HBT Technology and Applications, Today and Tomorrow

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Abstract

This paper briefly reviews the status of GaAs Heterostructure Bipolar Technology (HBT) material, process and device developments. Representative device performance being achieved today is reported. System applications of digital and mixed signal circuits are described. Finally, further development of the HBT technology necessary for commercial applications is discussed.

Introduction

The idea of applying heterostructures to improve the performance of the bipolar transistor by increasing the bandgap of the emitter relative to its base was recognized as early as the 1950's [1]. Only during the last decade, however, has this idea been fully realized in the commercialization of the Heterojunction Bipolar Transistor (HBT) technology. This time lag has been largely due to the difficulties encountered in the material growth of the base-emitter junction interface with two dissimilar materials and its impact on device characteristics, reliability and yield. During the 1970's, primarily driven by the needs for better materials for electro-optical applications, major improvements in Molecular Beam Epitaxy (MBE) and Metal Organic Chemical Vapor Deposition (MOCVD) were made that laid the foundation for the ability to attain fully the potential of the HBT's for ultra- high speed applications.

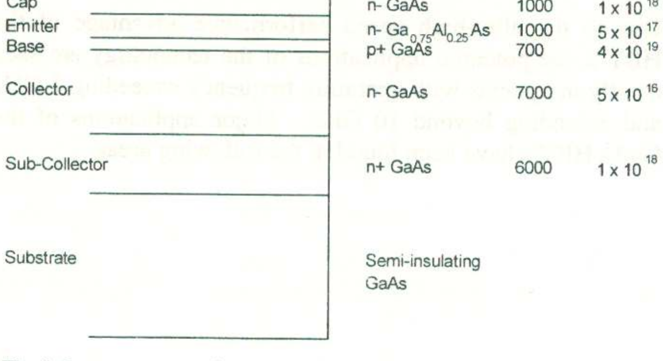
During the last decade, most of the development of the HBT technology was based on the AlGaAs/GaAs material system. More recently, major progress in HBT's implemented with the AlInAs/GaAs and SiGe has been reported. In this paper, we will primarily focus on the technology and applications of the more mature AlGaAs/GaAs HBT's.

GaAs HBT's enjoy many advantages compared with Field Effect Transistors (FET's) and Silicon Bipolar Junction Transistors (BJT's). In comparison with FET's, the HBT's have much higher current driving capability and high transconductance, g_m. The transistor has low output conductance, g_o, and high amplification factor (g_m/g_o), but because the base is well shielded and sandwiched between the collector and emitter region, it also benefits from the absence of trap induced effects -- output transconductance dispersion effects (hysteresis), 1/f noise, backgating (sidegating), etc. In addition to the high amplification factor, the HBT device matching is much better than the FET's. Since current flow is bulk rather than surface related in HBT's, the device matching is determined by the built-in potential of the base-emitter junction compared to the FET device where the device matching is determined by the uniformity of implantation as well as material properties.

In comparison to Si BJT's, the HBT's have a higher electron mobility, and the wider emitter bandgap permits very high base doping which reduces the base resistance while still maintaining high emitter injection efficiency. The reduced base resistance and higher electron drift velocity result in a much higher f_t and f_{max} compared to the BJT's.

Material Structure and Process Technology

A representative material layer structure of HBT's [2] is shown in Fig. 1. Taking advantage of the wider bandgap material for the emitter, typical base doping of the HBT's ranges from 1×10^{19} to 1×10^{20} cm^{-3}. This very high doping density effectively reduces the base resistance improving the maximum frequency of oscillation, f_{max}, of the transistor as well as helps to increase the output resistance. A base layer thickness of 400 to 1000 angstroms is used to achieve high cutoff frequency, f_t. The emitter doping is in the range of 1×10^{17} to 1×10^{18} cm^{-3}. This relatively low level of emitter doping is used to reduce the emitter-base capacitance. This same principle is applied to the collector region where doping levels in the range of 1×10^{16} to 1×10^{17} cm^{-3} are used to reduce the junction capacitance. A heavily doped subcollector region is used to reduce the collector resistance and the collector contact resistance.



	Composition	Thickness (Angstroms)	Doping (cm-3)
Contact	n+ InAs/InGaAs	800	1×10^{19}
Cap	n- GaAs	1000	1×10^{18}
Emitter	n- $Ga_{0.75}Al_{0.25}As$	1000	5×10^{17}
Base	p+ GaAs	700	4×10^{19}
Collector	n- GaAs	7000	5×10^{16}
Sub-Collector	n+ GaAs	6000	1×10^{18}
Substrate	Semi-insulating GaAs		

Fig. 1. Layer structure of representative AlGaAs/GaAs HBT.

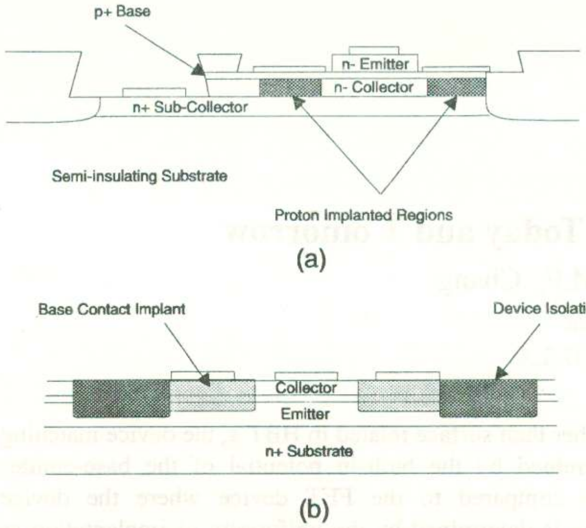


Fig. 2. HBT Cross sections (a) Emitter-up. (b) Emitter-down.

Fig. 2. shows the cross-sectional view of both the emitter-up [3] and the emitter-down [4] HBT device structures. In the emitter-up structure, the isolation of the collector regions is achieved with ion-implant damage. Implantation species including Boron and Protons have been demonstrated to be very effective for achieving this isolation. The base pedestal is defined by wet chemical etching. The collector contact is typically defined by alloying with Ni/AuGe based metallization. The base contact can be formed with direct deposits of refractory Pt/Ti metallization. The emitter contact can be formed either by alloying or by a direct W or Ti contact to a highly doped InAs emitter cap layer.

The emitter-down device structure shown in Fig. 2 was developed by Yuan et al at Texas Instruments for use in Heterojunction Integrated Injection Logic (HI^{2}L). This implementation takes advantage of a thin film resistor used as the current injector and the integration of Schottky diodes directly on top of the collector to provide the output isolation and to clamp the output to a low voltage. The common emitter design makes use of the naturally formed N$^+$ interconnect obtained with the emitter-down structure. This approach not only eliminates the need for routing of a power supply line, it also eliminates the need of providing isolation between the N+ emitter region of the devices. This structure greatly enhances device packing density -- circuits with more than 10,000 gates have been demonstrated.

System Applications

Due to the ultra-high speed performance advantage of the HBT's, the potential applications of the technology are seen mostly in systems with operating frequency exceeding 1 GHz and extending beyond 10 GHz. Major applications of the GaAs HBT's have been found in the following areas.

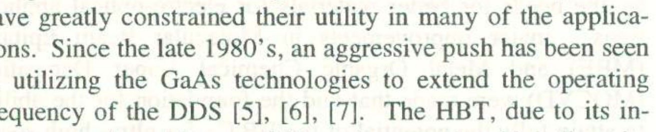
A. *Communication Systems*

Direct Digital Synthesizer

Direct Digital Synthesizer's (DDS's) offer a unique approach for frequency synthesis versus conventional techniques. These devices directly construct the desired waveform rather than obtaining it from manipulating the output of oscillators by dividing, multiplying, or shifting the frequencies while comparing them with a reference. Since a DDS is not subject to the electrical inertia of oscillators and complex filters, it can switch between frequencies very rapidly. Waveforms are generated digitally and their manipulation can be both precise and inexpensive. It provides very fine frequency steps that would not be practical using competing techniques (Phase Lock Loop or direct analog). The DDS offers very wide bandwidth, low phase noise, very fast switching of frequency and a very fine frequency resolution. It is found in many military communication systems, synthetic aperture radars, frequency hoppers, and EW systems. It is used extensively in test instrumentation for generating arbitrary waveforms.

Fig. 3 shows an architecture of a typical DDS which employs an accumulator, a sinewave generator, and a digital-to-analog converter (DAC). The input bit to the accumulator determines the output frequency of the DDS system. A sinewave generator, either implemented as a read-only-memory (ROM) sinewave look-up table or as a combinatorial logic circuit, maps the accumulator output into a digital representation of the sinewave. The DAC converts the digital amplitude information into the desired analog waveform. Clock alias signals are generated in this process, which are removed from the output by a conventional low pass filter.

Today the DDS market is dominated by the Si BJT and Complementary Metal-Oxide-Semiconductor (CMOS) technologies. However, the speed limitation of these products have greatly constrained their utility in many of the applications. Since the late 1980's, an aggressive push has been seen in utilizing the GaAs technologies to extend the operating frequency of the DDS [5], [6], [7]. The HBT, due to its intrinsic speed and its capability of supporting high linearity circuitry, is ideally suited for the DDS applications. Test results of the DDS based on the HBT will be described in the



$$f_{out} = f_{in} \times (A_{N-1} \times 2^{N-1} + A_{N-2} \times 2^{N-2} + \ldots\ldots + A_0) / 2^N$$

Fig. 3. Typical Architecture of DDS.

next sections.

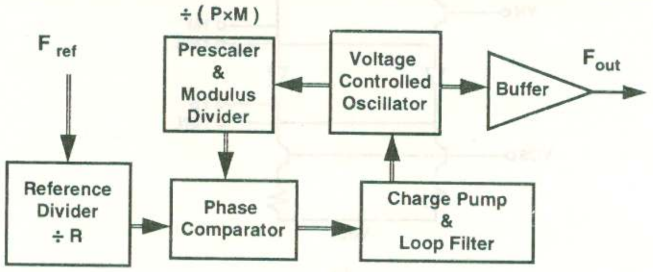
Phase Lock Loop

While the DDS offers numerous advantages in frequency synthesis with fine frequency resolution and fast switching, it is relatively expensive as a general frequency synthesis building block. Moreover, the operating frequency is typically limited to less than 1-2 GHz. Today, the Phase Lock Loop (PLL) is the cardinal signal generation technology in use with 250 million integrated circuits (IC's) built worldwide annually. The majority of the applications are served by Si IC's. As new communications, telecommunications, and navigation markets steadily saturate available frequency bands and channels and push operational frequencies upward, GaAs products which can access these higher bands are growing rapidly. Personal Communication System (PCS) operation is now possible at ~ 6 GHz, satellite communications are typically at 5 to 12 GHz and wireless LAN's operate up to 18 GHz. High bandwidth video is now being considered at Ku-band and above. Microwave radio links now operate near millimeter wave.

A block diagram of a typical PLL system is shown in Fig. 4. The Voltage Controlled Oscillator (VCO), uses the capacitance versus voltage characteristic of a pn diode, which is supported by the HBT process technology. It is driven by an analog input obtained by feedback from the phase detector to determine the desired PLL output frequency. Many VCO's developed with HBT technology have been reported, [8], [9], [10], with output frequencies up into the 20 GHz range. The other key component of the PLL system is the prescaler which divides the high frequency signal at the output of the VCO, with a fixed ratio, to generate a lower frequency signal for further functions of the loop. Prescalers built with HBT's have shown capability of operating into the 20 GHz range, also.

Lightwave Communication System

Since the establishment of synchronous digital hierarchy (SDH) / synchronous optical networks (SONET), the GaAs technologies have played a prominent role in implementing circuits which must operate in excess of one gigabit per second. GaAs FET devices are being used in many of these systems where the line rates are 622 Mb/s and 2.488 Gb/s (STS-48). More recent studies indicate that even higher data rates (>2.488 Gb/s), are required to meet the demands of the new computer-age "information super-highway". To achieve the next anticipated SONET rate of 10Gb/s, advanced IC's and IC technology are needed.



$$F_{out} = F_{ref} \times (P \times M) / R$$

Fig. 4. Block diagram of a typical Phase Lock Loop System.

Fig. 5 shows a generic block diagram of a transmitter and receiver for a lightwave communication system. Many of the components of the transmitter and receiver have been demonstrated, [11],[12],[13], based on the HBT technology. Examples of results obtained from the design and fabrication of the basic building blocks including Multiplexer, De-Multiplexer, Decision and Driver circuits will be discussed in a following section. In the upcoming 2-3 years, wide applications of the HBT technology can be expected in the 10 Gb/s lightwave communication systems.

B. Instrumentation and Data Conversion Products

As the performance associated with Si and GaAs device technologies advance rapidly, there is a corresponding need for faster test instruments to test the resulting devices and circuits. The HBT technology, in addition to its inherent speed advantage, offers tight control of the "turn-on" voltage which leads to well matched transistors. It also features devices which can have high breakdown voltage and devices free of low frequency substrate effects often seen in GaAs FET technology. These attributes make it a strong candidate for key high speed tester pin-electronics including comparators, formatters, pin drivers and pattern generators.

The aforementioned advantages of HBT technologies also make it an ideal choice for high speed and high accuracy Analog/Digital (A/D) conversion. Many ADCs fabricated with HBT have been reported with bit resolution from 4 to 8 bits and sampling rates up to 3Gb/s [14],[15],[16]. As the HBT technology matures and the integration level increases, more activity will be seen using it to develop high performance data conversion products.

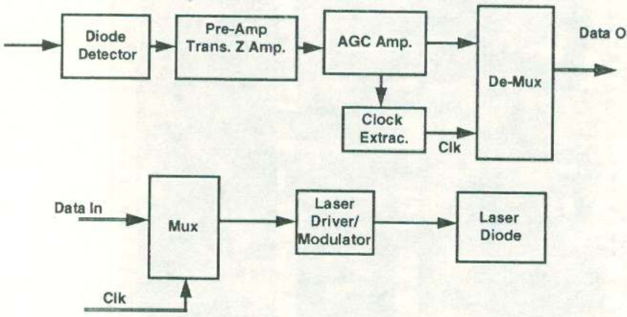


Fig. 5. Generic block diagram for Lightwave Communications System.

C. Computers and Related Applications

The achievement of high performance, low cost microprocessor chips has ignited the growth of personal computer and work station markets at the expense of main frame computers. The performance of these processor chips have roughly doubled every two years, yet the cost has remained relatively constant. There are needs, however, where very high speed computation units are required. For these applications, while the emitter-up HBT offers the ultimate high speed potential, it is limited in circuit integration capability with relatively high power dissipation. Most of the work on computer chips with HBT technologies, therefore, is based on the emitter-down approach. A Central Processor Unit (CPU) design containing 12000 HI^2L gates has been reported. A photo micrograph of a 32 bit CPU is shown in Fig. 6.

As the operating frequency of the microprocessor reaches hundreds of megahertzs, it is more and more important to generate precise timing for interfacing the CPU with its peripheral devices. An HBT based clock generator chip with the capability of phase locking to a lower frequency reference, and the ability of generating a precisely placed clock edge at different time delays, will greatly improve the over all system performance of the computer system. A delay generator based on HBT HI^2L with 15 programmable time steps has been reported. [17]

D. HBT Gate Array Products

In contrast to the customized design of circuits for a specific systems application, gate arrays are often being used by system designers because of its flexibility and fast turn around time. Although the gate array design approach typically cannot utilize the full performance advantage achievable with a given device technology, HBT is probably the best technology for high speed gate array implementation because of its excellent driving capability and high transconductance. An HBT gate array was first successfully demonstrated with a Common Mode Logic (CML) design of 1000 gate complexity. Prescalers personalized onto the array have shown operation up to 15 Ghz [18]. More recently, another HBT array has been developed utilizing a diode shifter as part of the emitter follower circuit. This makes it possible to operate the gate array at the standard power supply voltage of -5.2V while achieving CML with 3 levels of series gating.

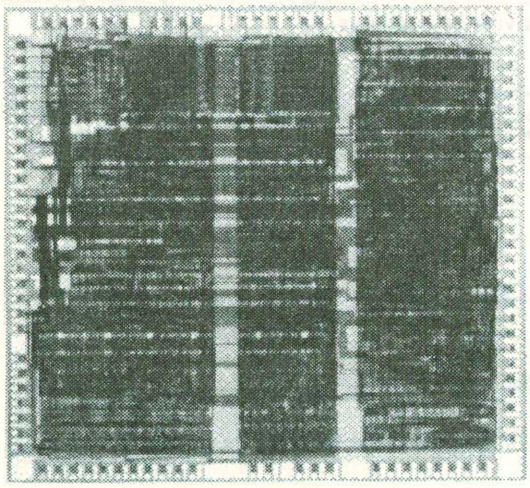
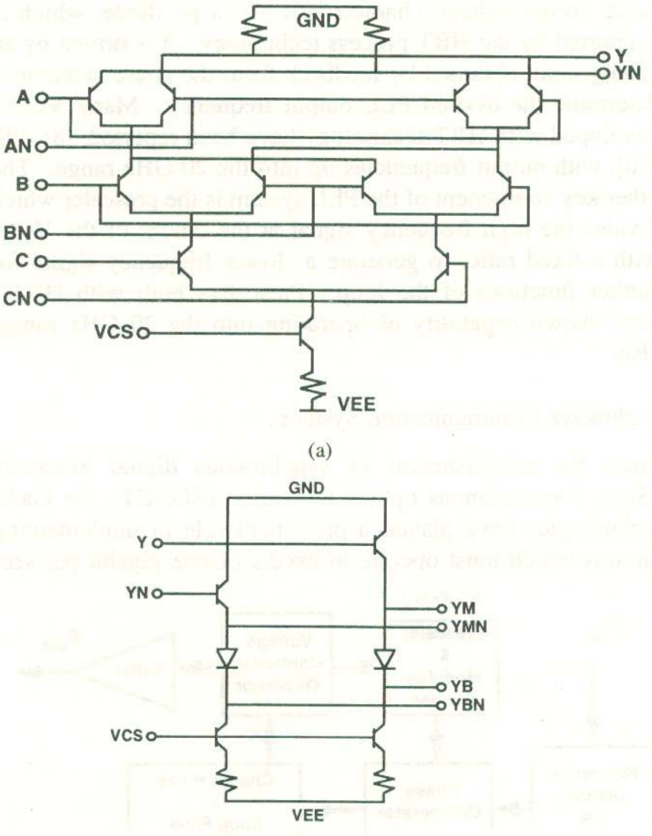


Fig. 6. 32-bit HI^2L Microprocessor.

Circuit Design and Performance of HBT ICs

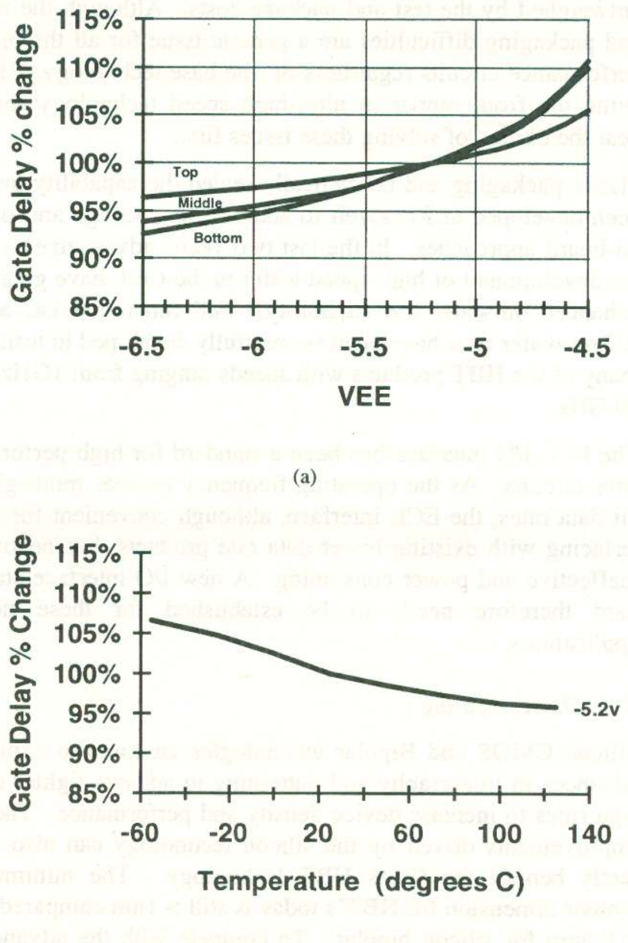
Silicon bipolar technology with non-saturating (CML) and Emitter Coupled Logic (ECL) designs has dominated high speed digital applications for decades. It is no accident then that the most commonly used logic implementation approaches for GaAs HBT's are similar to the Si bipolar, i.e. CML/ECL. Fig. 7 shows a circuit diagram of the basic CML gate and its associated emitter follower. The typical voltage swing of the CML/ECL circuit is around 200mV to 500mV. Due to its larger V_{be} compared to Si BJT's, it is difficult to achieve 3 levels of series gating with HBT's using the standard Si ECL power supplies. Recently, Yinger et al proposed using a diode shifter in place of a HBT transistor in conjunction with the emitter follower circuit. Excellent operating



(a)

(b)

Fig. 7. Basic logic gate schematic (a) Three input exclusive OR, (b) Level shifter.



(a)

(b)

Fig. 8. Operating margin of 3 level HBT logic gate (a) Percentage change in gate delay vs. V_{EE}, (b) Percentage change in gate delay vs. temperature.

margin over power supply and temperature variations has been demonstrated with this 3 level logic gate circuit technique as shown in Fig. 8.

Numerous circuits have been successfully demonstrated utilizing a HBT ECL design approach. Prescalers, multiplexers, demultiplexers, decision circuits operating in excess of 20 GHz have been reported. Table 1 shows representative results from a few of these circuits.

Table 1. High Performance HBT Circuits

Freq. Divider (÷4)	39.5 GHz	Hughes AlInAs/GaInAs [19]
Freq. Divider (÷4)	34.8 GHz	NTT [20]
MUX 2:1 & 4:1	30/27 Gb/s	Rockwell [11]
Selector	28 Gb/s	NTT [21]
DEMUX 1:2	27 Gb/s	Rockwell [11]
Decision Circuit	20 Gb/s	Rockwell [11]
Limiting Amplifier	15 GHz	NTT [12]

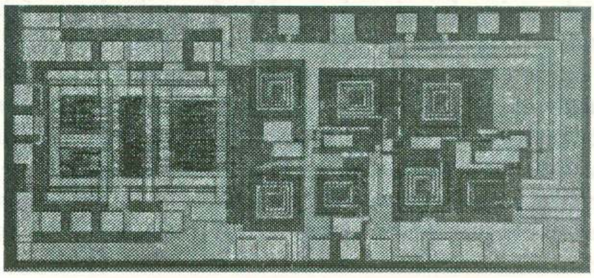


Fig. 9. Photo micrograph of HBT VCO and Prescaler.

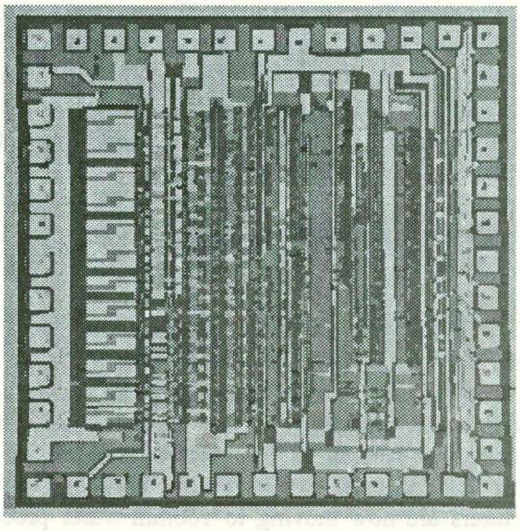


Fig. 10. Photo micrograph of 12-bit DAC.

Due to the semi-insulating property of the underlying GaAs substrate, inductors can be readily incorporated in the fabrication of HBT circuits. The availability of inductors and varactors in addition to high precision NiCr thin film resistors, makes the HBT technology very attractive for the design of VCO's, ADC's, PLL's, and DAC's. Fig. 9 shows a photo micrograph of a VCO which operates in the frequency range of 11-18 GHz with an on chip prescaler. Fig. 10 shows a photo micrograph of a 12 bit DAC .The 11 plus bits of linearity is achieved without laser trimming. This result indicates the outstanding device matching achievable with HBT as well as the excellent control in the deposition of the thin film resistors.

Another design approach based on the GaAs HBT is HI^2L developed by Texas Instruments. In this approach depicted in Fig. 11, the switching transistors are driven into saturation. Schottky diode clamps are integrated directly on top of the collector. The logic swing is determined by the turn on volt-

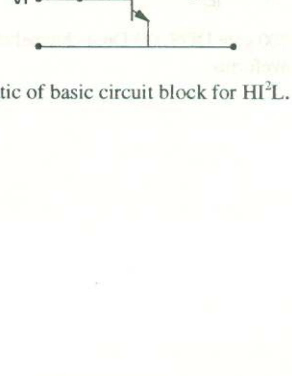


Fig.11. Schematic of basic circuit block for HI^2L.

age of the emitter base junction and the forward voltage of the integrated Schottky diode plus the saturation voltage, V_{ce} *(sat)*, of the HBT. The logic swing is typically 0.4V. The HI^2l approach requires only the common emitter transistors and the integrated diode to implement all logic functions. The absence of complicated and power consuming emitter follower stages makes it possible to achieve lower power and higher integration levels compared to the CML/ECL approach.

Fig. 12 shows two monolithic integrated DDS HI^2L circuits. The first shown in Fig. 12(a) uses 3700 gates and includes an additional phase shift adjustment function implemented with a 12-bit adder. The second circuit shown in Fig. 12(b) provides a dual channel chirp synthesis function. Two cascaded accumulators are used to generate a linear frequency modulation. The chirped output waveform is shown in Fig. 12(c).

Future Developments

A. *Manufacturing*

Although, the GaAs HBT features superior intrinsic speed performance, high precision and ease of mixed signal function integration, some challenges need to be overcome before it can be fully deployed in all its potential applications. The cost of the HBT circuit, once very high, is being reduced as manufacturers are now moving to 100mm wafer processing with submicron stepper technologies to reduce fabrication cost and to increase circuit yield. Achieving cost effective die, however, is not sufficient since the die cost soon becomes outweighed by the test and package costs. Although the test and packaging difficulties are a generic issue for all the high performance circuits regardless of the base technology, HBT being the front runner in ultra-high speed technology must bear the burden of solving these issues first.

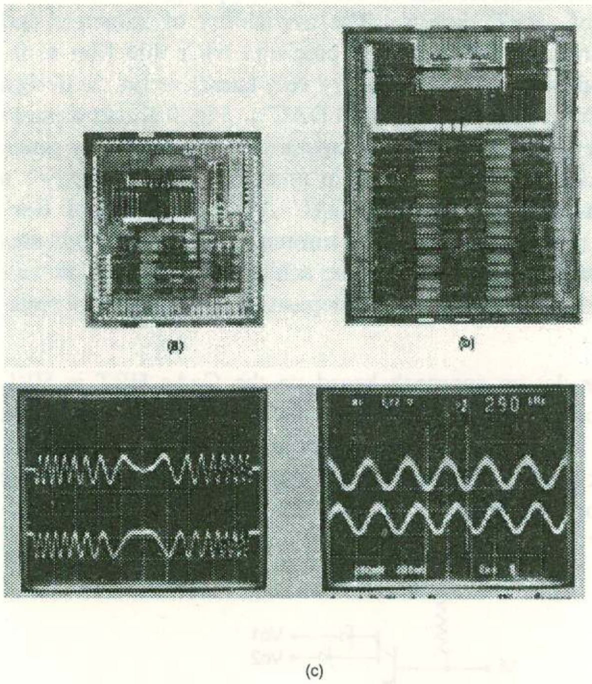


Fig. 12. HI^2L Circuits (a) 3700 gate DDS, (b) Dual channel chirp synthesizer, (c)Chirp output waveforms.

Plastic packaging and hermetically sealed die capability have been developed at Rockwell to address the package and die-on-board approaches. In the last two years, advancements in the development of high speed wafer probe card have greatly enhanced on-wafer test capability. Full functional DC and AC on-wafer tests have been successfully developed in testing many of the HBT products with speeds ranging from 1GHz to 20 GHz.

The ECL I/O interface has been a standard for high performance circuits. As the operating frequency reaches multi-giga bit data rates, the ECL interface, although convenient for interfacing with existing lower data rate products, has become ineffective and power consuming. A new I/O interface standard therefore needs to be established for these new applications.

B. *Device Scaling*

Silicon CMOS and Bipolar technologies continue to exploit advances in lithography and patterning to achieve tighter design rules to increase device density and performance. These improvements driven by the silicon technology can also directly benefit the GaAs HBT technology. The minimum emitter dimension for HBT's today is still > 1um compared to < 0.5um for silicon bipolar. To compete with the advancements in Si technology, it is important for HBT to incorporate many of the applicable device scaling techniques.

C. *Material Development*

While the GaAs based HBT's have been exploited for high speed applications, the development of other III-V materials are also being actively pursued. This includes development of GaInAs/AlInAs HBT's on an InP based material. The InP based HBT offers the advantages of high electron mobility, low base emitter voltage, V_{be}, and direct compatibility with optical devices operating at wavelengths of 1.3um to 1.5um. Excellent device performance has been reported including f_t and f_{max} reaching values of 165 GHz and 100 GHz, respectively. Frequency dividers operating at 39.5 GHz [19] have also been achieved with the InP based HBT. There are, however, some remaining issues to overcome for further application of this technology. These include increasing breakdown voltage, integration of Schottky diodes, and routinely achieving very precise control of the material composition for lattice matching in a manufacturing environment.

HBTs fabricated on SiGe material have shown rapid advancements in recent years. Optimization of the SiGe HBT's with respect to the f_t and breakdown voltage was utilized in developing a 1 GHz, 12 bit Digital to Analog Converter [22]. Device performance was benchmarked by measured ring oscillator delay of 17.2ps, f_{max} of 46 GHz and a breakdown voltage, BV_{ceo} of 3.5V. The SiGe HBT's share many of the same characteristics of the GaAs HBT's. However, due to the lower electron mobility and the lack of a semi-insulating substrate, the SiGe HBT's do not achieve the performance level of GaAs based HBT's.

Summary

The HBT technology has advanced rapidly over the last decade having been transferred from a research environment into commercial manufacturing. Products operating in excess of 10 GHz have been demonstrated. HBT products will find applications in lightwave systems, communication systems and mixed analog-digital systems. Further improvements in materials and device structures will be used for even higher performance systems.

Acknowledgment

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