Implanted MESFETs - Still Going Strong

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Abstract

GaAs MESFETs have traditionally been the preferred technology for most RFIC applications. The past few years have seen a change, as other GaAs and Si technologies have competed for market share in various areas. This paper reviews that phenomenon and shows that while there are some RF and telecommunication circuits better done in other technologies, MESFETs still have significant advantages in a number of important market segments.

1. Introduction

There is a tide in the affairs of men
Which taken at the flood, leads on to fortune;
Shakespeare, Julius Cæsar. Act iv. Sc. 3.

There are "tides" in the affairs of technology as well. This paper examines GaAs MESFETs in the current sea of high frequency microelectronics.

The worldwide GaAs IC industry was largely built on simple implanted MESFET technology in the 1980's and 1990's. The end of that period and more recent times have seen an increased presence of epitaxial GaAs-based HBT and PHEMT technologies and the advent of high frequency Si CMOS, SiGe Bipolar, and SiGe BiCMOS processes for many traditional MESFET niches. At the same time, broadband and other markets for GaAs have pushed to ever-higher frequencies, sometimes beyond the real or perceived limits of implanted MESFETs. However, those simple devices still produce a significant share of current revenue for many GaAs houses. Moreover, some new applications are very well met with that traditional implanted MESFET technology. Overall, demand for IC's based on the once ubiquitous implanted MESFET is down from its peak, but to paraphrase Mark Twain, "the news of its death has been greatly exaggerated."

Device comparisons between the various GaAs candidates have been presented in previous MANTECH conferences [1] and elsewhere, so that will not be our focus. We are rather concerned with GaAs vs non-GaAs questions, with integrated circuit rather than device properties and with practical, market-driven choices now being made that affect us all. That this departure from a pure GaAs picture is appropriate is immediately clear from a perusal of recent proceedings of our sister conference, the GaAs IC Symposium, which in recent years has more and more SiGe and Si CMOS content, and in examination of the IEEE RFIC Symposium and others like it, which have less compound semiconductor content. Of course, paper counts are not necessarily reflective of manufacturing volume, but these results are suggestive.

There have been many related studies. A comparison of GaAs technologies for X-band Power Amplifiers for military applications was given by Murgadella et al [2] and curiously found that PA's built with MESFETs, PHEMTs and HBTs all showed similar behavior. Their ICs, strongly affected by design options, passive elements and thermal management, were also all about the same size. This is very different from the handset power amplifiers we will discuss below, where GaAs HBTs are clear winners. Nakagawa et al from NTT [3] used a mix of GaAs MESFET, GaAs PHEMT and Si bipolar components to make a 0.9 – 2.5 GHz direct conversion receiver, exploiting the advantages of each technology. Yoon [4] reported as good or better results for a GaAs MESFET-based 6.7 GHz oscillator than seen with CMOS or SiGe. In making a "highly integrated commercial GPS receiver", Young [5] used 0.9 um GaAs MESFETs for most of the product to achieve the lowest noise figure and best system performance. For a wireless LAN transmitter at 5.8 GHz, Raghavan et al [6] found that a GaAs/AlGaAs HBT implementation offered significant improvement and lower die size than a previous GaAs MESFET version.

The overall impression from the literature is that one can usually do any given IC in several different ways with clever design. If one of those is Si-based, the traditional bias is to favor it automatically unless there are significant advantages to any GaAs approach. What we need to do as a community is to find and celebrate the advantages of all GaAs approaches, and particularly those of low-cost and simple-to-fab MESFETs. We will see in the rest of this work that there are several such advantages. At the same time, there are applications that are not best done in MESFETs, and we need to let those go.

2. The Competition

An old joke asks, "Where does a 900 pound gorilla sleep?" with the predictable answer "Anywhere he wants to." In the IC world, the "900 pound gorilla" is Si CMOS, which has not stood still these last few years. Fig. 1 shows unity current gain frequency Ft for the NMOS part of a Si CMOS process, with data from Mitsubishi Electric [7] to which we have added year dates for the various generations of technology, met by most leading IC suppliers. Current state of the art is the 0.13 um technology node on 300 mm wafers. Physical gate length is smaller, e.g. Intel [8] reports a physical gate of 0.07 um for the 0.13 um generation.

When looking at this data, it is important to remember that the unity power gain frequency Fmax is a better figure of merit

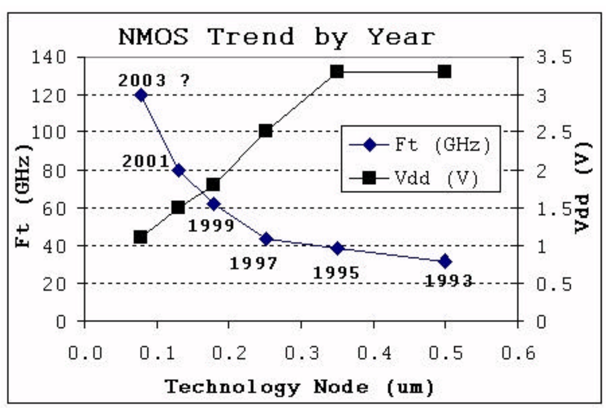

Fig. 1 Progress Continues in Si CMOS

in most cases, and Fmax is only about one half of Ft for very short gate CMOS. For example, Intel [9] reports an NMOS

(PMOS) Ft of 83 (41) GHz for 0.08 um nominal Lg in "0.13 um", in agreement with Fig. 1, but only a 39 (25) GHz Fmax for the same devices. For digital applications, this and power considerations are why a 0.13 um technology node with Ft of 80 GHz is needed for a 2.2 GHz Pentium 4, for example. Basically, the very small gate length leads to very low capacitance between the gate and channel, driving up Ft. But the same gate has a very high gate series resistance, driving down Fmax. Space does not permit further explanation here, but see Sze [10].

Figure 1 also shows the continuing lowering of the drain bias voltage Vdd as gates get shorter. 0.13 um CMOS can use Vdd from 0.7 to 1.4 V, in general. This downward trend limits the voltage swing available in CMOS amplifier applications, and can be a slight weakness that GaAs can ameliorate.

If Si CMOS is the 900-pound gorilla, SiGe bipolar or BiCMOS is perceived to be a kind of 600-pound gorilla, which can still sleep anywhere he wants to, unless the 900-pound gorilla also wants to sleep there. SiGe was the first non-GaAs approach to take market share from GaAs in the high frequency wireless area in the late 90's in high volume applications like cell phones.

Within GaAs fabs, MESFETs were also complemented in many volume applications with HBTs and PHEMTs, starting in the mid to late 90's. An overview of the situation is shown in Table 1.

3. Costs and Manufacturing

The cost of a completed integrated circuit wafer has three components, whose exact values are universally considered highly proprietary. All components are also very negotiable, but some generalities can be given.

The first component is the cost of the raw wafer, currently (in very large volumes) about \$0.20 - \$0.25 per cm^2 for 150 or 200 mm bulk Si (but \$0.60 or more for 300 mm Si) and about \$1.50 - \$2.50 per cm^2 for bulk GaAs 100 or 150 mm wafers. Epi Si is about \$0.35 per cm^2, and epi GaAs anywhere in the \$5 - \$10 per cm^2 range. Si clearly has a large advantage here.

Next is the cost of doing the fab, which depends totally on the process flow, another set of highly proprietary and closely held details. TriQuint processes MESFETs, PHEMTs and HBT IC wafers internally, so we can at least compare relative complexities among them. In the three cases, the "backend" interconnection fab details are the same and the only differences are in active device formation. MESFET processes are offered with one, two, or three different FET threshold voltages providing great design flexibility but adding fab steps. As TriQuint defines "steps", FET and HBT processes have about 60 steps for active device formation, while PHEMTs have about 45. All three then take 53 more steps to complete. So, all GaAs processes are pretty similar in fab complexity, and are, in general, simpler than Si CMOS and much simpler than SiGe Bipolar and Si or SiGe BiCMOS.

The third component in fab costs is overhead. This can be dominant in times like now when fabs are relatively empty, with fewer wafers output to cover fixed costs and depreciation. In this area, GaAs benefits from being able to use simpler fab equipment in smaller fabs. RF Si processes of all kinds need sophisticated processing toolsets, resulting in very expensive, high-overhead fabs. However, those Si fabs always produce bigger wafers than GaAs fabs can do, leading to another IC price edge to go with the cheaper wafers.

Publicly disclosed numbers are rare. One account from the Fables Semiconductor Association [11] gives volume prices (not costs!) for 0.35 um Si CMOS of \$624 for a fully fabbed and tested 150 mm wafer and \$1187 for the same in 200 mm. Obviously, GaAs cannot match prices like those, but our competition is more advanced Si CMOS and SiGe Bipolar or BiCMOS, which is much more expensive.

In the end, GaAs devices of all kinds are hard pressed to compete on fab price with Si. However, simplifications in the final product, higher RF integration, simpler assembly, smaller die and other advantages do help even things out. GaAs parts can compete successfully directly with Si, bring advantages to the application, and their costs are certainly already low enough, even for high volume consumer applications.

4. RFIC Applications

GaAs MESFETs are widely used in very high volume Radio Frequency Integrated Circuit (RFIC) applications. The benefits and liabilities of GaAs MESFET technology for Cellular Handset Power Amplifiers (PAs) have been widely discussed in the public domain for years, but considerably less has been published about RFICs for receiver and low-level microwave signal processing applications. One reason for this is that the RFICs for receiver applications have been primarily ASICs covered by non-disclosure agreements, and another is that they have been so successful that there is not a set of well-known problems to write about. Hundreds of millions of GaAs MESFET receiver RFICs have been shipped, and the technology remains competitive, with a few distinct advantages over newer processes.

Before discussing the advantages of GaAs MESFETs for receiver and low-level transmit applications, it is worthwhile to look at real and perceived disadvantages. High cost and manufacturing problems plagued GaAs MESFETs in the early days, but evolution to 150 mm wafers and the

Factors	**MESFET**	**PHEMT**	**HBT**	**SiGe**	**CMOS**
Max F_T	55GHz	90GHz	80GHz	120GHz	75GHz
Power Diss. @ 10 GHz MESFET= 1	1 +/- 40%	0.7 +/- 40%	0.7 +/- 20% Vbe=1.3V	0.5 +/- 20% Vbe=0.7V	0.4 +/- 20%
Device matching Vt, Vbe	Fair	Good	Excellent	Excellent	Very Good
Process Spec. limits Vt, Vbe	Fair	Fair	Excellent	Excellent	Good
Breakdown Voltage	6V	8V	7V Bv_{CEO}	1.8V Bv_{CEO}	1.5V
Noise Jitter pp < 0.1 Unit Interval	Low	Lowest	Very low	Moderate Meets SONET Spec.	Moderate Meets SONET Spec.
Passive Qs	20 - 50	20 - 50	20 - 50	5-12	5-12
Integration & lithography	50K devices 0.3um	5K devices 0.25u	10K devices 1.0um	> 50K devices 0.15um	> 100M devices 0.13um

Table 1. Typical <u>Production</u> Device Attribute Comparison

experience of building components for several generations of cellular handsets have relegated these concerns to ancient history. A significant fraction of the cost of RFICs is in packaging and test, and the ease and speed of testing a GaAs MESFET RFIC with 50-ohm ports may more than compensate for the slightly increased die cost over a SiGe RFIC with numerous critical off-chip matching components. Variation of threshold voltages over process and temperature require clever DC bias circuit engineering. Probably the biggest single disadvantage of GaAs MESFETs for new RFIC designs is the challenge of design. There is no classic textbook on MESFET RFIC design (like Gray and Meyer [12] for bipolar ICs), and much of the best work devoted to the development of ASICs is unpublished. GaAs MESFET RFIC designers often have to start with a clean slate and design every single circuit block, from the DC bias circuitry to the fundamental frequency conversion cells.

With experienced design talent and a good process, GaAs MESFETs have significant advantages for RFICs. They set benchmarks for noise figure in the lower microwave bands, and the insulating substrate has very low RF loss. Capacitors typically have quality factor Q > 50 and no non-linearities or substrate coupling. Inductors on GaAs are far superior, with typical Qs of 20 to 50. The best research lab inductors on silicon stretch to reach a Q of 12. With high Q inductors, it is possible to build low loss transformers, both tuned and broadband. On-chip matching to a MESFET gate using high Q narrow-band impedance transformers provides significant power saving and broadband noise suppression.

MESFETs are ideal as switches for analog signals, with a low-resistance on state and high-resistance off state controlled by a high impedance gate. Besides the obvious applications for RF switches and switched attenuators, the use of passive FETs as frequency conversion mixers sets the industry standard for intercept efficiency. With zero drain-to-source voltage, the mixer device draws no current, and the gate takes little Local Oscillator drive power in narrow-band applications that take advantage of the high Q passives for impedance matching.

GaAs MESFETs have a significant advantage for those RF subcircuits that consist of a few active devices and many passive reactive elements. These circuit blocks are common to all microwave receivers and transmitters. With GaAs MESFET technology, the critical RF passive components may be integrated on-chip, where manufacturing tolerances are tightly controlled and interconnecting line lengths are precise to within microns. Silicon bipolar or CMOS transceivers commonly have all the active devices one large IC, surrounded by 50 to 100 close-tolerance passive chip components on precisely manufactured printed circuit board. Figure 2 is a block diagram of a microwave receiver. In a GaAs MESFET implementation, each of the microwave blocks is replaced by a small IC package with a few pins and often just a single bypass capacitor off-chip.

The GaAs MESFET image reject mixer shown in Fig. 3 needs only one external resistor and one external capacitor and results in an 8 cm^2 application circuit board. The same function implemented in SiGe [13] required seven inductors, thirteen capacitors and nine resistors, all external, and gave a

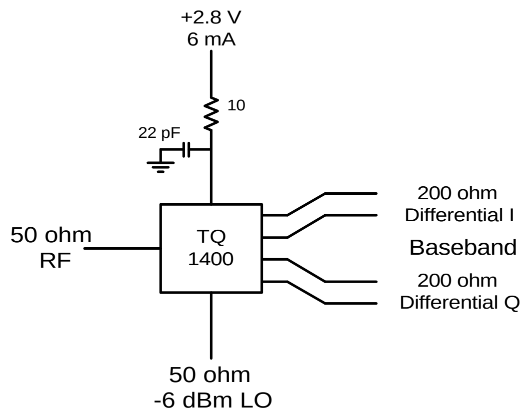

Fig. 3 TriQuint GaAs MESFET Image Reject Mixer Application Circuit

26 cm^2 application circuit board.

GaAs MESFETs for power amplifiers have a few disadvantages, mostly related to DC biasing. The inconvenience of a negative gate bias supply is significant in battery powered cell-phone handset applications, as is the difficulty in shutting off the PA during receive. These disadvantages do not apply in base station applications.

GaAs HBTs are the technology of choice for portable handset power amplifier applications. TriQuint manufactures such PA's in all technologies and has seen anywhere from a 25% to an 80% increase in die count for HBTs over MESFETs, PHEMT or SiGe implementations of similar

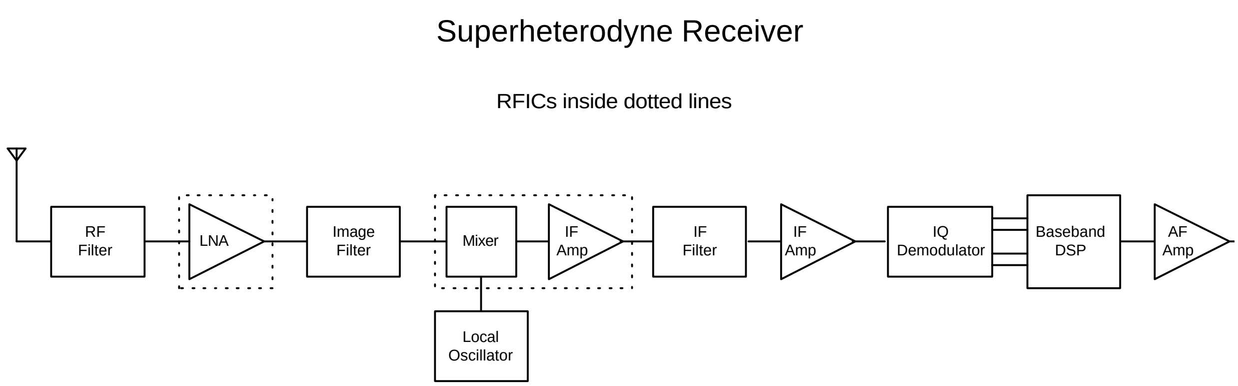

Fig. 2 Typical Receiver Schematic

circuits. SiGe, also a bipolar technology, has lower usable current density and needs bigger die than GaAs HBT designs.

In addition to the higher die count per wafer, HBTs have better device uniformity, good reliability and less gain degradation in class AB power amplifiers [14] than FET-type approaches. Moreover, they have achieved broad commercial acceptance and have demonstrated good reliability, especially for InGaP emitter HBTs. PHEMTs are more efficient, in general, and better at higher frequencies, but they either need a negative supply voltage to be shut off, or must be E-mode PHEMTs with the accompanying limitations in drive.

5. Digital Applications

Early in their evolutionary process, MESFETs were predicted to be the enabling technology for multi-GHz computers. We saw ®GigaBit Logic standard SSI parts and ®Cray attempts at GaAs-based computers. Unfortunately, these products were based on DFETs, which required multiple high value voltage supplies. That hindered efforts to minimize power dissipation and further optimize the DFET speed power product. In addition, desired integration levels were hampered by material and processing defects and did not materialize as required by market pressures in the mid to late 80s.

With the development of the EFET in the late 80's as a high yield, low speed-power product device, there was a renewed effort to go for the GaAs computer chip. Again, intrinsic limitations of the forward conducting gate and the difficulty in maintaining Vp process control prevented this vision from materializing. However, all was not lost since there were some very attractive newly emerging digital markets that could be very effectively addressed with the EFET. No computer-on-a-chip, but functions with high market value possessing fidelity and speed would be very effectively and profitably produced to address the telecommunications and semiconductor tester markets through the 90's.

The E-mode MESFET advantages began to diminish toward the end of the 90's as competing technologies began to deliver acceptable performance. The competitive pressures forced evolution of the MESFET to smaller, faster devices, but smaller and smaller device geometries resulted in lower breakdown and higher parametric variability. In addition, CMOS is setting the system level supply voltage requirement. SiGe appeared on the scene during this period and was able to deliver equivalent performance with lower power in many cases. With greater parametric variability, head to head competition from SiGe, and lowering supply voltages as mandated by CMOS, MESFETs for the digital market began to face significant competition.

In the telecommunications industry, the need for MESFETs in digital applications such as in Mux, DeMux and Clock/Data Recovery functions has been seriously eroded. However, there remains a very promising analog niche for medium rate OC48 (2.5 Gigabits per sec) and OC192 (10 Gbps) circuits. Circuits designed to address this space can be designed to exploit the low noise and high Ft*breakdown product inherent with GaAs MESFETs. These advantages can be exploited by integrating multiple functions such as a photo-diode and transimpedance amp (TIA) or a laser driver and surface emitting laser on one chip. Early results of a 12 channel integrated OC48 photodetector – TIA – limiting amp done in 0.40 um MESFETs were recently presented by Mayampurath [15].

The Ft breakdown product also offers a strong defensive edge for use in laser and modulator drivers since both CMOS and SiGe have much lower overall products for this quality factor, with breakdown much less than 4V. However, real Ft limitations of MESFETs, as shown in Fig. 4, will limit their use to 10 Gbps and below.

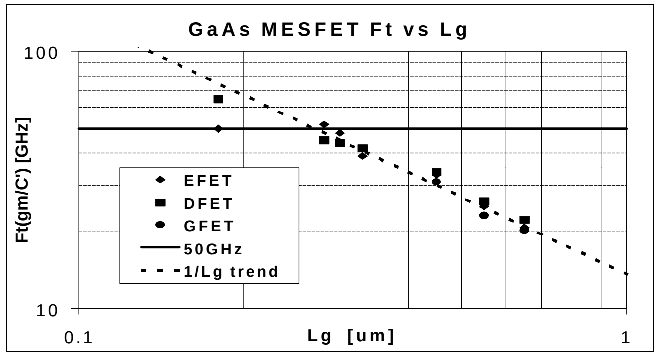

Fig. 4 GaAs MESFETs at High Frequency (G = -2.2V Vp)

6. Conclusions

We have only touched on a fraction of possible RFIC applications of GaAs MESFETs. Other possible areas abound. Large commercial applications are, for example, global positioning systems around 1.5 GHz, wireless local area networks at 2.4 and 5.4 GHz, 2.4 GHz Bluetooth personal area network chips (especially power amps), and direct broadcast satellite TV at X-band and other frequencies. Military radio and other systems are also possible uses. In applications like cable TV, at 0.4 – 0.9 GHz, GaAs MESFETs capture applications that Si can reach by virtue of better performance.

The first author's grandmother, Winifred Mulcahy, lived to the fine old age of 93, and would good-naturedly lament the consequences of advanced age by singing the old children's song "The Old Gray Mare, She Ain't What She Used to Be," while going about her business. Similarly, although the old gray GaAs MESFET has seen some slowdown from its vigorous youth, there are still many strong market applications to be pursued and good business to be done with that technology.

References

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