RF POWER DEVICES FOR WIRELESS COMMUNICATIONS

(Invited Paper)

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Abstract - **A wide variety of semiconductor devices are used in wireless power amplifiers. This paper will review the advantages and disadvantages of these devices for handheld and infrastructure applications.**

I. INTRODUCTION

Key components in any wireless communication system are the RF power semiconductor devices that enable the RF power amplifiers. These devices must meet strict performance specifications, output power and linearity, so that the wireless systems comply with ITU (International Telecommunication Union) regulations. In addition, system manufacturers have their own requirements: power-added efficiency (PAE), supply voltage, ruggedness, physical size, reliability, and cost. These devices are used in handheld and fixed products that have very different specifications depending on the modulation format of the wireless system: GSM, DCS, CDMA, or WCDMA.

II. HANDHELD APPLICATIONS

At this time the principle handheld application is cellphones which require relatively small power devices that deliver several watts of RF power from a battery power source of a few volts. The use of a battery power source dictates that one important figure of merit is power added efficiency (PAE).

A. *GSM900*

For the constant envelope applications, GSM and DCS, the other important figure of merit is RF power density because higher power density devices yield physically smaller, usually less expensive amplifiers. The device data in Fig. 1 allows a comparison of the performance of a Si LDMOS [1], GaAs FET's [2-3], and an InGaP HBT [4] in the 900 MHz GSM application. Each of these devices has output power greater than 35 dBm and PAE greater than 70% which are adequate for the output stage of a handheld GSM power amplifier. However several differences are worth noting. The large signal gain of all of the FET's is > 12 dB, but that of the InGaP HBT is 10 dB. The Si LDMOS FET has the lowest power density 41mW/mm and the HBT has the highest power density 0.68mW/um^2. The different units used for comparing the power density of FET's and HBT's is a result of the

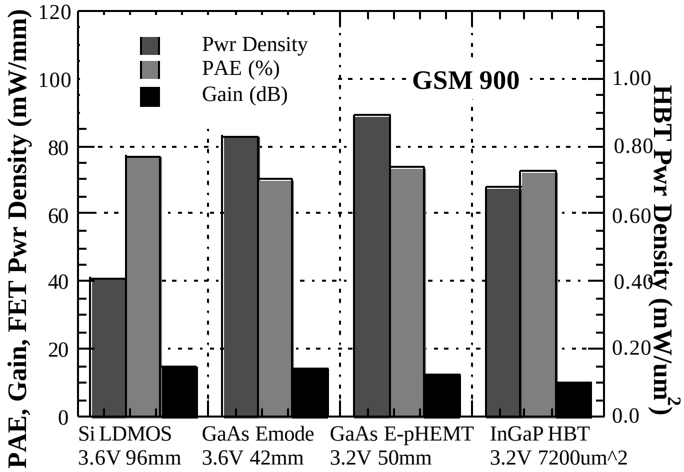

Fig.1. GSM RF performance comparison of Si LDMOS GaAs FET's and InGaP HBT devices.

fact that a FET is a planar device whereas the HBT is a vertical device. The power density comparison between FET's and HBT's can be made clearer by expressing the HBT power density in the same units as the FET. In this case the InGaP HBT power density is 1360 mW/mm of emitter width. This value is misleadingly large because it does not take into account several HBT design requirements that increase the area of a high power HBT: emitter or base ballasting, ruggedness protection circuitry [5], and device fragmentation to reduce thermal resistance. FET's do not require ballasting and ruggedness protection circuitry or fragmentation on thermal concerns. In spite of these factors, GaAs HBT output power devices require about 50% less chip area than comparable GaAs FET's. However, a portion of this size advantage is lost in RF amplifier chips because of other factors: bond pads, input and output manifolds, passive components, bias circuitry, and level of integration.

B. *DCS1800*

The device data in Fig. 2 allow a comparison of the performance of a Si LDMOS [1], GaAs FET's [2,6], and a SiGe HBT [7] in the 1800 MHz DCS application. Each of these devices has an output power greater than

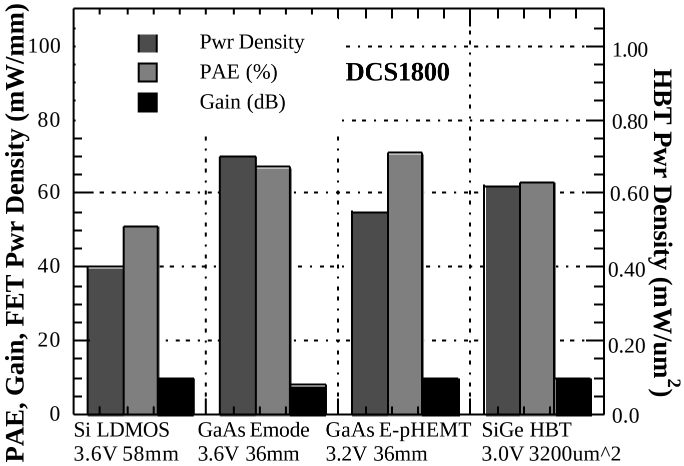

Fig 2. DCS RF performance comparison of Si LDMOS GaAs FET's and SiGe HBT devices.

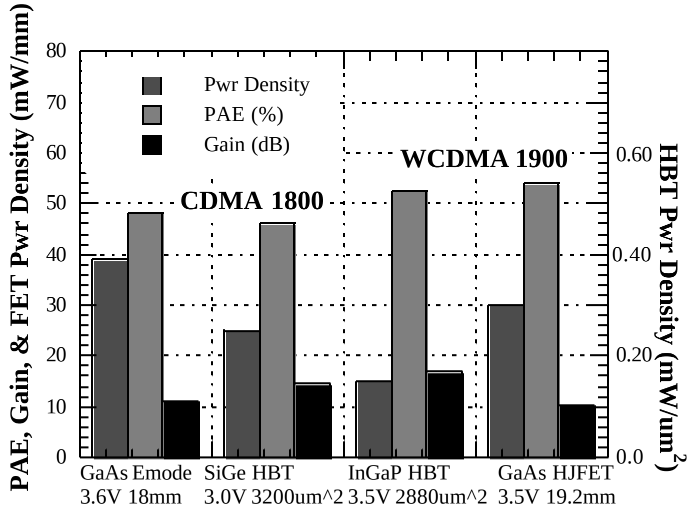

Fig 3. CDMA/WCDMA RF performance comparison of GaAs FET's, SiGe HBT, and InGaP HBT devices.

or equal to 33 dBm which is adequate for the output stage of a handheld DCS power amplifier. In general, however, the other performance parameters have been degraded by the higher operating frequency. The FET gate length plays a major role in the large signal gain degradation. The GaAs Emode (Lg=0.85um), Si LDMOS (Lg=0.4um), and GaAs E-pHEMT (Lg=0.4um) have large signal gains of 8, 9.7, and 10 dB, respectively. The highest PAE is 71% for the E-pHEMT and lowest is 51% for Si LDMOS. Not surprisingly, the SiGe HBT has the highest power density, but the comments regarding the GaAs HBT design requirements, made previously, are also applicable to this device.

C. *CDMA/WCDMA*

For linear applications, CDMA and WCDMA, PAE and power density are also very important, but only so long as linearity specifications ACP (Adjacent Channel Power) and ALT (Alternate Channel Power) are met at the required output power levels. Device data in Fig. 3 allows a comparison of GaAs FET's [2,9], an InGaP HBT [8], and a SiGe HBT [7] in CDMA and WCDMA applications. In general, the output stage power devices for these applications are smaller in size because the power requirements are substantially lower. In addition the PAE and power density are lower because the devices are not operated at their optimum power levels in order to meet the ACP and ALT requirements. The ACP and ALT performance of these devices are shown in Table 1. For comparison the handheld system specifications for these applications are also shown. All of these devices have lower ACP's and ALT's than the system specifications, but normally several dB of margin are required to compensate for other system components.

D. *HANDHELD SUMMARY*

As has been shown in Figs. 1-3, a wide variety of semiconductor devices can meet the requirements for output stage power devices in GSM, DCS, CDMA, and WCDMA handheld applications. However there are some important tradeoffs among these devices. The higher power density of HBT's leads to smaller die size. GaAs FET's have higher power gain and PAE. Si LDMOS FET's are the lowest cost even though they have the lowest power density and therefore, the largest die size. In general, FET's are much more rugged than HBT's which is the ability to survive large load mismatches, up to 20:1, while delivering the rated output power. Compared to Si LDMOS, GaAs FET's and GaAs HBT's, SiGe HBT's are relatively new to this application space.

III. INFRASTRUCTURE APPLICATIONS

Cellphone infrastructure base stations are the largest market for high power RF semiconductor devices. In general, these relatively large devices deliver tens or hundreds of watts from tens of volts. At this time Si LDMOS FET's are the most widely used technology for this application, but they struggle to meet required performance above 2 GHz. In recent years, very high

TABLE 1. Device ACP's and ALT's compared to System ACP and ALT Specifications

Ref.	Device	Band	Device ACP	Device ALT	System ACP	System ALT
[2]	Emode FET	1800 CDMA	-45 dBc	-59 dBc	-42 dBc	-54 dBc
[7]	SiGe HBT	1800 CDMA	-46 dBc	-63 dBc	-42 dBc	-54 dBc
[8]	InGaP HBT	1900 WCDMA	-35 dBc	---	-33 dBc	-43 dBc
[9]	HJFET	1900 WCDMA	-40 dBc	---	-33 dBc	-43 dBc

TABLE 2. Si, GaAs, SiC, and GaN Material Properties

Property	**Si**	**GaAs**	**4H-SiC**	**GaN**
Bandgap (eV)	1.11	1.43	3.2	3.4
Relative Dielectric Constant	11.8	12.8	9.7	9.0
Breakdown Field (V/cm)	6E5	6.5E5	35E5	35E5
Saturated Velocity (cm/sec)	1E7	1E7	2E7	1.5E7
Electron Mobility (cm^2/V-sec)	1350	6000	800	1000
Hole Mobility (cm^2/V-sec)	450	330	120	300
Thermal Conductivity (W/cm-°K)	1.5	0.46	4.9	1.7

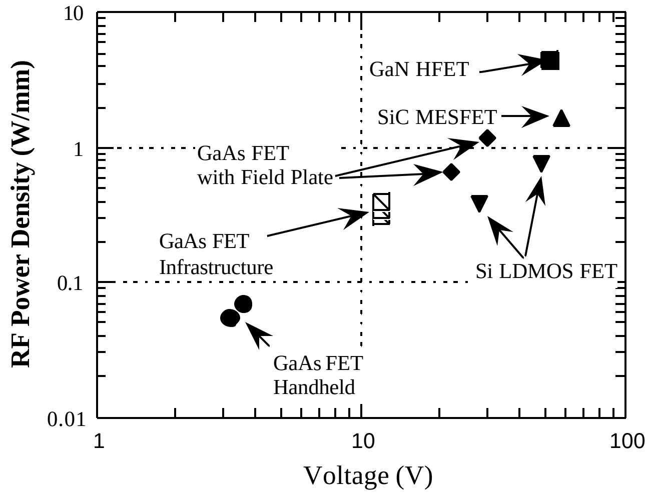

Fig.4. RF power density vs. voltage for GaAs FET's, Si LDMOS FET's, GaN FET, and 4H-SiC FET.

power GaAs MESFET's and pHEMT's have been shown to have superior performance compared to Si LDMOS devices especially at higher frequencies. However, the cost of these GaAs FET's is several times that of the Si devices even though much of the device cost is in the cost of the package.

Another important development in the last several years is the emergence of wide bandgap semiconductors SiC and GaN for high power RF applications. Their unique material properties, high electric breakdown field, high saturated electron drift velocity, and, for SiC, high thermal conductivity, are what gives these materials their tremendous potential in the power device arena. The data in Table 2 allow a comparison of the basic material properties of silicon, gallium arsenide, 4H silicon carbide, and gallium nitride. The 5-6 times higher breakdown field of both SiC and GaN is what gives these materials their advantage over Si and GaAs for RF power devices. SiC clearly has an advantage over GaN in thermal conductivity, but the AlGaN/GaN heterojunction which can be grown in the GaN material system enables lateral GaN HFET's to have superior current handling capability compared to lateral SiC devices. Moreover, GaN can be epitaxially grown on SiC, taking advantage of SiC's higher thermal conductivity.

A. *RF POWER DENSITY*

Power density is a very important figure of merit for high power devices because a higher power density yields smaller die size and more easily realized input and output circuit matches. Saturated CW RF power densities versus operating voltage at about 2 GHz for the device technologies are shown in Figure 4. Since infrastructure applications require very high RF powers, only some of the largest devices in each technology are shown. Smaller devices invariably have higher power densities, but can only be used for driver stages in base station amplifiers. Theoretically the power density should increase with the square of the voltage if FET current saturation and thermal effects are ignored. The power density of these devices increases at a slower rate illustrating the deleterious affect of these phenomena on output power. The wide bandgap devices (SiC and GaN) have the highest power densities 1.67 W/mm [10] and 4.5 W/mm [11], respectively, but the use of field plates in GaAs FET's has achieved power densities of 0.67 W/mm [12] and 1.16 W/mm [13]. Conventional GaAs FET's have power densities around 0.4 W/mm [14-16] that are similar to those of LDMOS FET's [17], but the GaAs FET's achieve this power density at 12 V and LDMOS at 26 V. Also included in Fig. 4, for comparison, are the power densities for several GaAs FET's [2,6] used in handheld applications.

B. *OUTPUT POWER*

The 2 GHz output power and PAE of the devices in Fig. 4 are shown in Fig. 5. The most widely used technology is Si LDMOS which has demonstrated an output power of 180 W with 46% PAE from 28 V [17]. GaAs FET's have demonstrated close to 300 W with 50% PAE at 12 V [14-16]. GaAs FET's with FP (Field Plates) have demonstrated higher operating voltage, but the output power and PAE are still lower than the standard GaAs FET's [12,13]. At 3.1 GHz the SiC MESFET has demonstrated an output power of 80 W with 38% PAE at 58 V [10]. However, the GaN HFET has demonstrated the highest CW power for a wide bandgap semiconductor device in this frequency range 108 W from 52 V at 2 GHz[11].

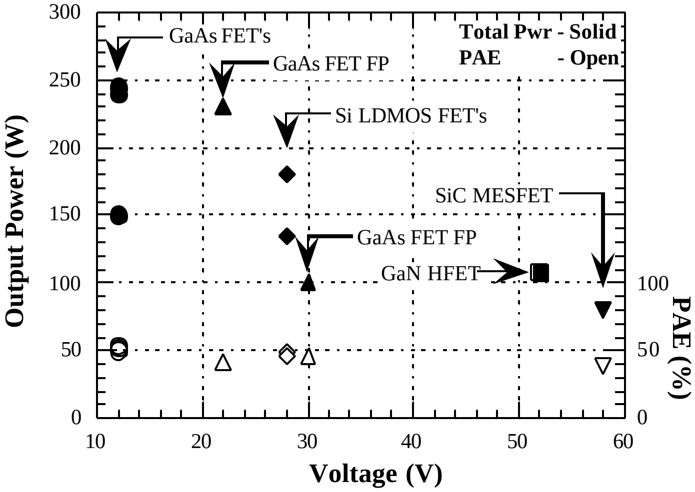

Fig.5. RF power & PAE vs. voltage for GaAs FET's, Si LDMOS FET's, GaN FET, and 4H-SiC FET.

C. *INFRASTRUCTURE SUMMARY*

Today the infrastructure RF power device market is dominated by Si LDMOS with GaAs devices finding increased usage above 2 GHz. The wide bandgap technologies have demonstrated impressive power densities, but mostly using relatively small devices. These devices face stiff competition from well entrenched, mature semiconductor technologies, silicon and gallium arsenide. For a new technology to gain a foothold in the market place it must offer all of the attributes of the mature technologies that customers have come to expect, such as proven reliability, multiple dependable sources, accurate device models, and low cost. In addition the new technology must offer a significant performance improvement at a reasonable cost.

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