Current Status and Emerging Trends in RF Power FET Technologies

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Abstract— **The growth in ISM and wireless communications markets, and the transition to 3G and embedded transceivers, are motivating an intense study of RFIC technologies. The power amplifier (PA) plays a critical role in the size, efficiency, and thermal requirements of wireless handsets. This paper reviews state-of-the-art and emerging power semiconductor devices for RF PAs. Comparisons are presented in terms of key specifications such as PAE, power gain, VSWR, package thermal resistance, and integrability.**

I. INTRODUCTION

The continuing growth of mobile communications markets is motivating a steady evolution of RFIC technologies. Frequency spectra are changing from older 800 and 900 MHz standards to today's 2G bands in 1.8 to 1.9 GHz. Emerging 3G systems will push the envelope further to 2.1 GHz, and new systems like Bluetooth are raising the bar to 2.4 GHz. These are summarized in Table I. New and legacy UHF/VHF ISM systems (e.g. at 13.56 MHz) also demand high performance levels.

All products must deliver expected performance while improving in power efficiency and component density. The PA is thus a critical component. It must operate with high linearity over a range of power outputs; have high power efficiency to reduce operating costs, improve battery lifetime, and ease thermal management; offer high power density to reduce size, weight, and form factor; and integrate matching networks to avoid extensive tuning.

TABLE I
SUMMARY OF WIRELESS COMMUNICATIONS SPECTRA

Family		*Spectrum*
2G and 2.5G	cdmaOne	900 MHz
	GSM	900 MHz, 1.8 GHz, 1.9 GHz
	GSM EDGE, PCS	1.9 GHz
3G	UMTS, W-CDMA	2.1 GHz
Embedded	Bluetooth	2.4 GHz

In ISM and basestation markets competition in PAs has been softer since the demands on size and efficiency are less stringent than in portable units. Commercial offerings in the 5 to 500 W range, where cost is a key criterion, are predominantly based on Si BJT technologies and Si LDMOS, VDMOS, and VLSI-scaled power FETs such as Motorola's TMOS. In the handset arena, however, numerous technologies are under investigation for applications in the 0.1 to 5 W range. Here the issues of integration, power efficiency, and power density can critically impact the marketability of a wireless handset.

This paper is arranged in several sections. First the key technologies of interest are identified. Then some characteristics of each are presented for ISM/basestation and handset applications, respectively. Finally, some emerging technologies are introduced.

II. TECHNOLOGY IDENTIFICATION

Power semiconductor devices for RF PAs are primarily from two families: Si and III-V. Recently SiGe has made inroads, particularly for handset use. Key characteristics of power FET technologies are summarized in Table II.

Silicon technologies include LDMOS, VDMOS, bipolar, CMOS, and hybrid technologies combining BiCMOS with power device enhancements. Silicon has a high thermal conductivity which eases thermal management, but the lossy substrate limits the quality of integrated passives. SOI greatly improves passives but enhances self-heating. The LDMOS enjoys low manufacturing cost and straightforward integration with peripheral analog and digital CMOS circuitry. The VDMOS is similar, except the vertical structure limits co-fabrication with signal-level circuits. Silicon BJTs have higher power density but lower gain. BiCMOS and CMOS, particularly SOI CMOS, are becoming attractive for low-power, low-voltage PAs, as for Bluetooth. SiGe offers higher gain, lower noise, and good integration potential but is presently immature.

TABLE II
COMPARISON OF POWER DEVICE TECHNOLOGIES FROM AN INTEGRATION VIEWPOINT

Technology	*Bias Supply*	*Passive Components*	*Integration Potential*	*Issues*
Si LDMOS/VDMOS	Single	Poor	Poor	Isolation
SOI LDMOS	Single	Excellent	Excellent	Thermal management; device optimization
Si BJT or BiCMOS	Single	Poor	Poor (good, with trench isolation)	Low efficiency at low-V
GaAs MESFET	Dual (single)	Good	Excellent	Enhancement mode
SiGe HBT	Single	Poor	Good	Integration with CMOS/BiCMOS
AlGaAs/GaAs HBT	Single	Good	Good	Thermal management
CMOS	Single	Poor	Poor (good, with trench isolation)	Isolation
SOI CMOS	Single	Excellent	Good	Thermal management

State-of-the-art III-V technologies are GaAs MESFETs and AlGaAs/GaAs HBTs. Both offer the highest PAE and power gain, as well as high linearity. Their ruggedness, in terms of output VSWR tolerance, is similar. The semi-insulating substrate permits high quality monolithic passives, but its poor thermal conduction also enhances self-heating. Depletion-mode MESFETs require dual power supplies, but new enhancement-mode devices operate from a single supply.

III. ISM and Base Station Applications

Power amplifiers for ISM devices and wireless basestations typically operate from below 10 W to over 100 W. Advanced communication techniques such as CDMA further demand highly linear operation from rated power to backed-off levels (down to about 10% of rated power). Since present PCS systems in the US rely on TDMA channel multiplexing the need for broad power gain linearity is relaxed. Key criteria therefore are a high PAE to simplify thermal management, high power gain to reduce the number of amplifier stages, high ruggedness, low thermal impedance packaging, and low cost. Largely because of the low cost of Si manufacturing, LDMOS, VDMOS, and bipolar technologies dominate in volume vendors such as APT, Ericsson, Motorola, Philips, and PolyFET.

Figure 1 shows the PAE of Si devices for UHF/VHF and 2G/3G applications as taken from published results and manufacturers' datasheets. The PAE and drain/collector efficiency are, respectively,

$$PAE = \eta\left(1 - \frac{1}{G_P}\right) \quad (1)$$

$$\eta = \frac{P_{out}}{P_{DC}} \quad (2)$$

In 2G/3G, LDMOS PAE is significantly higher than BJT, although BJT shows less degradation in PAE when moving to 3G applications. The trend in LDMOS toward higher PAE at low output power is also evident in low-power devices for handsets, as shown in the next section. For UHF/VHF, competition is between VDMOS and TMOS with VDMOS achieving significantly higher PAE. Si LDMOS is encroaching on UHF applications, with PAE superior to TMOS beginning at 10-W output.

Figure 2 shows the power gain over the same power range. Again, LDMOS clearly delivers better performance for 2G applications; in 3G the margin is decreased but still significant. It is yet unclear how LDMOS will fare for emerging systems such as Bluetooth. The TMOS delivers the highest gain throughout the band, although at lower frequencies it is comparable to VDMOS. LDMOS gain is below TMOS and VDMOS to 80-W levels; from the trend it appears LDMOS may deliver competitive power gain at >100-W levels in UHF applications.

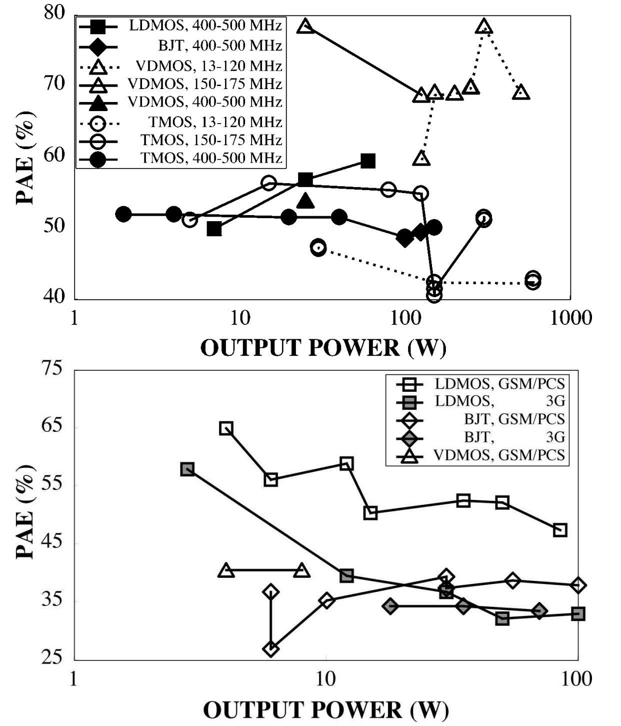

Fig. 1. Reported PAE as a function of RF output power for Si PAs in (a) UHF/VHF and (b) 2G and 3G applications.

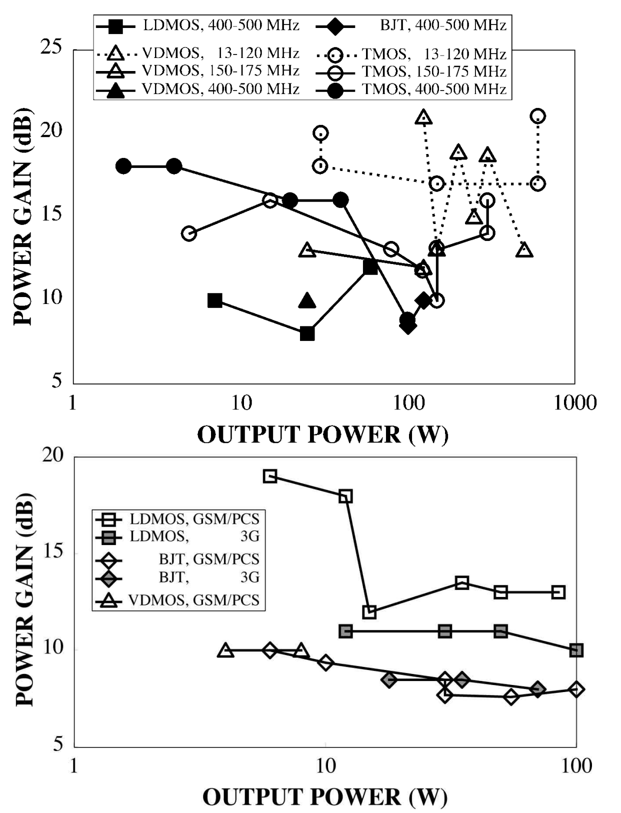

Fig. 2. Reported gain as a function of RF output power for Si PAs in (a) UHF/VHF and (b) 2G and 3G applications.

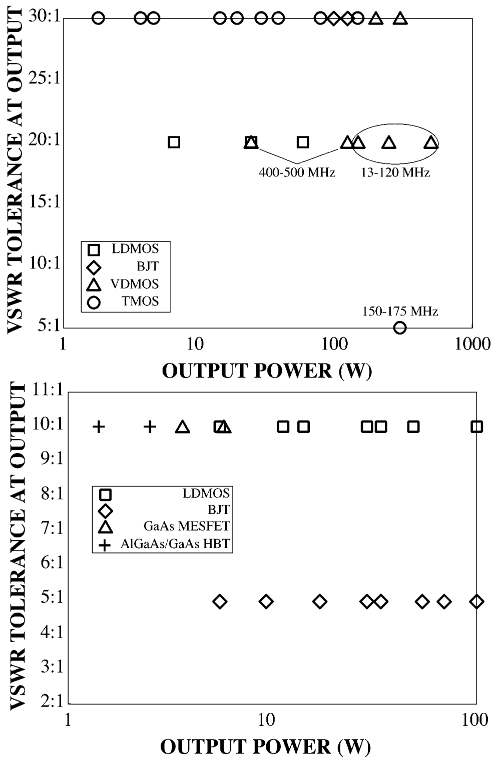

Fig. 3. Reported VSWR as a function of RF output power for Si LDMOS/VDMOS and bipolar, GaAs MESFET, and AlGaAs/GaAs HBT PAs in (a) UHF/VHF and (b) 2G and 3G applications.

Another consideration for high-power PAs is the degree of output mismatch that a device can tolerate without reliability degradation. A common metric is the tolerance to output VSWR, as in Fig. 3. The 10:1 ratio of FET and HBT technologies in 2G/3G indicates a high degree of flexibility in tuning the PA for high gain, PAE, or output power. Silicon bipolar devices in contrast demonstrate much lower VSWR rating indicating that matching for gain or PAE may be sacrificed to match for output power. Little difference is seen in UHF/VHF, although LDMOS shows VSWR of 20:1 versus competitors at 30:1 in UHF.

A final characteristic of high-power RF PAs is the thermal management imposed by the device packaging. Shown in Fig. 4 is the junction-case thermal resistance of Si LDMOS/VDMOS and bipolar devices. Several observations are made. First, for output power under 30 W, LDMOS heating is lower than VDMOS/TMOS and bipolar. Above 30 W, bipolar and VDMOS retain a slight advantage in heating. Second, in moving to 3G LDMOS heating is largely unchanged under 30 W, but improves above 30 W. Third, TMOS exhibits a low variation in R_{jc} across a wide power range as a function of frequency.

These trends are more significant when combined with the PAE data of Fig. 1. Although LDMOS has a higher thermal resistance at low output power, its 10-20% better PAE implies that the device self-heating will be much lower than in bipolar, VDMOS, and TMOS.

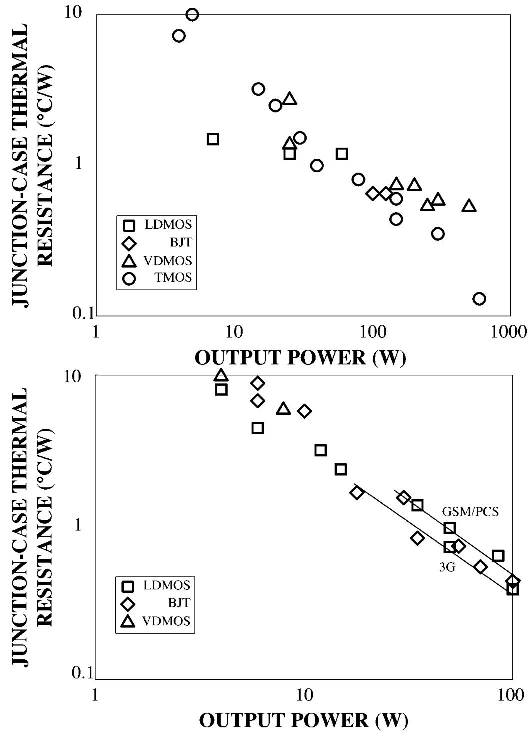

Fig. 4. Reported R_{jc} as a function of RF output power for Si LDMOS/VDMOS and bipolar PAs in (a) UHF/VHF and (b) 2G and 3G applications.

IV. Portable Wireless Handset Applications

Compared to ISM and basestation activity, many diverse technologies are under investigation for handset PAs. Since handsets have numerous performance criteria nearly every device technology offers some desirable characteristic. As will be shown in this section, no single technology clearly meets all requirements. Instead several contenders—notably LDMOS, SiGe, and GaAs MESFET—offer a similar combination of PAE and gain.

Research is most active into LDMOSTs [1]-[4] and GaAs MESFETs [5]-[10] since each is an excellent candidate for monolithic front-end integration. Although Si benefits from low-cost manufacturing, MESFET MMIC technology is more mature. SiGe [11]-[12] and AlGaAs/GaAs [13]-[15] HBTs are considered since they have the advantages of bipolar for linearity and PAE, without the low current drive of BJTs at low supply voltages. Also, low-power output CMOS PAs have been reported with impressive PAE and gain [16]-[17].

Figure 5 shows published PAE data for a variety of technologies in the 0.01 to 10 W range. LDMOSTs and MESFETs lead in 2G applications, with AlGaAs/GaAs HBTs appearing. State-of-the-art LDMOSTs and MMICs integrate matching networks utilizing either on-chip passives or bondwire inductances. On-chip passives are more common in GaAs since the semi-insulating substrate lends itself to integration. The PAE of PAs using on-chip passives is thus slightly degraded due to the finite Q.

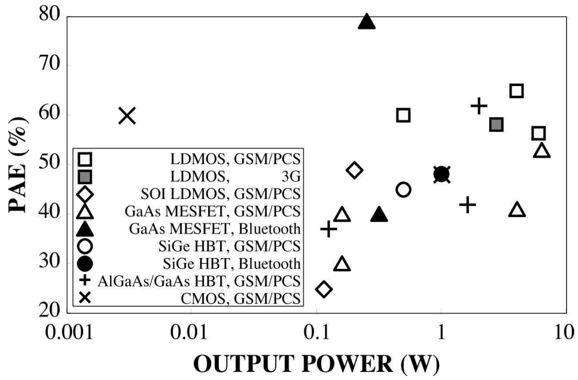

Fig. 5. Reported PAE as a function of RF output power for Si and SOI LDMOS, GaAs MESFET, SiGe HBT, AlGaAs/GaAs HBT, and CMOS PAs in 2G and 3G applications.

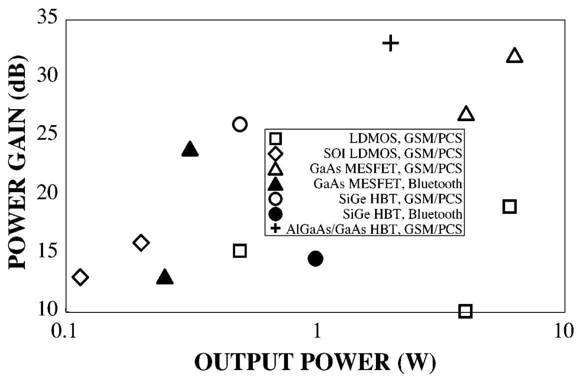

Fig. 6. Reported gain as a function of RF output power for Si and SOI LDMOS, GaAs MESFET, SiGe HBT, AlGaAs/GaAs HBT, and CMOS PAs in 2G and 3G applications.

Data for 2.4-GHz applications are sparse but suggest that MESFETs and SiGe HBTs can deliver PAE >50%. Reports of CMOS PAs are promising, suggesting PAE >48% up to 1 W, but as with Si LDMOS the integration of matching networks is impractical. Early efforts in SOI LDMOS show PAE to 48%. These devices could exceed Si LDMOS PAEs with further optimization.

Figure 6 shows published power gain data for the same PAs. Performance is led by MESFETs and HBTs, with gains typically above 25 dB. Silicon LDMOSTs show power gains to 18 dB, and early results of SOI LDMOSTs exceed 15 dB. Again, as these devices are optimized gains above 20 dB are expected.

V. Emerging Technologies

Besides established Si and III-V offerings, PAs utilizing wide bandgap semiconductors such as SiC, GaN, and AlGaN/GaN have been reported. Presently these devices target S- and K-band applications with an emphasis on extreme power density and thermal ruggedness. With applications primarily in satellite and military communications, cost is less critical but reliability and compactness are essential. If low-cost versions become available for commercial spectra, such devices may appear in ISM or wireless applications. Their use in handsets will continue to be impractical until these technologies mature and can compete with the integration potential of Si/SOI LDMOSTs and GaAs MMICs.

VI. Conclusion

Intense competition among device technologies is observed, especially in handset applications. In UHF/VHF, VLSI-scaled power FETs (e.g. TMOS) exhibit the highest gain and VSWR and lowest thermal resistance, better than VDMOS and Si BJTs. LDMOSTs are beginning to encroach into UHF, with superior gain and PAE beginning in the 20 to 80-W range, although their thermal performance is best below 50 W. Present leaders in power FETs for IPAs in 2G/3G handsets are MESFETs and HBTs, which have intrinsically high PAE and power gain, although LDMOSTs remain competitive, especially in PAE. MMICs, which support on-chip matching networks, currently have the edge in compact PAs, but this balance may shift as optimized SOI LDMOSTs appear. Finally, SiGe is emerging as a unique enhancement to older CMOS/DMOS processes. A hybrid SiGe/MOS technology could offer exceptional low-cost performance, with the sole limitation of low-Q passives due to the lossy Si substrate.

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