# Will GaAs Survive for Wireless PA's ??

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**Abstract**

**SiGe HBT's and Si CMOS continue to capture more and more of the handheld wireless communication application space. However, GaAs will continue its dominance in handset PA's because of superior performance. GaAs will also capture sockets in wireless base stations at higher frequency applications.**

INTRODUCTION

Silicon based technologies, SiGe HBT and CMOS, have captured almost all of the cellular handset application space with the exception of the RF power amplifier. In time will they also push GaAs out of these sockets? For cellular base stations Si LDMOS is the dominant technology, but as wireless applications move to higher frequencies, will GaAs displace Si LDMOS or lose out to the rapidly developing GaN technology? This paper will discuss and attempt to answer these important questions.

LOW RF POWER (< 5 W)

1) Emergence of SiGe and CMOS RF: Ever since its emergence about 30 years ago as a commercial semiconductor technology, GaAs has had the reputation as a higher performance technology than either CMOS or bipolar junction transistors. This was true for discrete transistors and was especially true for high frequency integrated circuits, called MMIC's. Silicon based technologies LDMOS and BJT's offered competition up to about 1 GHz, but GaAs had the higher frequency space to itself. However over the last several decades CMOS gate lengths have shrunk and gate oxides have become substantially thinner. Moreover the bipolar base thickness has decreased and bandgap engineering has allowed substantially lower base resistance. These advances have significantly increased the $F_T$'s and $F_{MAX}$'s of silicon based technologies to the point that their performance now rivals that of GaAs devices above 1 GHz. This first occurred in small signal applications, such as LNA's, but now includes RF power amplifiers.

Reports of 1W, 1900 MHz SiGe power devices started appearing in the mid 1990's [1]. Similar reports for 900 MHz CMOS power amplifiers started appearing several

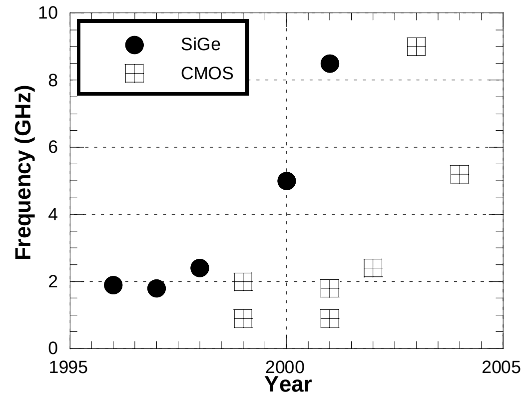


Figure 1. R&D progress for SiGe HBT and CMOS RF power amplifiers by year reported.

years later [2]. Since these first reports, both CMOS and SiGe HBT technologies have continued to increase power amplifier operating frequencies, as shown in Figure 1. Both technologies have achieved useful output powers above 8 GHz [3, 4].

Although this early work has clearly demonstrated the RF power amplifier potential of CMOS and SiGe HBT technologies, none of these reports were directed at specific wireless applications which have stringent specifications for amplifier performance. However these early reports did show the importance of not only having high performance devices, but also the importance of having low loss passive components, especially inductors for power amplifiers [2, 5-8]. With high performance devices and low loss passives, complete RF transceivers [6] could be fabricated on a single chip.

2) 2.4 GHz WLAN: Because of its lower frequency (2.4 GHz) and lower data rates, the ISM band standards are less demanding of semiconductor technologies than the higher frequency bands. Therefore silicon CMOS is widely used for RF power amplifiers. CMOS offers adequate RF performance plus the advantage of being able to integrate other RF functions in addition to the conventional RF gain stages: diode linearizer [9], mixer and switch [10], and power control [11]. In fact a single chip transceiver has been demonstrated [12]. Figure 2 shows a comparison of the

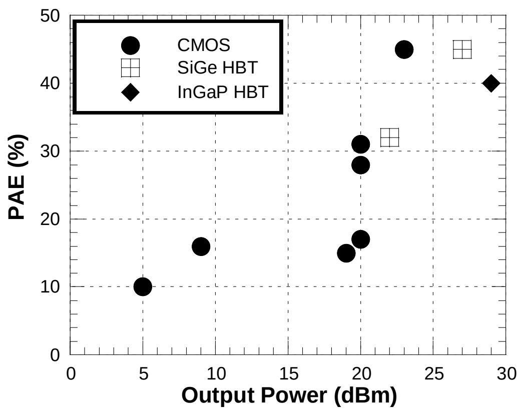

Figure 2. 2.4 GHz WLAN RF power amplifier Pout versus PAE for CMOS, SiGe HBT, and InGaP HBT technologies.

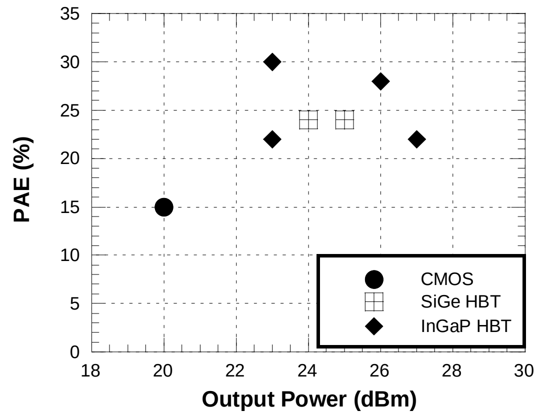

Figure 3. 5 GHz WLAN RF power amplifier Pout versus PAE for CMOS, SiGe HBT, and InGaP HBT technologies.

output power and power added efficiency of 2.4 GHz WLAN power amplifiers fabricated with CMOS FET's, SiGe HBT's and an InGaP HBT. From the reported performance it is clear that Si based technologies CMOS [13] and SiGe HBT [14] are capable of achieving power added efficiencies equivalent to those of InGaP HBT's [15] albeit at lower output powers. Gate lengths between 0.18µm and 0.35µm were used to achieve these CMOS RF power results. The highest PAE's were achieved in all three of these technologies with the use of very low loss, high Q passive components fabricated in multi-layer LTCC substrates.

3) 5.2 GHz WLAN: The preponderance of power amplifiers for 5.2 GHz operation are fabricated using InGaP HBT's. Notable exceptions are a dual-band 0.18µm CMOS power amplifier that achieved 15.3% PAE with an output power of 19.5 dBm [16] and a SiGe HBT power amplifier that achieved 25 dBm with 24% PAE [17]. Unlike the 2.4 GHz application space the HBT power amplifiers at 5.2 GHz do not have other RF functions integrated on the same chip, but are rather classical multi-stage amplifiers. The InGaP HBT amplifiers achieve higher power levels and higher PAE at equivalent power levels than SiGe HBT amplifiers [15, 18-20]. The CMOS amplifier clearly has lower PAE performance than any of the HBT amplifiers at 5.2 GHz. The relative performance of these amplifiers is clearly shown by the data plotted in Figure 3. Because of the lower performance of CMOS and SiGe power amplifiers a common practice is to use CMOS or SiGe at lower power levels followed a higher power level GaAs based device [21].

4) GSM 900 MHz Cellular: For the constant envelope applications, GSM and DCS, the important amplifier figures of merit are RF power and power added efficiency (PAE) at the supply voltage. The amplifier data in Fig. 4 allows a comparison of the PAE of GaAs based InGaP HBT's [22-24] and HFET's [25-27] and Si based BJT's [28], SiGe HBT's [29, 30], LDMOS [31], and recently announced CMOS technologies in the 900 MHz GSM applications. In comparing amplifier performance knowledge of the supply voltage is very important because output power and PAE should both increase as the supply voltage is increased. Therefore, technology comparisons would be easier if all amplifiers were tested at the same supply voltage. When comparing literature data this is not possible and therefore, the supply voltage for each amplifier is included in Fig. 4. The GaAs FET amplifiers achieve their high PAE's with the lowest supply voltage 3.2V. Since the other amplifiers are operated at higher supply voltages, especially the Si BJT 4.5V, their PAE's should be lowered somewhat because operating these power amplifiers at lower supply voltages would necessarily lower their PAE. Having done this, the GaAs FET's clearly have the highest PAE followed by the InGaP HBT's, SiGe HBT's, Si LDMOS, Si BJT, and CMOS amplifiers. The Si BJT amplifier [28] uses a push-pull design approach and achieves high PAE 59%, but requires a 4.5 V supply voltage. All of these amplifiers have an output power equal to or greater than 35.5 dBm except the SiGe HBT and CMOS that have 35 dBm and 34.7 dBm output power, respectively.

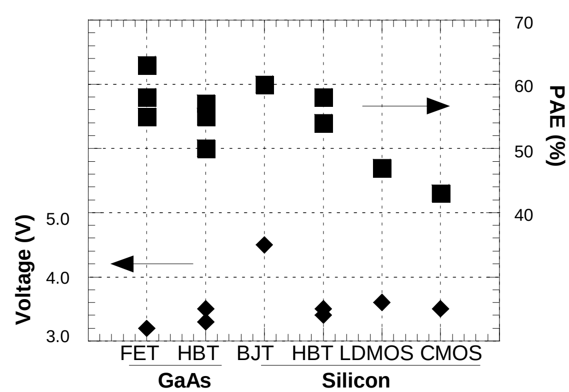

Figure 4. GSM RF power amplifiers using GaAs (FET and HBT) and Si (BJT, HBT, LDMOS, and CMOS) technologies.

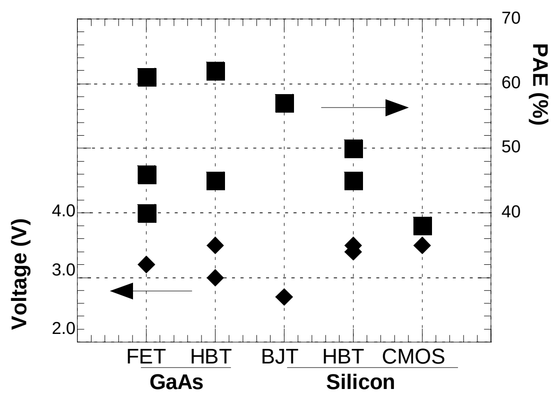

Figure 5. DCS RF power amplifiers using GaAs (FET and HBT) and Si (BJT, HBT, and CMOS) technologies.

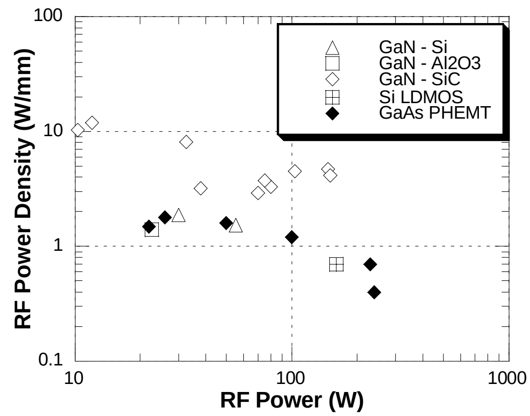

Figure 6. RF power density vs. output power of GaAs PHEMT's, Si LDMOS, and GaN HFET's.

Several other factors need to be considered when comparing the reported performance of RF amplifiers fabricated with different device technologies. The first of these is the issue of amplifier ruggedness that is its ability to survive load mismatch while delivering rated output power. FET's offer adequate ruggedness for cellphone PA's without the need for protection circuitry that is often used with HBT's. Using ruggedness protection circuitry, an AlGaAs HBT PA survived 10:1 VSWR at Vcc = 3.2V [32] and a SiGe HBT PA survived 10:1 VSWR at Vcc = 5V [29]. BJT and HBT PA results that do not report ruggedness performance should be viewed with some skepticism because the PA may have been designed to maximize output power and PAE with no thought to the equally important ruggedness requirement. Other factors that can affect PA performance that cannot be taken into account for this comparison are the skill of the amplifier designer and the accuracy of the RF characterization.

5) DCS 1800 MHz Cellular: DCS is also a constant envelope application and therefore, important amplifier figures of merit are RF power and power added efficiency (PAE) at the supply voltage. The amplifier data in Fig. 5 allows a comparison of the PAE of GaAs based InGaP HBT's [32, 33] and HFET's [25-27], and Si based BJT's [34] and SiGe HBT's [29, 30] technologies in the 1800 MHz DCS application. In comparing these amplifiers the operating voltage must be taken into account again. Unfortunately three of the bipolar references [30, 33, 34] do not report on amplifier ruggedness that raises several questions that cannot be answered definitively. Are these amplifiers sufficiently rugged for cellphone applications? If they are not sufficiently rugged, how much will their performance deteriorate in the process of improving their ruggedness? Therefore the highest GaAs HBT, Si BJT, and SiGe HBT PAE's shown in Fig. 5 should be viewed with some skepticism. Putting these questions aside, the GaAs HBT, GaAs HFET, and Si BJT have the highest PAE around 60% (Fig. 5). The PAE of the SiGe HBT amplifiers has dropped substantially at 1800 MHz when compared to that at 900 MHz. All of these amplifiers have an output power equal to or greater than 33 dBm except the SiGe HBT and CMOS that have 32 dBm and 32.3 dBm output power, respectively.

High RF Power (> 10 W)

1) Higher Frequency Applications: For high RF power applications (base stations) the situation is essentially reversed. Here the overwhelmingly dominate technology is Si LDMOS with about 95% market share. However as wireless applications move to higher frequency (WiMax 3.5 GHz) GaAs FET's easily outperform LDMOS in PAE and die size. However GaAs faces competition from the rapidly developing GaN HFET technology.

2) Technology Comparison: The data in Figure 6 offers a comparison of the RF power density and output power demonstrated by Si LDMOS, GaAs PHEMT's, and GaN HFET's. To date many of the GaN reports have been for devices with power less than 10W, but in this graph only devices with greater than 10W output power are shown. Of these three technologies LDMOS has the lowest power density (0.7 W/mm), largest die size, and lowest cost. GaAs PHEMT's with output powers greater than 10W have power densities ranging from 1.8 W/mm to 0.4 W/mm which is highly dependent on output power and frequency. The 1.8 W/mm result was achieved at 2.14 GHz with $V_{ds}$ = 26 V and a power level of 26 W using a "step gate" gate cross section to increase off-state breakdown [35]. At the other end of this range (0.7 W/mm) four GaAs chips achieved 250 W of output power also at 2.14 GHz with $V_{ds}$ = 28 V [36]. These power densities compare favorably with GaN results on sapphire and Si substrates where 55 W of output power were achieved at 2.14 GHz with $V_{ds}$ = 28 V and a power density of 1.5 W/mm [37]. However, the high thermal conductivity of semi-insulating SiC substrates allows GaN FET's to achieve significantly higher power densities at higher frequencies than the other technologies. Focusing on devices with greater than 10 W of output power, a 12 W/mm

power density was achieved with a 1 mm wide FET at 2 GHz and $V_{ds}$ = 60 V [38]. The 2 GHz power density decreases to below 5 W/mm for the highest output power devices, 150 W with a power density of 4.2 W/mm at $V_{ds}$ = 63 V [39] and 149 W with a power density of 4.7 W/mm at $V_{ds}$ = 47 V [40]. These and many more data points in Figure 5 clearly show that GaN on SiC substrates has about a 4X power density advantage over GaAs PHEMT's of similar size. Today GaN is still a very immature technology compared to GaAs. In addition the cost per unit area of GaN on SiC is about 25 times that of PHEMT starting material. If the higher power density of GaN on SiC is accounted for, GaAs PHEMT's have about a 6X lower cost per watt than GaN at the die level. This cost difference will have to close significantly before GaN will have a major commercial impact.

## CONCLUSIONS

For the foreseeable future GaAs based power amplifiers will be used in low power and higher power applications. In the low power space GaAs will be used to achieve the highest power levels and highest PAE's, especially at higher frequencies. In the high power application space GaAs will challenge LDMOS for base station applications. GaN commercialization will require substantial cost reduction to challenge GaAs.

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