Status and Application of Advanced Semiconductor Technologies

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ABSTRACT

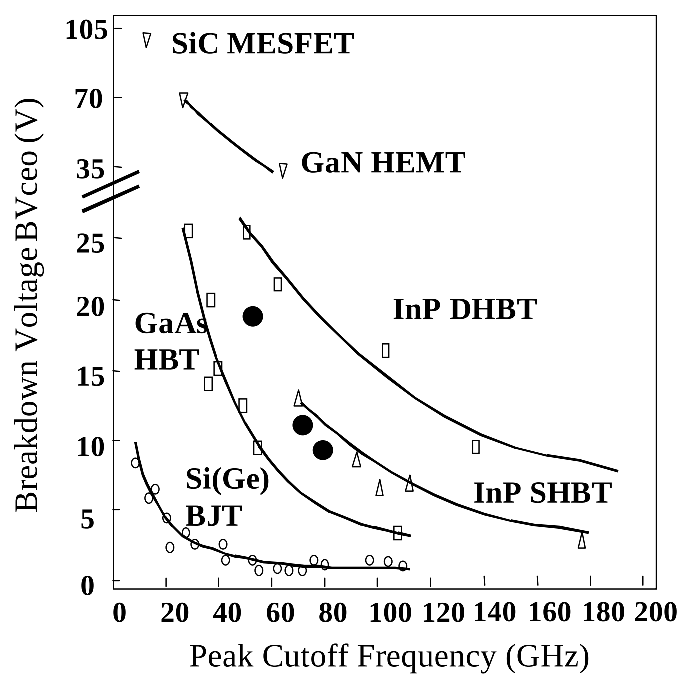
GaAs HBT technology is being challenged for existing and new product applications. SiC FETs and GaN HEMTs have been shown to have significant power delivery advantage when large supply voltages are required. InP HBTs are emerging as the next technology for very high-speed applications. After years of promise and controversy, the SiGe HBT is beginning to be applied in high-performance systems. Part of this success is due to an improved understanding of on-chip silicon-based passive components and isolation capability. As an example, a 10GB/s limiting amplifier is described. Although one is forced to acknowledge that silicon-based design is now capable of very high-speed performance, it is important to recognize GaAs HBTs continue to dominate extended-voltage / power applications. There are many examples of this in the wireless area. A 5V GaAs modulator driver chip is provided as an example in this paper. At this time there are numerous potential GaAs HBT challengers, however, only SiGe HBT's appear ready for large volume, cost competitive deployment in both bipolar and BiCMOS variants.

INTRODUCTION

The selection of high-performance, compound semiconductor technology is increasingly diverse. The historical mainstay of the industry, GaAs, is continually being challenged for existing and new product applications. A partial list of challengers includes SiC FETs and GaN HEMTs for power delivery, InP HBTs for very high-speed and low-power analog-digital applications, and SiGe HBTs where high levels of integration and low-power are requirements. The later can also be combined with CMOS providing the potential for system-on-a-chip solutions. Although not compound semiconductors, there have been significant strides in silicon LDMOS and homojunction bipolar transistors recently. It is also notable that deep sub-micron CMOS has Ft, Fmax and noise performance to rival some currently available compound semiconductor technology. All this in the context of GaAs technology continuing to improve in performance, cost and manufacturability.

In addition, the availability of high-performance semiconductor technology has improved considerably in recent years as the thirst for commercial bandwidth increases. Once the exclusive domain of the military, new commercial data centric applications in both wireless and fiber-based product now require the high levels of performance offered by these technologies. These conditions have made the task of choosing the most appropriate technology for product applications more difficult.

This paper will focus primarily on the challenges to GaAs HBT technology, and will begin with a review of selected performance characteristics of available active components. An additional requirement for good high-performance design is the correct use of passive components and on-chip isolation techniques. These have long been the exclusive territory of III-V technology. However, silicon-based passives and isolation have improved recently, and as such, will be discussed. Both contribute to the ability to integrate analog-digital functions on a single chip in order to reduce high-performance packaging complexity, and therefore cost. Two 10GB/s datacom circuit blocks will be described in order to place performance capabilities in context. Finally, an attempt will be made to estimate the time when manufacturable versions of these technologies will be available.



DEVICE PERFORMANCE

Transistors

Semiconductor electronic devices can be divided into roughly two categories; power and speed. There are numerous variations on these themes, including low-noise, as well as integration of additional functionality. One view of how each of the device technologies fit into this categorization is to plot peak cutoff frequency (Ft) vs. breakdown voltage (BV), Figure 1.

Figure 1: Breakdown Voltage versus Peak Cutoff Frequency for a selection of technologies

Each of these devices is capable of delivering reasonably efficient power into an antenna, particularly in the 2GHz band. Table 1 summarizes representative power density results at 2GHz. Current cellular phones are dependent on GaAs (HBT) technology for power amplification, as they are capable withstanding supply voltages of ≥5Volts, while tolerating large VSWR mismatch. The primary difference between these technologies is stand-off voltage capability, production maturity notwithstanding. The 0.8 um SiC MESFET demonstrates the largest breakdown voltage at 105V. This device yielded 2.8W/mm, class A using a supply voltage of 40V. The 0.3um GaN HEMT demonstrated a breakdown voltage of 35 volts [1]. 4.2 W/mm was achieved using a supply voltage of 10V at a channel temperature approaching 125C. This result is all the more impressive as it was achieved using sapphire substrates. SiC substrates, with their superior thermal performance should serve to improve power densities considerably.

Technology	**Power Density** (W/mm @ 2GHz)	**Comments**
GaAs HBT	4.0	2um emitter stripe
SiC	2.8	0.8 um gate
GaN	4.2	0.3 um gate on Sapphire substrate

Table 1: Power density for a range of technologies

Another method of comparing the various technologies is to consider Ft and Fmax performance. As shown in Figure 2, there is a wide range of Ft performance available from the bipolar technologies under consideration. Figure 2

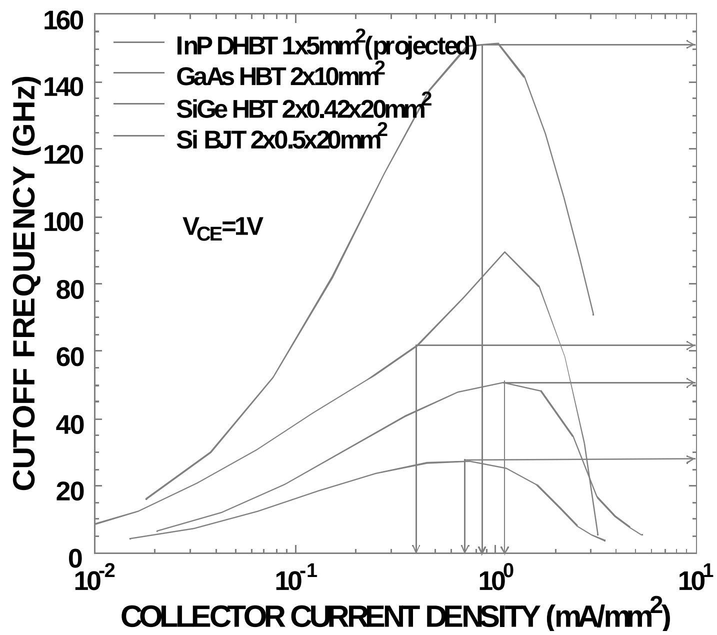


Figure 2: Cutoff Frequency (Ft) for a selection of bipolar technologies

shows measured results of state-of-the art silicon and GaAs devices (Nortel Networks) and SiGe (IBM) devices. The results are normalized to device size and displayed against current density. In addition, the projected performance of an InP DHBT is included. The peak Ft is consistent with the curves captured in Figure 1. However, the operating current limit, as denoted by grid entries, limits the GaAs HBT Ft to 65GHz, only somewhat better than the SiGe HBT. This method of de-rating III-V devices is common and is often driven by thermal and reliability considerations. At this operating current density our circuits achieve 10FIT performance. It is interesting to note that silicon suppliers specify their maximum operating current density to coincide with peak Ft. Also note that this condition is projected for InP DHBT devices based on the improved thermal performance of InP substrates. Fmax is shown in Figure 3 for the

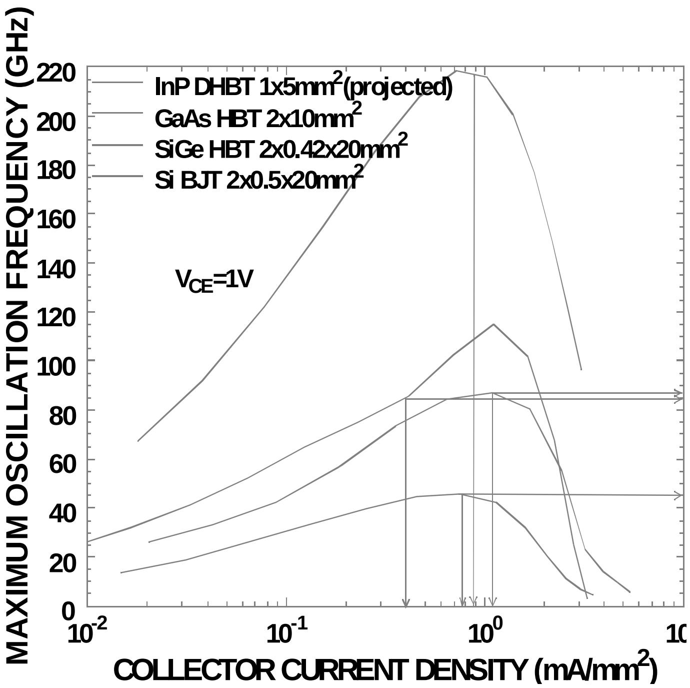


Figure 3: Maximum Oscillation Frequency (Fmax) for a selection of bipolar technologies

same suite of devices. The most noteworthy observation to be derived from this figure is that the maximum usable frequency of oscillation is the same for GaAs and SiGe devices. Combined with narrower emitters and intrinsically better thermal dissipation afforded by silicon substrates, SiGe devices should exhibit superior power characteristics, particularly in single battery regimes. This will also be the case for narrow emitter stripe InP DHBTs.

Passives and isolation

A great deal of time has been spent modeling active devices, particularly transistors. As important as this activity may be, the passives quite often make the crucial difference when designing both wireless and datacom circuits. The III-V technologies have an intrinsic advantage in this area as they have semi-insulating substrates. In addition, the semi-insulting substrate results in high levels of isolation between devices, and therefore circuits integrated together on a single die. However, significant advances have been made recently in the area of silicon microwave integrated circuit design.

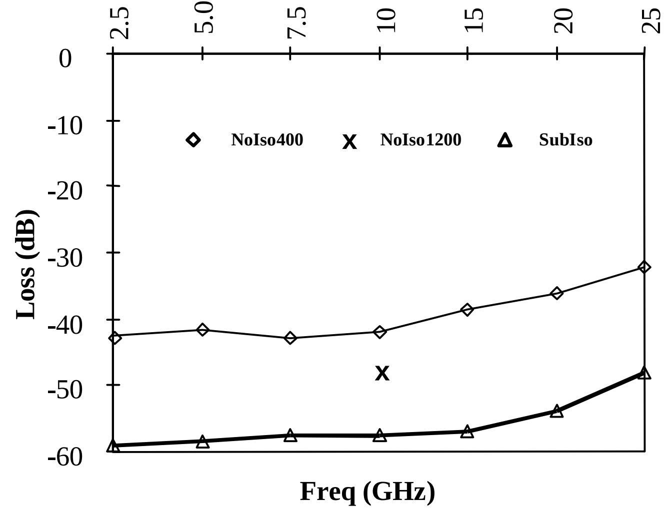


Figure 4 shows measured results of an integrated inductor on a silicon substrate. A 2.25 turn spiral inductor, constructed in metal3, is 175 X175 um^2 and yields an inductance of 0.45nH and quality factor of 7 at 10GHz. In addition, there is usable inductance and Q upwards to 20GHz. As a demonstration of the utility of these components, several (>30) inductors, constructed in a similar fashion, have been used to implement a 5.2GHz wireless IP / ATM transceiver with on-chip image reject filtering of greater than 40dB over a 20MHz bandwidth [2]. The transceiver was implemented as a balanced differential design where the inductors are used for filtering and matching. Also notable is the 80dB of input-to-output isolation achieved with this silicon design.

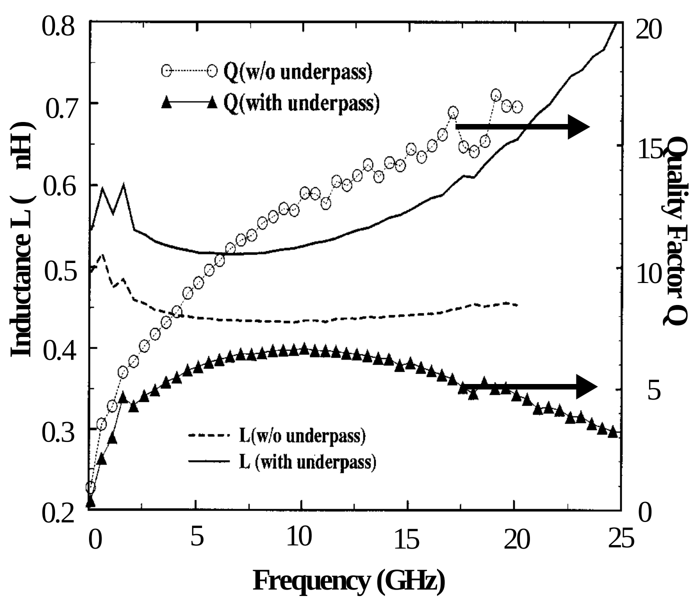


Figure 4: Inductance and Q factor for an example silicon-based spiral inductor

Figure 5 shows measured results of on-chip isolation for a SiGe trench isolated technology. 40dB of isolation is available with 400 um of structure spacing. Increasing the spacing to 1200um increases the isolation to 47dB. Design of specialized isolation barriers yields 57dB isolation at 10GHz with better than 50db at 25GHz. This result holds real promise for integrating multiple bipolar circuits on one die and further adding CMOS digital signal processing capability. This combination will provide an avenue for future high-performance systems-on-a-chip.

It is also possible to construct transmission lines on silicon. Non-dispersive, constant 100ohm Zc has been achieved up to 26GHz. Loss rises from 0.3 to 0.6 dB/mm over a 5 –to- 25GHz frequency range.

Figure 5: Isolation afforded by silicon-based structures versus frequency

CIRCUITS

Combining these silicon passive and isolation results with the transistor performance described earlier creates a powerful toolbox for use in high-performance datacom circuit design. One such circuit is a limiting amplifier designed for 10GB/s fiber optic transmission products [3].

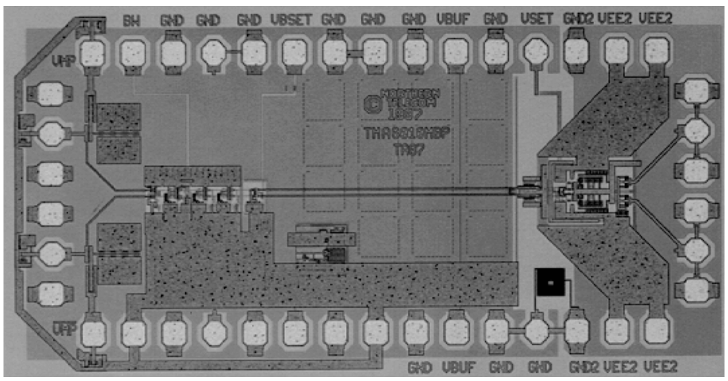


Figure 6: Microphotograph of SiGe 10GB/s limiting amplifier chip

Figure 6 shows a die microphotograph of a SiGe limiting amplifier. The die is 1.2 X 2.6 mm^2 and incorporates all the passive components and isolation thus far described. The three gain stages of the limiting amplifier core are visible on the left side of the microphotograph. These are connected to the receiver / output buffer by transmission lines. Used in combination with the (square shaped) isolation structures creates a truly high-performance circuit with input sensitivity of 3.5mV @BER 10E-9 in spite of the very high 60dB of gain. Digital and analog sections of the device are further isolated through the use of separate supply rails, which are coupled by virtue of on-chip inductor filtering. The performance is summarized in table 2.

AC differential gain	> 60dB
Sensitivity	< 3.5mV_{p-p} @10E-9 BER
Input Dynamic Range	55dB (3.5mV_{p-p} –to– 2V_{p-p})
AM – to – PM Conversion	< 5ps @ 2mV_{p-p} –to– 2V_{p-p}
S_{21} Bandwidth	15GHz @ 10mV_{p-p}
S_{11}, S_{22}	< -10dB @ F < 10GHz
Differential Output Voltage	2V_{p-p} @ 50 ohm load
Power (1V_{p-p} Output)	600mW (100mW core)
Power Supply Range	-3.5 … -5V

Table 2: Performance summary for SiGe HBT Limiting Amplifier Chip

Silicon supporters have begun to forcast the demise of GaAs technology. Although one is forced to acknowledge that silicon-based design is now capable of very high-speed performance, it is important to recognize GaAs continues to dominate the extended-voltage / power applications. There are many examples of this in the wireless area. One datacom example is the 5V GaAs Modulator Driver [4], shown in Figure 7.

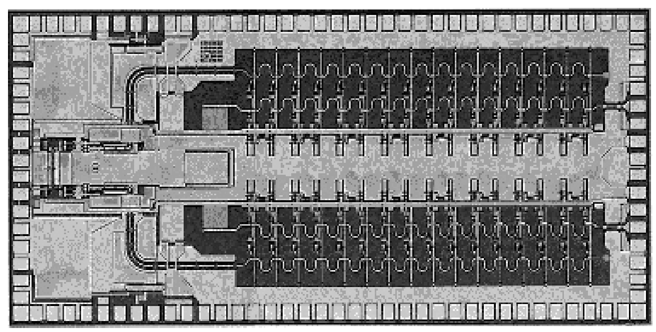


Figure 7: Microphotograph of GaAs 10GB/s modulator driver chip

The modulator driver ASIC is a limiting amplifier which provides a 5V, high power output drive sufficient to modulate an optical modulator at 9.952Gb/s data rate. Variations on this basic design will permit operation at higher voltages. The data format is NRZ (non-return to zero). It performs the functions of providing on chip termination (50 ohms to ground) on the differential inputs, single-ended or differential output drive to an external modulator, and a means to adjust the output amplitude between max and min values over all temperature and process conditions. The combination of transistor speed and superior passive components helps to create performance beyond the reach of similar silicon-based circuits. The performance is summarized in Table 3.

Differential Drive Capability	10V_{p-p}
Limiting Input Signal Amplitude	350mV_{p-p}
Output rise/fall time 10-90%	60ps
Input return loss DC-10GHz	15dB

Output return loss DC-10GHz	10dB
Positive Supply (Vcc /Icc)	5V / 240mA
Negative Supply (Vee / Iee)	-8.4V / 1020
Max power dissipation	8W

Table 3: Performance summary for GaAs HBT Modulator Driver Chip

SUMMARY

Several alternative technologies are challenging GaAs HBT technology for prominence in both power and high-speed applications. SiC FET and GaN HEMT technology will find application in power applications where large supply voltages are necessary. InP HBT technology is beginning to be applied to very high-frequency applications. SiGe technology will make inroads, particularly with the improved understanding of silicon passives and isolation techniques at microwave frequencies. SiGe BiCMOS will provide an avenue for highly integrated systems-on-a-chip, again at frequencies up to, and exceeding, 10GHz. At this time, SiGe technology appears to be the only challenger ready for large volume, cost effective deployment. However, the other technologies discussed in this paper will be available for product sales in the 1 –to– 3 year timeframe.

ACKNOWLEDGEMENT

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