-wave applications are made possible using InP-based HBTs. For instance, InP HBTs were used for the implementation of the MMICs such K- and Ka- band amplifiers and for LMDS applications [49], [50]. Recently, an InP-based HBT has been favorably applied in the generations-ahead-40-Gb/s optoelectronic IC (OEIC) for the front-end receiver modules due to the monolithic integration capability of optical-to-electrical and microelectronic components [51]–[53]. The InP-based HBT will be another important device technology for next-generation wireless systems: the InP-based HBT presumably has a higher current gain cutoff frequency, which translates to a higher RF transducer gain at a given frequency band compared with their GaAs-based counterparts. In addition, the lower base-to-emitter turn-on voltage along with higher thermal conductivity and better device linearity makes it an attractive alternative for next-generation ultrawide band (UWB) power amplifier applications.



(a)

(b)

Fig. 10. (a) SEM photograph of a fabricated submicrometer InP/InGaAs SHBT. (b) The measured RF performance.

A variety of InP-based HBTs are available for circuit applications. Depending on the collector material, it can be either a single HBT (SHBT) that uses identical material system in both base and collector, or a double HBT (DHBT) that uses different materials in the collector and the base. The most talked about InP-based HBT employs a lattice-matched InGaAs base. SHBT has shown fairly simple processing fabrication and impressive high-speed performance. The state-of-the art InP/InGaAs SHBT demonstrated an f_T of greater than 500 GHz on a 0.35×12-μm^2-emitter-area HBT with a breakdown voltage of 2.7 V [54]. Fig. 10 shows a fabricated InP/InGaAs SHBT with a 0.35-μm-wide emitter and the measured RF performance at $J_c = 1.24\ \mathrm{MA/cm^2}$. The raised posts on emitter, base, and collector facilitate the planarization that may allow high-density IC fabrication. This is the highest speed (in terms of f_T) ever reported in all *bipolar transistors* up to date. The high-speed performance in InP SHBT is attributed to the intrinsic high electron saturation velocity and to a relatively simple scaling effort in the collector thickness. Compared with the high-speed silicon counterpart, SiGe technology, InP SHBT employs less complicated fabrication and the device feature size can be kept fairly large ($\sim$ 0.25 μm) that can be easily implemented in relatively low-cost stepper technology nodes. This feature is of great importance because the use of InP HBTs may potentially reduce the fabrication cost for future ultrahigh-speed circuits without much capital equipment investment as people expected in silicon world.

InP DHBT was also developed in a hope to increase the device breakdown voltage and device performance. The intended collector material for DHBT is usually InP. Due to the bandgap discontinuity at the base and collector junction in a so-called "Type-I" material system, the InP DHBT suffers the current blocking problem that reduces the current gain at high current collector density. A careful collector design is often required. A submicrometer InP DHBT can easily achieve a f_T of over 300 GHz with a reasonable $\mathrm{BV_{CEO}}$ of 5 V [55]. The next-generation InP DHBT under investigation is the Sb-based DHBT that have a "Type-II" heterojunction between InP and GaAsSb. In a "Type-II" GaAsSb/InP junction, the electron transport from GaAsSb to InP sees no energy barrier, while the holes are blocked and are confined in the GaAsSb layer. The results are that the carrier injection efficiency in the InP-base "Type-II" HBT as well as device linearity will be greatly improved in theory. However, the Sb-based InP DHBT needs to refine the crystal epitaxial growth technique in GaAsSb base layer for manufacturability reasons.

Much of the attention in InP HBT development has been on the ultrahigh-speed millimeter-wave applications. Fewer results were reported on the power application for commodity wireless communications. The major reason has been economical rather than technological issues. With an increase in collector thickness, an InP DHBT was able to achieve a $\mathrm{BV_{CEO}}$ of 26 V with a $f_{\max}$ of 93 GHz and an InP-based DHBT with 90% PAE and 1-W output power at 2-GHz class C operation has also been reported [56], [57]. It is our opinion that the InP HBT is promising for power application in next-generation wireless communication judging from the material properties as well as reported research results. The potential commercialization of InP HBT technology may become reality based on the fact that most of the processing steps are compatible with the much matured GaAs HBT process. A few InP-based foundry services and 4-in InP fabrication lines are readily available. However, the availability of low-cost substrate and the evolution of InP substrates toward a larger wafer diameter, i.e., from 100 to 150 mm and larger size, are more critical issues to the commercialization of InP HBT technologies for scale economy.

5) GaN HBT: In the high-power wireless communication, GaN-based HBT has been speculated as one of the rising stars for the future semiconductor device technology. Unfortunately, the development of GaN HBT is still in its infancy stage. The material growth and the processing technology for GaN HBT are going through the trial-and-error period and few groups in the world have successfully demonstrated the real working GaN HBT [58]. The technology obstacles lie in the unavailability of good ohmic contact on p-type contact and the nonselective etching of different layer of materials. In the opinions of the authors, more technological breakthroughs in GaN HBT will be required before one can even consider this technology for future wireless communication systems.

6) Passive Components and Switches: In the course of monolithic integration of RF transceivers, passive components, such as inductors, capacitors, and resistors, are also the key factors in manufacturing. In contrast to external passive devices of traditional RF designs, on-chip passive components provide a highly integrated solution. However, the on-chip passive components usually cost a large portion of the chip area and, hence, increase the fabrication cost.

There are a variety of ways to fabricate a resistor. A versatile way of using semiconductor is to use a strip of n-type or p-type material as a resistor, given the fact that each semiconductor layer has its specific sheet resistance value. The semiconductor-based resistor may suffer high thermal coefficient and velocity saturation effect. They can be used as a high-resistant resistor applications that are less sensitive to the variation in temperature and electric field. For precision resistance value control, thin-film resistors with low temperature coefficient and low bulk resistivity characteristics are deposited. Tantalum nitride (TaN) and nickel chromium (NiCr) are widely used in the fabrication of precision resistors. The TaN and NiCr resistors have extremely small and negative thermal coefficient of resistivity and are ideal for IC applications with large operating temperature range.

The commonly used on-chip inductors are planar spiral inductors. They have poorer quality factor (Q) and do not scale in size as transistors do. The problem is even worse in conducting substrates such as silicon. Various technologies were proposed to improve inductor Q including patterned ground shields, tapered spirals, and groove-etched suspended inductor. Low-loss and high-density inductors are of major research interest in the fabrication of inductors.

As for capacitors, two approaches are commonly used, parallel plate capacitors and active device capacitors. The parallel plate capacitors are composed of metal/insulator/metal (MIM) or poly/dielectric/metal. These capacitors are linear and can be scaled proportional to the device area.

The effort for capacitor development has been in the increase of capacitance density per unit area in a hope to shrink the capacitor size. The active capacitors use part of the active devices, e.g., reverse-biased p-n junctions or Schottky diodes. The electrical responses of active-device-based capacitors are nonlinear and the Q is usually low. Due to high dielectric constant in a semiconductor material, the active-device-based capacitors have higher capacitance density. They are especially useful when various capacitance values are required in a circuit design.

In the construction of RF transceivers in wireless communication systems, one may not overlook the importance of the switch. An RF switch is responsible for directing the signal path in a Tx/Rx module. An ideal RF switch should be lossless and linear so that no signal loss will occur during the switching. Conventional RF switches are made of active devices such as an FET or p-i-n diode. The intrinsic resistances in a semiconductor material result in an RF loss when RF power passes through the switch. The insertion loss in semiconductor-base switches increases as frequency goes higher. In addition, the signal distortion due to device nonlinearity in a switch also causes performance degradation and energy loss in an RF transceiver. Advanced switching technology has been aggressively sought and RF MEMS switches are among the most interested device over the past few years.

The RF MEMS switch is a rather exotic technology that emerged in just less than a decade. The RF MEMS switch is essentially miniaturization version of mechanical relay built on the semiconductor substrate. The nearly ideal switching functionality with high isolation ($>$ 20 dB) and extremely low insertion loss ($<$ 0.1 dB) across ultrawide bandwidth of $>$ 100 GHz did draw a lot of attention for next-generation communications. For example, by controlling the metal positions up (on, signal through) and down (off, signal blocked), the RF switch shown in Fig. 11(a) has an isolation of greater than 22 dB and an insertion loss of less than 0.2 dB for signal frequency up to 40 GHz [59].

The high performance of broadband MEMS switch can essentially be used from dc to $>$ 100 GHz. Fig. 11(b) shows the switching characteristics of an RF MEMS switch measured up to 110 GHz. An insertion loss of less than 6 dB and an isolation of greater than 16 dB were measured at frequency as high as 110 GHz. The demonstrated results are encouraging, since none of the active-device-based switch can ever operate at such high-frequency bands without suffering tremendous RF losses. Despite their excellent RF performance, the reliability of such devices has been one of the major concerns. Only a few research organizations have demonstrated the reliability data on RF MEMS switches. A comparison of the reliability testing data as a function of actuation voltage is shown in Fig. 12 [60]–[63]. The state-of-the-art RF MEMS switch can sustain switching cycles of over 7×10^9 times with relatively low voltage operation.

RF MEMS switches found their niche market in switching applications that require only a few milliseconds of switching time such as reconfigurable phase antenna arrays. A RF MEMS switch provides at least one order of magnitude less RF loss than any device technologies available to date. However, to the best of the authors' knowledge, the maturation of RF MEMS technology will need a few more breakthroughs in terms of device reliability and RF power handling capability before it can fulfill its role of being a commercially accessible technology. Active-device-based switches will remain a mainstream technology in RF switching blocks for years to come.

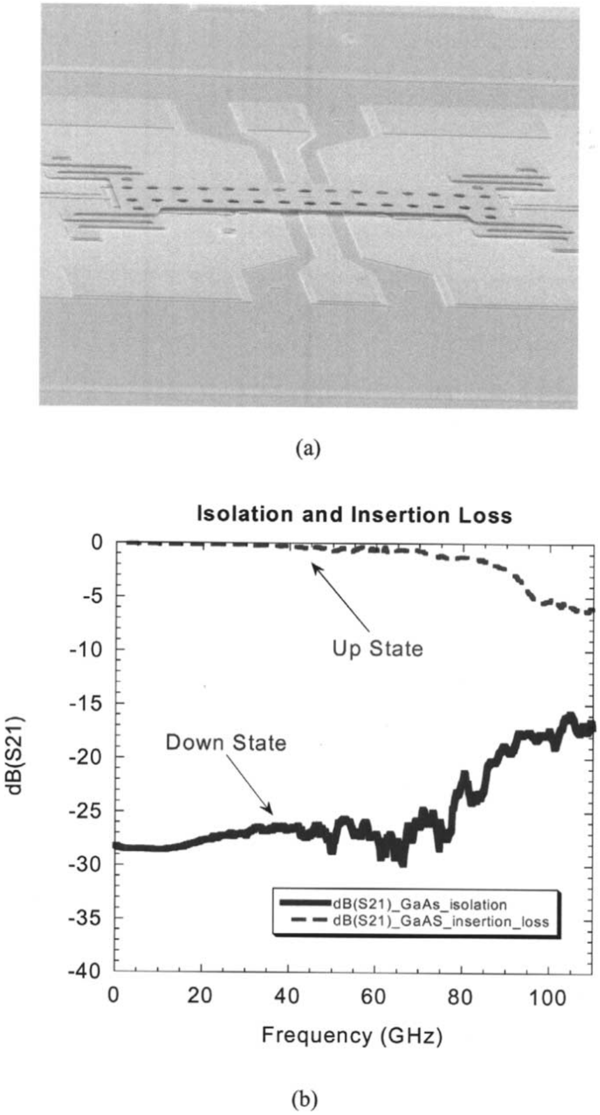


Fig. 11. (a) SEM photograph of a fabricated shunt RF MEMS switch. (b) A typical measurement result of RF MEMS switches fabricated at the University of Illinois. The frequency range of the measurement extends from dc to 110 GHz.

Another viable MEMS-based RF passive components is the film bulk acoustic-wave resonator (FBAR) first developed at Agilent Technologies. This device technology employs MEMS technology and incorporates stacks of piezoelectric thin films to achieve high Q filtering functionality. FBAR uses semiconductor manufacturing techniques for high volume production and the competitive performance make it an attractive alternative device choice in wireless communications applications. These devices are 50% to 80% smaller than conventional ceramic duplexers, enabling ever-smaller mobile handsets with enough room

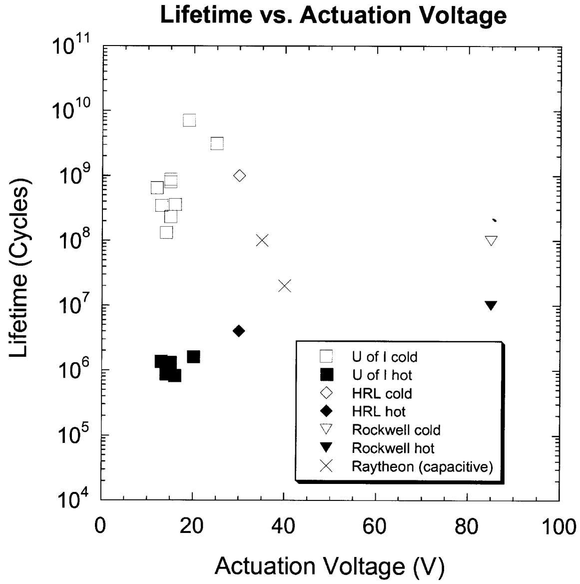


Fig. 12. A comparison of the reported reliability data on RF MEMS switches.

to incorporate things such as PDA, MP-3, and GPS capabilities. Compared with conventional surface acoustic wave (SAW) devices, the FBAR-based device also offers a better power handling capability with smaller device size. Agilent announced plans for its first FBAR-based duplexers aimed at the CDMA market in early 2000. The market share of this device technology was expected to grow as the real estate issues in next-generation mobile communication become one of the determining factors for key passive components.

IV. Circuit Components for Next-Generation Communication Systems

Having discussed the currently available semiconductor device technologies and potential novel technologies for next-generation wireless communications, we will discuss the essential circuit building blocks for an RF transceiver. Each transceiver block is backed up by the semiconductor device technologies that provide the optimal circuit performance. We will start with a comparison of FET and BJT and try to find the pros and cons of each device technology and their niches in each circuit application. We will then turn our attention to each major transceiver component and go through the discussion on the requirement of each component. A favorable device technology for each component will then become apparent.

A. Comparisons of Field Effect Transistor and Heterojunction Bipolar Transistor Technologies

Shown in Table 4 is a comparison of some device parameters for both FET and HBT devices. First of all, the physical dimension limitation set the ultimate device speed performance. Fundamentally, a shorter gate length in an FET can reduce the carrier transport time and a narrower base as well as thinner collector in a bipolar device can decrease the carrier transit time. In FET devices, the gate length is defined by photolithography while the vertical layers in HBT are defined by epitaxial growth. The high-performance submicrometer FET cannot be realizable without advanced photolithography tools such as e-beam photolithography and Deep-UV stepper. On the other hand, commonly available crystal growth techniques such as MBE and MOCVD can precisely control the epitaxial growth with a precision level of monolayer ($\sim$ 5 Å). A base width of $<$ 500 Å is easy to achieve and the lateral device dimension of an HBT can be much relaxed compared with FET devices. The resulting microwave performance with f_T and $f_{\max}$ in 100- to 300-GHz range can be achieved with a conventional 1-μm photolithography technology in HBT, while the gate length of less than 0.15 μm in a III-V FET will be required to achieve the comparable RF performance.

Device turn-on characteristics of an HBT are controlled by a material band gap or the turn-on voltage in the base-emitter junction. In contrast, the pinchoff voltage of an FET depends on the doping and thickness of active channel. The pinchoff characteristic in a III-V FET can be a complex function of channel formation under the gate region, semiconductor surface properties, and subsequent process variations in gate recess etching. Therefore, an HBT intrinsically has better device matching and are suitable for differential pairs. The HBTs are suitable for differential circuitry such as high-accuracy comparators in circuits such as analog-to-digital converters, low offset dc coupling in analog amplifiers, and input voltage matching for low voltage swings.

HBTs usually have higher current density than that for III-V FET devices because the entire emitter area ideally contributes to the current in an HBT rather than a thin channel in an FET. Thus, HBTs are capable of handling more power within a smaller chip size when compared with FET-based power circuits. The breakdown voltage of an HBT can be tailored for optimized power performance via epitaxial growth. In contrast, the breakdown characteristic of an FET is affected by the lateral device dimensions such as gate-to-drain distances and the amount of recess etching. In general, an FET has better noise performance at high frequency. The noise source of an FET is mainly from the thermal noise. For a BJT, the noise figures are determined by shot noise, which is related to the operating currents. An HBT is, thus, suitable for low-power LNA applications [39].

In terms of manufacturing, the major advantage of a III-V FET over an HBT is its simplicity in device fabrication. A FET device-level fabrication needs only three to four mask layers. The recess etching is required to achieve targeted threshold voltage in recessed-gate FET technologies such as p-HEMT and ion-implanted MESFETs. A wide variety of techniques are available on the gate formation as well as the recessed etching of III-V FET to meet different circuit requirements. However, the versatility in the fabrication of FET used to bring in troublesome device uniformity issues. Delicate gate formation processing sequences were the yield-limiting factor for large-transistor-count circuits. Seldom did we see an FET-based circuit exceeding MSI integration level with an exception of the proprietary H-GaAs

Table 4
A Comparison Chart of FET and HBT Characteristics

Parameters	FET/HEMT	BJT/HBT
Physical dimension limitation	Gate length	Base & Collector thickness,
Turn-on characteristics	Gate threshold voltage (V_{th})	Base-emitter voltage ($V_{BE(on)}$)
Output current density	Medium	High
Noise Source	Thermal	Shot, 1/f, Phase
Processing Complexity	Medium	High
Input impedance controller	Gate voltage	Base current

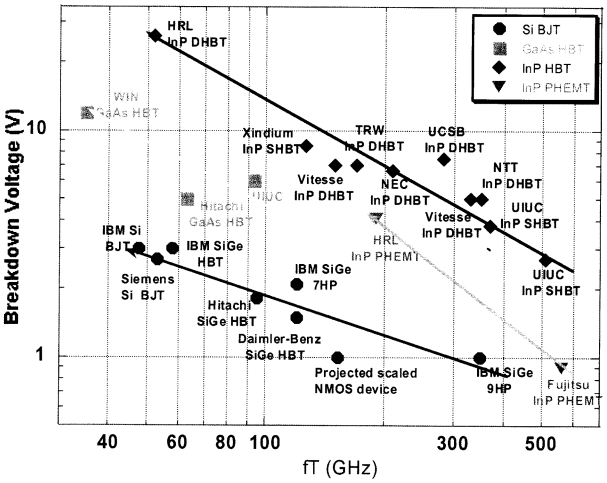


Fig. 13. A comparison of f_T versus breakdown characteristics for SiGe, GaAs, and InP devices.

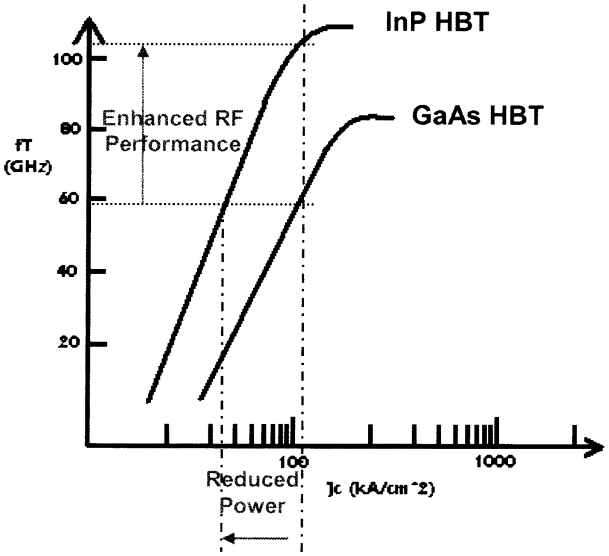


Fig. 14. A typical plot of f_T v.s. collector current density for GaAs HBTs and InP HBTs.

process at Vitesse that employed highly reproducible ion-implantation scheme. On the other hand, the fabrication processes of an HBT are far more complicated than those for a III-V FET. They usually involve multiple etching and metal deposition steps in device fabrication. However, the devices have more uniform characteristics because the device characteristics suffer less from the process variation. A transistor count of over 3000 is commonly seen in mixed-signal circuits such as analog-to-digital converters in HBT technologies. One of the major concerns will be the planarity of HBT. The mesa etched HBT may become the limiting factor for HBT technology.

The higher breakdown voltage of III-V-based devices differentiates themselves from Si-base devices in high-speed applications. Fig. 13 shows a summary of the breakdown voltage versus unit current gain cutoff frequency (f_T) for different device technologies [37], [44], [45], [55], [56], [64]–[67]. Each device technology with the same material system shows a consistent trend in the plot. A reasonable breakdown voltage is a must in transceiver designs in order to handle spurious signals and VSWR issues. A higher f_T-breakdown-voltage product implies higher RF gain with better robustness in power handling capability. For a given device technology, a higher breakdown voltage can always be achieved at the cost of device operating speed through a proper device scaling in both vertical and lateral directions. For a given breakdown voltage, it is clear that III-V devices are apparently faster than silicon-based devices. It is also worth noting that, among III-V device technologies, InP-based devices outperform GaAs-based devices in terms of higher breakdown-f_T product.

In semiconductor device technologies, a device with similar device size but higher f_T value is usually a favorable choice of technology. As shown in Fig. 14, we take GaAs HBT and InP HBT as examples and show the reasons behind this argument. The reasons are: 1) the higher f_T device can operate at lower power without a compromise in switch speed and 2) the devices with higher f_T have a faster switching time, higher power gain, and better efficiency without an increase in power consumption. Considering that both device speed and breakdown voltages are essences in RF transceiver design, InP HBTs should be a better choice for next-generation high-speed transceivers. However, the decision on the choice of the device technologies for next-generation RF transceivers will be compounded by other factors such as cost/performance and risk tradeoffs.

B. RF Transceiver Circuit Blocks

1) PA: In transceiver designs the PA is perhaps the most critical component, and the choice of PA class is strongly dependent on the system applications. The design of the PA is generally classified depending on the relation between input and output signals. Class A operation is characterized by a constant dc voltage and current. It has the highest linearity among PA classes but poor efficiency. Class B can be used for PAs where the linearity is not a big concern. Class AB uses signals with conducting angle larger than 180°. It is often biased at a constant voltage and the quiescent current increases with drive power.

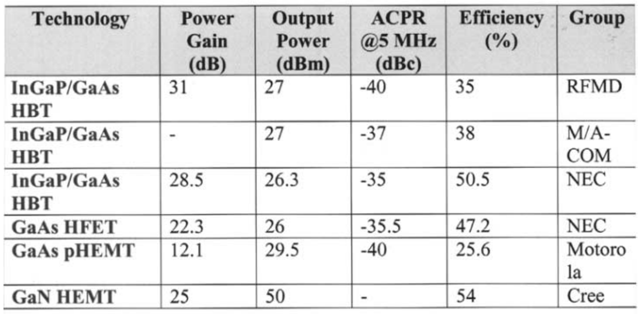
Most commercial handset PAs are two or three-stage circuits with the output stage operating in deep Class AB operation at the minimum input power level and Class A operation at the maximum input power level. It is critical to keep the transistors in the PA operating below their maximum current density for reliability across the entire output power range. This results in quite large output stages being needed to deliver the maximum power, which increases chip size and, thus, cost. Semiconductor technologies with lower transistor thermal resistance and better heat removal can sustain higher current densities, since their junction temperature will be lower, and lifetime will be improved. A smaller output stage could be used, and chip cost will decrease.

External to the chip, most commercial PAs employ a second harmonic trap to improve PAE and reduce distortion. A two-stage *LC* output match transforms 50 Ω to the very low load impedance required for maximum output power. The two-stage match improves bandwidth and also gives a sharper rolloff above cutoff, which suppresses harmonics more than a single-stage *LC* match. For three-stage bipolar-based PAs, the input impedance of the input stage is high enough on-chip resistors and off-chip bondwires can match the input of the PA to 50 Ω without requiring addition SMTs for *LC* matching. For two-stage bipolar-based PAs, the input stage has a lower magnitude impedance, and a simple one-stage *LC* match can be made on or off-chip. Interstage matching is typically done using series *LC* resonant networks realized by bondwires, package inductances, and off-chip SMT capacitors.

Typical requirements for handset PAs are low cost, high PAE, small size, and high reliability. Typical requirements for handset PAs are low cost, high power added efficiency, small size, and high reliability. The output power level is an important benchmark for base stations, while PAE is a big concern for handsets once output power level is satisfied. With more stringent requirements of wider channel bandwidth, higher carrier frequency, and higher ACPR in next-generation wireless communications, linearity becomes a very important issue in choosing technologies for PAs. For example, the currently working GSM PA may not meet the specification of W-CDMA because it fails to meet the bandwidth as well as the ACPR spec. A new development in the device technology will be required.

Currently, the GaAs-based HBTs have superior power gain and linearity due to their vertical layer structure and their capability of high current density. GaAs-based HFETs are also used for PAs due to their inherent efficiency. Power devices need large breakdown voltages (10–20 V) to accommodate the potential mismatch loading for device robustness reasons. To enhance heat removal during device operation, backside via holes or thermal shunt bridges are applied to achieve low thermal resistance. Table 5 shows a comparison of power performance of PAs at frequency around 2 GHz [68]–[74].

Table 5
A Summary of PA Power Performance at Frequency Around 2 GHz



Technology	Power Gain (dB)	Output Power (dBm)	ACPR @5 MHz (dBc)	Efficiency (%)	Group
InGaP/GaAs HBT	31	27	-40	35	RFMD
InGaP/GaAs HBT	-	27	-37	38	M/A-COM
InGaP/GaAs HBT	28.5	26.3	-35	50.5	NEC
GaAs HFET	22.3	26	-35.5	47.2	NEC
GaAs pHEMT	12.1	29.5	-40	25.6	Motorola
GaN HEMT	25	50	-	54	Cree

2) Switches: RF switches play a key role in controlling signal flow and adjusting the phase and amplitude of the signal. There are also demands for diversity switches that allow access to different systems with various services because it is advantageous for transceivers to share as many building blocks as possible to reduce system redundancy. PIN diodes and MESFETs are commonly used in transceiver design. PIN diodes have advantages of low RF insertion loss and the capability of handling high power. MESFETs are also advantageous in terms of design flexibility and low power consumption. The insertion loss of these active-device-based switches is often rated at ~ 0.3 –0.5 dB at 2-GHz range.

3) Mixers: Mixers are used to up-convert or down-convert signals from one frequency to another. They can be regarded as switches with input RF signal modulated by local oscillator (LO). Devices for mixers need to have high nonlinearity, low noise, and low distortions at wide frequency band. Schottky diodes are widely used due to their fast switching speed. FETs are also chosen for mixer designs due to their excellent frequency response and low noise properties. However, the precise process control of threshold voltage of a mixer is the major yield limiting issue in MESFET mixer fabrication, especially for ion-implanted MESFETs. An inserted etch stop layer in MESFET material is a general solution. The design of mixers can be divided into single-ended and balanced mixers. Today, the Gilbert cell is probably the most popular type of mixer used for MMICs. It has the advantages of low LO power, high conversion gain, and good isolation. [75]

4) LNA: In an LNA, one wants to minimize the noise figure of the amplifier, to lower the power consumption, and to increase the power gain. The matching circuits are often applied in the input and output ports to minimize the insertion loss or noise figure for LNA design. The LNA circuits have been fabricated by various technologies. Fig. 15 shows the performance of LNA by taking small signal gain, dc power consumption, and noise into consideration [76]–[82]. GaAs

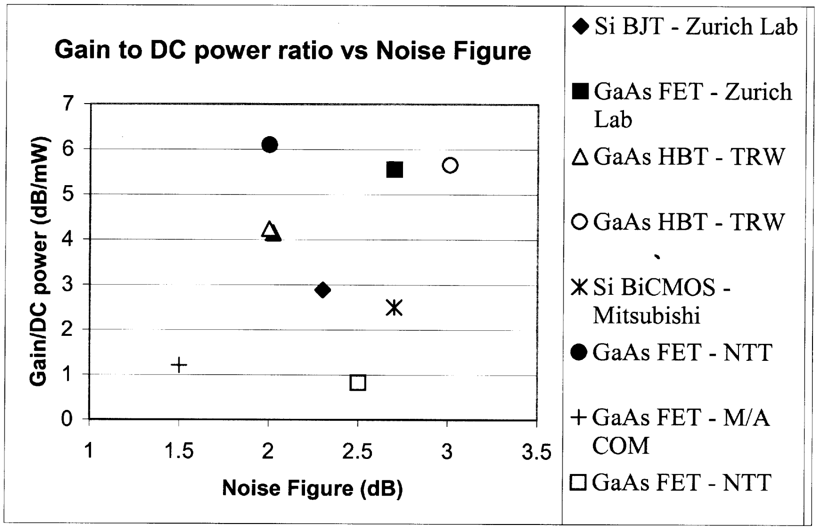


Fig. 15. Comparisons of LNA with different device technologies.

Table 6
A Comparison Chart for Different Device Technologies in Wireless Communication RF Transceiver Applications

Parameters	GaAs MESFET	GaAs HBT	GaAs HEMT	Si RF CMOS	SiGe HBT	InP HBT
Device speed	Good	Good	Good	Fair	Good	Excellent
Chip density	Low	High	Low	Low	High	High
Transconductance	Medium	High	High	Low	High	High
Device matching	Poor	Good	Poor	Poor	Good	Good
1/f noise	Poor	Good	Poor	Poor	Good	Good
PAE	Medium	High	High	Medium	Medium	High
Linearity	High	High	High	Low	Medium	High
Device matching	Poor	Good	Poor	Poor	Good	Good
Output conductance	Medium	Low	Medium	High	Low	Low
Integration level	MSI, LSI	MSI, LSI	MSI, LSI	VLSI	LSI, VLSI	MSI, LSI
Breakdown voltage	High	High	High	Medium	Medium	High
Possible primary applications in RF transceivers	VCO, Mixer, Switches	PA, Pre-Amp gain blocks, Oscillator amps.	LNA Gain blocks, Switches	Back end logic control, switches, mixers	LNA, PA, Gain blocks	PA, LNA, VCO

FETs and HBTs are usually used for making LNAs while Si BJTs, BiCMOS, and SiGe HBTs are also employed for cost-effective solutions.

A qualitative performance summary of each device technology is listed in Table 6. In most designs, the minimum noise figure, maximum power gain, stability factor and reflection coefficient (VSWR) usually do not occur at the same input/output impedance in the Smith chart. Therefore, the selection of bias point and input/output impedance is determined by the spec requirements of each component. For example, the choice of optimum noise figure is preferred for LNAs while maximum power gain for PAs. For a given transistor technology, higher bias voltage and current are suitable for PA. But lower noise figure can be found at lower collector or drain current, which is desired for LNAs. Proper choice of device technology can help achieve better overall performance.

It is clear to see that the optimum technology choice for RF transceivers is complicated because of the stringent performance goals, integration, and fabrication cost. The tradeoff between noise figure, power dissipation, and intermodulation properties along with the integration and wafer cost lead to a mix of technology choices. Current results show that GaAs MMICs provide higher performance than silicon ICs at 2 GHz. A compact chip size is also an important factor for commercial products. Passive elements in the transceiver usually occupy larger amount of area than active devices. Spiral inductors and MIM capacitors are commonly implemented on III-V semiconductors with higher Q because of the availability of the semi-insulating substrates. RF circuit design is, therefore, comparably easy on compound semiconductor than that on Si substrates. To achieve a higher integration level without a compromise in each constituent RF component, the concept of system-on-a-package (SoP) may be a suitable solution for future RF transceiver modules [83], [84].

V. CONCLUSION

We have discussed the device and circuit technologies for next-generation RF transceivers. To provide higher transmission speed and data bandwidth, transceivers used in wireless communication systems are expected to offer higher RF power, better ACPR, lower noise figure, and higher sensitivity. The chosen device technology will depend greatly on the tradeoffs between manufacturing cost and circuit performance requirements. Over past decades, there have been attempts to integrate as many components as possible into MMICs. Unfortunately, hardly did we find a currently available semiconductor device technology that offers an ultimate solution to RF transceivers in SoC integration. The choices of optimum device technologies for each constituent component are then important and complicated issues.

In the compound semiconductor world, GaAs MESFETs are widely used in the III-V semiconductor industry due to their process simplicity and their excellent RF performance. Heterostructure FETs such as HFETs, p-HEMTs, and m-HEMTs provide higher f_T and $f_{\max}$, better noise figure, and breakdown voltage, making them ideal candidates for LNAs and PAs. The GaAs-based HBT has been an excellent device choice for PAs in wireless communications that provided higher power gain and higher power added efficiency.

Silicon-based device technologies are showing their presence in high-frequency applications. Si RF CMOS, Si BJTs, Si BiCMOS, and SiGe HBTs are advantageous for low-cost, highly integrated applications. With the gate length scaling and emitter size shrinkage, the frequency response of Si devices will become the contenders for next-generation wireless components.

Future device technologies such as GaN-based devices and InP-based devices have great potential for the quick and seamless insertion in future RF circuit blocks with higher linearity and power density. The demand of low insertion loss switches will also motivate the continuing development efforts of innovative RF MEMS technologies for switches and other passive components.

The economic downturn has slowed down the deployment of 3G (both W-CDMA and CDMA-2000) in mobile communication sectors and it is difficult to draw a big picture of what a 4G or gigabit wireless communications will bring us. However, the future trend is clear that the data and voice streams will be merged and will be carried in higher carrier frequency bands at higher data rates and wider bandwidth using more efficient modulation schemes. The variety performance portfolios and continuing advancement in semiconductor device technologies will enable the realization of future RF transceivers in the high data rate wireless communication systems.

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