Moving past the hype: real opportunities for wide band gap compound semiconductors in RF power markets

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Abstract

Recent advances in wide band gap research give confidence that devices based on GaN technology can outperform incumbent Si LDMOS technology for the base station high power amplifier application. The remaining technical challenges can be resolved within a 3 years time frame. The base station power amplifier market is characterized by medium-sized volume and sustainable price erosion up to 20% p.a. In order to drive costs down this specific technology-market combination requires forming cooperative ways of working that will allow success in the marketplace as well.

INTRODUCTION

Significant progress has been made in the performance of wide band gap materials for RF power transistors. However, it has not yet been demonstrated that technical progress can translate into market success. This paper will discuss the likely target markets, the current state of technology, and the key issues to market penetration. The main focus will be on applications using frequencies below the 10 GHz range.

POTENTIAL MARKETS

There is considerable confusion about the "real" size of the RF Power market, with estimates ranging from a few hundred million dollars to several billion. In addition to the inherent difficulty of estimating the market size of a niche product that is used in a diverse range of applications, there are two specific issues: defining the relevant market scope, and keeping up-to-date with innovations that have enabled significant price reductions over the past five years - a trend that will continue for another two to three years at least.

Relevant market

Typical market studies use a very broad definition of "RF Power Devices", including power levels of a fraction of a Watt though hundreds of Watts. This paper will limit the discussion to the market for devices > 20W (due to requirements for low supply voltage and integration GaN cannot compete in these lower power, largely consumer markets).

Price reduction

In the base station application, which has made the move to lower cost solutions (e.g., high volume 8" CMOS fabs, low-cost plastic packages), suppliers have been able to provide significant cost benefits. Since 2000, these applications have seen price reductions grow from 4% p.a. to a range of 15-20%, which is sustainable for the next few years.

A practical illustration

Taking the ABIresearch report on "RF Power Devices" (Feb 2004) [1] as a starting point, these effects can be illustrated. The example uses ABI's "moderate forecast", which shows a total market of $ 1,946 million for 2003. However, almost 60 % of this market is for devices < 4W, and with the relevant market for wide band gap of > 20W the total is reduced to $ 579 million, or 30 % of the original total. This particular study includes an assumption of 12 % price erosion p.a., while current innovations will drive levels of 15-20% in markets that accept low-cost solutions. Taking this innovation into account, the market forecast is in the range of $ 400-500 million (see Figure 1)

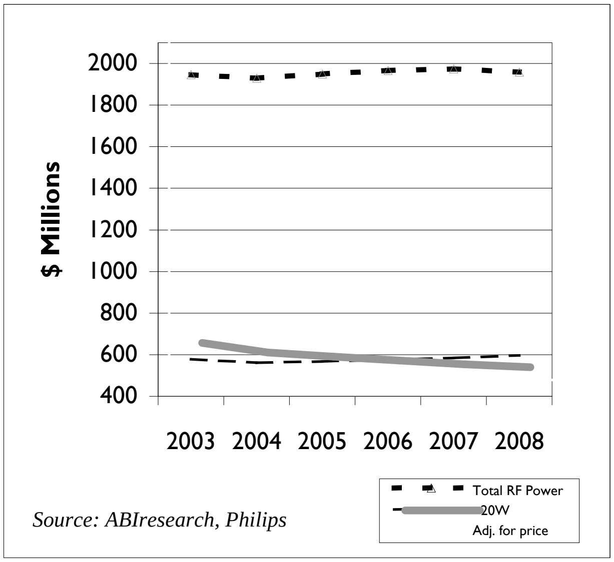

FIGURE 1 Market forecast for RF power devices

This range in market value is a good starting point for understanding the RF power market; although it must be stressed that cost pressure and innovation are at very high levels, which could result in even lower market figures.

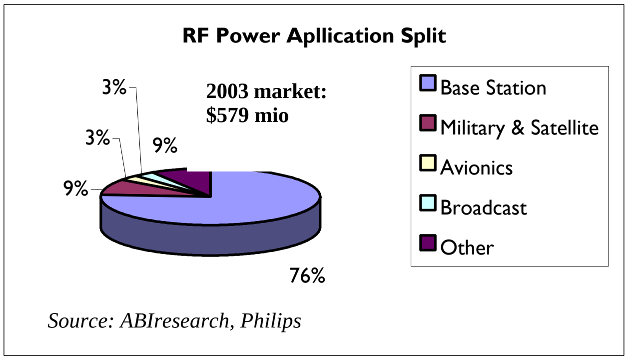

FIGURE 2 This figure shows a split by applications area, which underlines the importance of the base station market.

Market requirements

The common denominator of the RF power markets is that the products are used in extremely expensive equipment where reliability and performance are essential. Whether the application is an airplane, a television transmitter or a cellular base station, customers require top performance along with absolute confidence about product reliability, supply reliability, and supplier viability over many years after the product has been designed into a product. This has significant impact on the introduction of a new technology. In addition customers expect to work in partnership during the design-in phase, when application support from RF experts is required of suppliers. Finally, since the general downturn in 2001, cost has become the driving factor for change and innovation within the base station market. This has led to the adoption of lower cost solutions. Since the base station market is the dominant application area for RF Power devices (see Figure 2), this requirement is necessary for any meaningful introduction of a wide band gap technology.

TECHNOLOGY

This section will briefly review the current status of technology thereby focussing on the base station application.

Si LDMOS

In base stations for personal communication systems (GSM, EDGE, W-CDMA), RF power amplifiers are key components. For these power amplifiers, RF Laterally Diffused MOS (LDMOS) transistors are currently the preferred choice of technology because of their excellent high power capabilities, gain and linearity. To meet the demands imposed by new communication standards, the performance of LDMOS is subject to continuous improvements.

The key players in Si LDMOS technology are Freescale and Philips Semiconductors as strong number one and two.

GaAs

It is well recognized that GaAs-based power devices are inherently suited for high-frequency operation due to their excellent electronic transport characteristics. However, conventional GaAs-based FET's have serious limitations in terms of operation voltage, as compared with LDMOS transistors. An additional disadvantage for GaAs results from its rather poor thermal conductivity. This limits the applicability of GaAs for the high power final stage amplifiers needed in base station transmitters.

Although in recent years a lot of effort has been put into further increasing the output power level obtainable from a single packaged device by increasing the breakdown voltage, GaAs-based device technology cannot compete with Si LDMOS at the device level.

On the other hand, GaAs devices offer the system designer the possibility of using advanced power amplifier concepts such as Doherty combination and class F matching. These concepts offer good efficiency improvements. Recently, GaAs pseudomorphic-High Electron Mobility Transistor (p-HEMT) technology has demonstrated very good results in systems employing Digital Predistortion (DPD). By applying these concepts designers can balance the shortcomings of GaAs at the device level.

Conclusively, the competition between GaAs and Si based device technology will be decided by the lower cost (in $ per Watt) of Si LDMOS technology.

The key players in high power GaAs technology are Toshiba, Fujitsu and NEC.

Wide band gap materials SiC and GaN

When taking the intrinsic material parameters as a starting point it is obvious that for the discussed application the wide band gap materials SiC and GaN are very favourable (see Table 1).

TABLE 1
Material properties of major semiconductors

	Si	GaAs	4H-SiC	GaN
Band gap [eV]	1.12	1.43	3.26	3.4
Thermal conductivity [W/K•cm]	1.5	0.46	4.9	1.5
Breakdown field [10^6 V/cm]	0.25	0.3	2.2	3
Sat. elect. velocity (peak) [10^7 cm/s]	1 (1)	1 (2.1)	2 (2)	1.5 (2.7)
Relative permittivity	11.9	13.1	10	8.9

The high electrical breakdown field E_{bd} and high saturation velocity v_{sat} of wide band gap materials translate into better breakdown voltage times cut-off frequency products $BV \times f_T$ which can be utilized either for RF or DC power applications. Research groups have reported much higher power density measured in Watts output power per gate width for transistors based on wide band gap materials compared to traditional semiconductor materials.

The wide band gap E_g results in low intrinsic carrier concentrations at device operating temperatures, which in turn allows high temperature operation and high radiation stability.

Specifically for SiC, the high thermal conductivity helps to efficiently remove the dissipated power from the device channel area. Therefore, less thermal memory effects are expected for SiC based devices in applications where linearity is critical and DPD concepts are utilized.

The AlGaN/GaN material system features in addition the possibility of growing heterostructure devices enabling HEMT's suitable for high frequency operation.

The advantage of high electron mobilities in GaN based HEMT devices together with recent advances of GaN epi growth and process technology make us believe that for high-frequency high power applications SiC will play a prominent role only as a substrate material for GaN, leveraging the good thermal properties and reasonable lattice match to GaN.

Technology comparison

Especially for wide band CDMA (W-CDMA), the linearity demands are very stringent and can only be met by operating the amplifier sufficiently far in back off. However, this comes at the expense of lower efficiency. A lot of attention is paid to improve the trade-off between linearity and efficiency on device level and on power amplifier level.

Another important parameter is power gain. A higher gain in the amplifier's final stage means that less power has to be generated by the previous stage, thereby increasing the overall amplifier efficiency and decreasing cost.

In Figure 3 the discussed technologies are compared with each other on these key performance values. It is clearly noticeable how GaAs based devices lag behind Si LDMOS at the device level, whereas GaN starts to challenge Si LDMOS in performance. A significant effort is currently spent on boosting the performance of GaN HEMT devices. This is done by applying device and process features well known from the established technologies Si LDMOS and GaAs like field plates and gate recess processing.

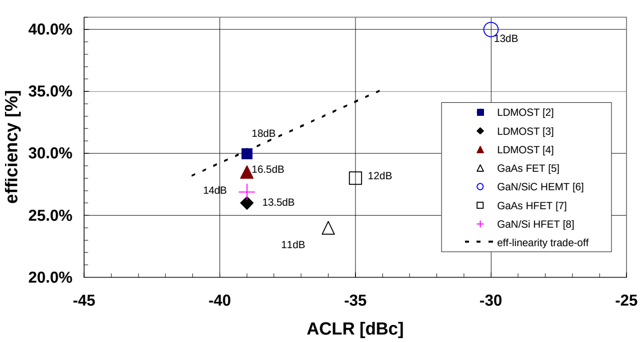

FIGURE 3 Benchmark of high-power devices with respect to efficiency-linearity trade-off. In the figure also the power gain of the devices is shown. In all cases W-CDMA modulation schemes are applied.

But wide band gap materials promise performance improvements not only on transistor level. Various power amplifier concepts developed to increase efficiency and improve linearity (e.g. DPD, Enveloppe Elimination and Restoration EER, Doherty, Linear Amplification by Nonlinear Components LINC and different classes of amplifiers, see Table 2) can profit from the advantageous material properties.

TABLE 2
Impact of GaN on power amplifier concepts.

Concept	**Si**	**GaN on SiC**
DPD	High thermal time constant Moderate bandwidth	Low thermal time constant Large bandwidth
Doherty	Low off-state impedance High output capacitance	High off-state impedance Low output capacitance
LINC	Large non-linear output capacitance	Small non-linear output capacitance
EER	Poor amplitude to phase modulation conversion Moderate bandwidth	Good amplitude to phase modulation conversion Large bandwidth
Class F Class E/G	Low f_T Moderate breakdown	High f_T High breakdown

The results from Figure 3 and Table 2 show that with respect to all important RF parameters GaN has the potential to outperform Si LDMOS for all current and future power amplifier concepts.

Reliability

More and more reliability data for GaN-based devices are published with improving results. Operating life tests are performed up to 1000 hours for both, DC-stress and RF-stress at high drain bias settings [8][9].

- Idss degradation (max. current stress) extrapolated to 20 years ~10% [8].
- RF-stress under P3dB conditions at high drain bias settings showed no degradation up to 1000 h [9].

Remaining technological challenges for GaN

Despite the encouraging reliability results there are still some technological issues to be solved hampering a quick market introduction of GaN technology for base station power amplifier applications:

- Current slump or RF dispersion,
- Reliability issues related to the piezo-electric doping and spontaneous polarization charges in the AlGaN/GaN system,
- Uniformity and consistency for substrate, epi layer and process technology,
- Thermal management of high power densities in conjunction with appropriate packaging technologies.

Given the significant progress made in GaN technology we estimate that the remaining technological challenges for GaN can be solved within a three years time frame.

KEY ISSUES FOR MARKET ENTRY

This paper has argued that for cellular base stations, GaN can be a dominant technology vs. currently available alternatives: providing better performance over all the important product specs. Indeed, it may emerge as a disruptive technology, allowing customers to significantly alter their own product architectures. However, as Figure 2 makes clear, the base station application dominates the RF power market. If the needs of this market cannot be met, it will be impossible to justify the industrial investment required to move from an exotic military technology and into the mainstream. To realize its potential, GaN must be able to meet certain hard market requirements regarding dual sourcing and cost.

Dual Sourcing

In the highly competitive base station market, customers have learned the discipline of insisting on multiple sources. From this strategy, they have reaped significant gains both in price and in stimulating innovation. In addition, dual sourcing provides security of supply in the case of serious interruption. Any new technology must meet this market requirement.

Cost

Even a superior technology must be cost competitive. Here GaN is facing a fast-moving target due to the high level of innovation in LDMOS. High volume applications provide a well-recognized path to cost reduction and process reliability (for example GaAs, which ramped up via the high-volume consumer market for cellular telephones). RF power markets however, represent low to medium volume infrastructure applications – with an entire world market on the order of tens of thousands of wafers, it is highly unlikely that the market will support more than 2-3 wafer fabs. These lower volumes create a special challenge to compete with the cost structure of established solutions like GaAs and Si LDMOS. Typically underrated, this lack of a high-volume "carrier" application will prove the most significant barrier to market adoption for GaN. To become viable, die yields need to be brought to levels above 80%, while substrate and epi costs need to come down by more than two-thirds. For substrates and epi, suppliers currently have roadmaps to meet these targets within the next 5-7 years. In order to be ready with acceptable die yields, suppliers need to go down the production learning curve in this timeframe.

The need for partnerships

The typical way to drive down costs in a new technology is to find a high volume application. This is the "learning curve" that enables suppliers to reduce yields, invest in better equipment, and improve their processes. From spark plugs to microwave ovens, much creativity has been spent searching for such an application for GaN. So far, unfortunately, no convincing case has been made.

A second approach involves pooling the learning that exists already, via a web of partnerships. Because the initial wide band gap research impetus was for defence applications, IP is currently scattered broadly across universities, research institutes, defence system houses, and semiconductor companies. System houses must recognize that their long-term competitive advantage does not lie at the semiconductor process level, and semiconductor companies must contribute RF, packaging, and production expertise. Industrial partnerships will facilitate the consolidation of IP, and allow the creation of a limited number of open foundries that can serve the needs of a variety of small to medium sized specialty applications. Otherwise, GaN will remain in the "technology of the future" and customers will be deprived of the benefits it can provide.

SUMMARY

Recent advances in wide band gap research give confidence that devices based on GaN technology can outperform incumbent Si LDMOS technology for the base station high power amplifier application. The remaining technical challenges can be resolved within a 3 years time frame. The base station power amplifier market is characterized by medium-sized volume and sustainable price erosion up to 20% p.a. In order to drive costs down this specific technology-market combination requires forming cooperative ways of working that will allow success in the marketplace as well.

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