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Good things come in small (high speed) packages.

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Abstract

This article discusses the pre-eminent importance of decisions regarding packaging technology for high speed functions realised in Gallium Arsenide. As these devices fulfil key functions in the commercial marketplace, the cost and manufacturability of the parts become as much of a deciding factor as the choice of device technology.

Introduction

Now that Gallium Arsenide ICs and devices are used in a wide variety of commercial applications, any 'novelty value' that might prove an attraction to this technology choice has completely disappeared, and the technology must sell itself on a pure cost/performance basis. As many of the applications move up to substantial volumes, the cost pressures become overriding, and the extent to which these are dominated by the choice of an appropriate packaging medium becomes key to the survival of a GaAs option against other contenders.

Decisions made early in a product life-cycle can easily become an embedded impediment to subsequent cost-reductions and thereby force a more fundamental re-evaluation of the technology choice that might well favour a more-advanced generation of Si technology.

The onus is on the GaAs designer to prepare for and enable the best possible (i.e.: the lowest cost and most manufacturable commensurate with required performance) packaging for the part, and 'small is beautiful' tends to be a key message to retain in this context.

Maturing of the basic GaAs technology capability

Five years ago I hosted a workshop for the IEEE GaAs IC Symposium [1], the focus of which was to highlight successful commercial applications of GaAs ICs, at a time when there was still heavy scepticism regarding the viability of the GaAs technology. The definition of *'successful commercial application'* was taken to mean that the parts were going into systems being sold in 'volume', where this ranged from supercomputer applications (a handful of machines per year) using VLSI digital GaAs chips, to Satellite TV receivers which were even then in the millions of units shipped. Of the cases discussed, several have held steady market growth, whilst some have experienced a significant downturn in demand, and others have enjoyed a major expansion, particularly in relation to the communications markets.

The only examples involving large digital GaAs ICs related to supercomputer applications (e.g.: Convex, Cray etc.) and both of these companies have seen depletion of their overall target market, essentially independent of the GaAs content of their products. In the case of the Convex C3800, which used a number of large (35-45,000 gates/chip) GaAs ICs, the application saw substitution of the GaAs parts in Si-like packages to do the job of Si arrays, only faster and for less power dissipation, resulting in an air-cooled machine of 2 Gigaflop capability. The Cray approach was pursuing more modest chip size but ultimate speed performance with 2ns clock speeds demonstrated for the CRAY-3, to be later halved in the CRAY-4 using larger GaAs chips and lower power enhancement-depletion technology. Unfortunately, the technical difficulties which plagued the CRAY-3, (and ultimately lead to the loss of investor confidence resulting in the bankruptcy of the company in 1995) related in large part to the ambitious packaging/interconnect approach selected for the whole machine. Total liquid immersion of several thousand MSI GaAs chips on densely packed motherboards involved flowing the inert coolant over the unprotected GaAs surfaces (which was not apparently a problem) as well as over the metal pins or pillars that formed the paths of high speed interconnect normal to the plane of the GaAs chips. The scale of this undertaking required very high reproducibility of the metal interconnect over huge numbers of connections, and proved to be more demanding than originally anticipated.

SSI digital GaAs has seen widespread application for multiplex/demultiplex functions in fibre-link systems from 600Mb/s to 2.4Gb/s, and although the volumes are not enormous, (several thousands of systems per year) a considerable improvement in reproducibility has built quite a steady reputation for these parts, in conjunction with many analogue functions (fibre preamps; laser drivers etc.) used in the same systems. Many of these parts were initiated as custom ASIC designs through PCM-defined foundry services, however as volume developed most were later re-designed to more closely align the functional requirements with the updated process spreads of the foundry capability in order to ensure the necessary yields for a marketable device.

By far the most spectacular growth has been in GaAs MMICs for microwave applications, both in wireless infrastructure (e.g.; units for cellular radio basestations) and even for the very large volumes involved in supply of hand-held terminals. This has generated powerful driving forces to tighten up the yields and reproducibility of the GaAs process lines, and in particular to minimise the overall cost of the finished part, much of which is dominated directly or indirectly by the packaging of that part. Recent market predictions suggest that by the end of this decade the market for GaAs ICs and semiconductors will exceed $2 billion [2], and that the expansion will be heavily dominated by wireless and cellular communications markets.

Implications of packaging choices

All too often the key decisions concerning interfacing of a new high speed IC to the outside world are taken too late in the design process, and severely compromise either the application or its future evolution. The packaging solution should ideally account for three key aspects of the device in its application:

1) Mechanical (including thermal, reliability, board placement/automated handling);

2) Electrical (impedance matching, conformance to power supplies, testability);

3) Cost (initial cost of the finished part, and scope for reductions as market grows).

Experience shows that a number of issues that become apparent in the manufacture of the packaged part could really have been minimised by their anticipation at earlier stages of the design process.

A recent example that has affected several parts of the GaAs industry has been the reliability issue associated with Pt- or Pd-gate electrodes on GaAs ICs enclosed in Kovar packages. The interaction of hydrogen (outgassing from the Kovar) with the structure of the FET gate electrode can provoke premature severe variation of device characteristics. Many of the highest volume parts have not experienced this phenomenon since plastic packages were being used, and in addition the effect does not occur in self-aligned gate technologies.

The electrical considerations clearly account for much of the performance advantage that usually forms the principal justification for using the GaAs technology, and these impart a major obligation to preserve as much as possible of that advantage, but with sufficient margin to ensure that the part may be tested automatically at high volumes. Parts that must be tested at various stages (especially for multi-chip modules) have to expect some guard-banding to accommodate the spreads involved in repeated tests of the same parameter. At very high volumes it is worthwhile to review the whole design approach in order to ensure 'known-good-die' for delivery to final assembly.

Most of the shortfall of the previous two categories becomes manifest in the cost. Here the relevant details are frequently less the first order cost of the GaAs die, but rather are more inherent in the cost of the package, its assembly and testing, and the cost of waste in the form of rejected finished parts. As volume demands increase, it is also important for the GaAs solution to be able to offer some relief with economies of scale, however the early self-satisfaction derived from pointing out that the package aspects dominate turns to a disadvantage with the realisation that *significant* GaAs savings are necessary to impact the final result.

Nortel examples of high speed GaAs applications

A. Functions for fibre optic links

Since 1989 Northern Telecom has been using a range of GaAs ICs for key functions in high bit-rate fibre-optic links systems running at rates from 150Mb/s to 10Gb/s, as well as for microwave radio applications from 400MHz to 8GHz. As discussed in previous papers [3], some of the particular considerations of manufacture of 2.4Gb/s systems demanded attention to key package-related aspects. In order to correctly terminate the high speed I/O lines to the 2.4Gb/s digital chips, a special package was developed, where the necessary passive components and diodes were fabricated onto a low-cost Si subcarrier onto which the GaAs chip was mounted within the multi-layer ceramic package. This provided much more effective termination than if the passives had been on the board outside the package, and meant that each part was tested and then assembled together with the termination configuration intact. At the time, this solution was more cost-effective than incurring extra GaAs real estate by having the passives on-chip, however recent progress in wafer costs and other package alternatives should enable a simplification of the scenario.

For analogue circuits such as the 2.4Gb/s laser driver, a commercial packaged part was used, although a subsequent study illustrated that a bare-die driver IC mounted onto an optimally terminated hybrid substrate results in a considerable improvement in the driven waveform, with noticeably less rise-time distortion due to parasitics. The bare-die approach also offers a cost-savings over the packaged commercial part.

Many of the considerations, especially those relating to optimised functional partitioning across package boundaries were then applied to the development of a similar set of functions for the next generation OC192 Fibre transmission system at 10Gb/s. Key electronics functions at this data rate are made using Heterojunction Bipolar Transistor technology, and following error-free system demonstrations in September 1995, these parts are now in the early stages of the manufacturing ramp.

B. Microwave Modules for wireless/cellular systems

A recent growth of Nortel Wireless business has resulted in a substantial supply ramp of 900MHz and 400MHz multi-chip modules that incorporate GaAs MMICs, SAW devices and the associated passives and Si control chips. These units are delivered in sets of 6 matching functions, and are used in cellular basestations that offer interfacing of either digital or analogue subscribers into the rest of the Nortel transmission network. Volumes required of these parts involve more than 100,000 GaAs ICs per year, most of which are fabricated internally. Already at this type of volume it is necessary to examine all means of optimising costs, in particular those associated with package parts, package assembly and testing, and especially the level of integration of functionality involved and its advantages relative to the constraints of sourcing options. As with any product of this nature, for a given integration scenario there is a relationship between the cost sensitivity to volume and to yield, and at some point in the volume growth, the yield of the parts becomes so predictable that their integration into a single testable unit no longer offers a major advantage.

A consideration common to the examples described above is that the choice of technology is dictated only by which technology offers the necessary performance margin at the lowest cost. In several instances, a progressive evolution from GaAs to Si is to be expected, and indeed a far-sighted approach to the packaging-related decisions would anticipate these changes and endeavour to avoid 'building-in' obstacles to such a potential cost-reduction. Typically, such obstacles can include:

- board-level power supplies only allow one technology;
- package footprint dictates expensive part;
- technology change requires board-level redesign, with associated extra overhead for system re-verification etc.

It is predictable that, as a product matures and yields improve, then the level of pre-final testing can be reduced, with associated cost advantages. However in some cases the functional partitioning is such that yields of one part mature much later than the others, and still require intermediate testing in order to minimise the waste from rejection of finished assemblies.

Examples of high volume industry GaAs applications

The following examples illustrate commercially-motivated packaging choices for GaAs-based products currently in the commercial marketplace, and ranging from 800MHz to 28GHz.

A. TriQuint GaAs ICs for cellular phones

With many years' experience as one of the first GaAs foundry organisations, TRIQUINT has a respected position as a supplier of high speed GaAs ICs into the communications industry. In particular for the cellular phone market, they have developed customised ASICs for the Japanese 'handy-phone' as well as standard ASICs (such as the TQ9203 low-current RFIC downconverter) used in cellular and cordless phones at 800-1000MHz. Because of the very cost-sensitive nature of the consumer handset market, the manufacture of these parts usually involves off-shore packaging in very low-cost plastic packages. For example a 2.5mm square chip will be shipped in a 14-lead plastic package only 3.8 x 8.6mm, and at the high volumes involved (several million parts shipped in 1995) this part will typically cost around $1, of which less than half the cost is due to the GaAs chip itself. In spite of the low cost and small size, this part provides a multifunction RF front-end for high dynamic-range cellular standards, with low-current consumption from a single 5V supply. Essential to maintaining quality at low cost is the capability developed at TriQuint for high speed testing at high volumes, for which custom-built equipment is still required.

In this type of application, the low contribution of the actual GaAs cost makes it difficult for a Si substitution to have much impact, even at sub-1GHz frequencies.

B. HP internally-matched 6GHz Power FET modules

Back in 1988 [4], HEWLETT-PACKARD described how their internal GaAs capability had enabled graceful introduction of GaAs ICs into their high speed test instrumentation, and how this was eminently justifiable even at low volumes if the performance or integration advantage was significant. Subsequent expansion of their capability brought additional market opportunities, and now sees HP involved in substantially higher GaAs volume supply into wireless and satellite links and terminals.

A recent new product that finds application in infrastructure equipment (such as satellite, mobile, base-stations, point-point longhaul and wireless local loop systems) is a range of power modules using single or multiple-chip GaAs power FETs, together with 50 ohm matching circuitry on low-loss thin-film substrates. This approach is more cost-effective than housing the matching circuitry on costly GaAs real-estate, and allows individual power devices to be selected and optimally tuned for in-package performance prior to lid-seal. For the volumes involved (around 10,000 units annually) the equipment needed to totally automate the assembly and testing would not be justifiable.

In contrast to the previous example, the power requirements and tuning interventions required for this product would not allow a plastic package solution, and an industry-compatible copper/ceramic package is used to ensure the necessary environmental robustness. Depending on the power output required (and therefore the number of power chips needed) the price of this part ranges from around $200 for a 4W unit to $1200 for units capable of 32W over the band 5.9-6.5GHz. In this case the GaAs forms less than one-third of the total part cost, and assembly, testing and package materials dominate the cost breakdown.

Nevertheless, the IM5964-xL series provides efficient power amplification functions for C-band applications, especially where high linearity may be required for handling digital signals.

C. Anadigics 12.75GHz DBS downconverter IC

In the years since the 1991 workshop described in [1], ANADIGICS have supplied millions of chips for Direct-broadcast satellite receivers. In response to the increasing pressure to optimise the cost of these parts, Anadigics have developed a low-cost plastic package solution that is compatible with the 12.75GHz operation requirements.

The AKD2575 part targets Ku-band downconverter requirements for the France Telecom market, and offers impressive performance characteristics within the target price of a few dollars. Typically, for this part the package contribution will be less than half the total part cost, as a result of high-volume off-shore assembly services. Design effort was focussed on minimising the GaAs chip size, to fit in a 12-pin package with a body size around 4.5mm square. Since plastic package costs are highly dependant on the number of leads, chip and system designers work together to minimise the number of external chip connections needed to ensure required operation and testability. This part is currently being supplied at volumes of several million chips/year.

D. M/A-COM 28GHz LNA on glass MIC

As frequency requirements move up into the higher bands, so the packaging and testing specifications become more demanding, and suppliers are pursuing alternate ways of meeting those needs. M/A-COM have pioneered a novel approach using a glass-on-silicon substrate configuration to meet the demands of 28GHz where performance limitations rule out plastic packaging, but where the manually-dominated processes of 'chip-and-wire-assembly' prove inappropriate to the cost constraints of medium/high volume markets.

'Local Multipoint Distribution Systems' provide redistribution of satellite broadcasts integrated with local programming, transmitted within a limited radius at 28GHz to hotel, condominium or individual dwelling subscribers. Tens of thousands of these systems are already in operation on Long Island, New York, and M/A-COM have developed a low-cost antenna and down-converter unit that will retail to the customer for about $250. Less than 10% of this cost can account for the LNA portion, calling for significant innovation in the packaging technology.

At these frequencies the reproducibility of MMICs does not yet offer the desired performance, however discrete pHEMT transistors and passive MICs can be successfully integrated together using a low-loss borosilicate glass layer deposited onto high conductivity Si substrates. The Si/glass wafer can be processed using standard semiconductor fab techniques, allowing 1µm pattern definition for interconnects and inductors, as well as thin-film MIM capacitors and even Si pedestals for conventional or flip-chip mounting of discrete chips or MMICs [5]. The wafer assembly can also be subjected to automated DC and RF testing prior to assembly of the higher cost components.

The LMDS receiver is a 150mm square unit providing 1GHz bandwidth, 15dB receiver gain with 4.5dB noise figure at 28GHz, and will be running at about 100,000 units/year.

Cost/design considerations

As discussed in the course of the preceding examples, the overall cost of the unit represents a careful marriage accounting for the best capabilities of the contributing technologies. However the ideal solution may not yet have been developed, and it is important to anticipate the viability of a given solution as and when a dependant technology improves, for example:

i) Si capability becomes able to do the key active functions satisfied by GaAs MMICs - is a re-partitioning of on-chip inductors to another substrate now appropriate?, or

ii) GaAs (or pHEMT) MMICs become capable of yielding high frequency parts that previously required discrete solutions - can a substitution be done to extend the life of the part without re-tooling of other subsystem components?

Conclusions

The developer and supplier of a forefront technology such as GaAs ICs can not be content with merely perfecting that technology in isolation, but must address the associated packaging, testing and general manufacturability issues to assess the overall potential of that technology for application to product.

Chip size, package size, and assembly approach can so dominate the cost of a finished part that the active GaAs contribution becomes relatively minor, and yet new high volume markets are now being satisfied on several fronts with a technology that only a few years ago was still perceived as marginal.

The challenge now is to maximise the learning from the high volume GaAs markets and to apply this to drive yields up and costs down in anticipation of further competition from other technologies, and increased cost pressure for market survival.

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