III-V Technologies: A Growth Industry for the 21st Century

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ABSTRACT

The role that III-V compound semiconductors will play in the early years of the 21st century will be subject to frequent change. This is not only because of the expanding capabilities of the III-Vs but also because of the advances in Silicon technologies, particularly Silicon-Germanium HBTs. It is possible to point out more than a few applications that will remain growth areas for the III-Vs. This paper will not dwell on those applications, which are related to LEDS and Lasers or on Millimeter Wave amplifiers, but will instead focus on those applications where the future is more subject to revision. These are the high speed applications of HBTs. The competition will be a boost to development of III-V HBTs because innovations and improvements will be implemented as a result.

INTRODUCTION

The overall state of the III-V technologies is quite robust. The current and near future markets for III-V compound semiconductor devices is described in Fig.1, which was based on data from Dataquest [1]. This bar chart shows clearly that the bulk of the III-V business volume is applications in which emitting photons is the primary function. Light Emitting Diodes are the largest segment and they constitute a solidly commercial application. With the arrival of the Gallium Nitride (LED), which provides a bright blue, or green, all the primary colors are provided. Recent developments have added a phosphor to the blue LED that converts the blue light to a bright white light. LEDS and Lasers and Other Opto, which includes primarily solar cells and detector arrays, constitute a secure 74% of the market. The Microwave/Analog and Digital applications are 27% of the 1997 market but drop to 26% while still growing in 2002. These latter applications face stiff competition from the improving Silicon devices.

The $1.5B Microwave/Analog and Digital business of Fig.1 is primarily in communication. The biggest application segment is power amplifiers for the cellular phone handsets. In that arena, cost is the all-important goal. That is not always true as, for handsets in particular, the efficiency of power amplifiers is equally important. In addition to power amplifiers below 2 GHz, the III-V technologies supply very high speed digital circuits such as multiplexer/demultiplexer ICs and digital switching circuits to the fiber optics applications. This constitutes about 30% of the $1.5B. Less that 10% is microwave/millimeter wave power and low noise amplifiers at frequencies above 10 GHz, although that will change with the growth of mmWave broad band distribution systems in Local Microwave Distribution Systems (LMDS). LMDS is a favored method for getting broad band data to the home from the nearest fiber terminal[2]. Such systems are growing in Europe, Japan and (less rapidly) in the USA. Table 1 shows the different III-V high speed transistors and their likely applications in the coming years. The current high volume applications are shown in bold print.

INFLUENCE OF MATERIALS

The Arsenide, Phosphide and Antimonide compounds of the column III elements provide direct band gap all the way from infrared through green. The Nitrides of Gallium and Aluminum provide direct band gap green to purple. The LEDs and Lasers that result from this circumstance will provide efficiently (~50%) for applications that will rise to a value over 6.8 B$ in 2002. The only alternative for outdoor display applications may come from LEDs fabricated using Organic semiconductors (OLEDS). As of 1999 OLEDS provide lower luminous efficiency (less than 25 Lumens/Watt for green) and a lower life expectation (~ 10e3 hours) than the III-V LEDs (over 30 Lumens per Watt, for amber through blue and over 10e6 hours)[3].

A most significant aspect of the III-V materials system is the number of lattice matches that exist between III-V compounds of differing band gap. The most well-known is the Aluminum Arsenide-Gallium Arsenide close match of lattice constant that gave the first lasers and heterojunction transistors. Others are (a) GaN to AlN, (b) GaP to AlP, (c) Si to GaP, (d) GaSb to AlSb . Then there are the ternary compounds that can be matched to InP: InAlAs, InGaAs, GaAsSb, or the ternaries matched to GaAs : InGaP. This richness of band gap engineering choices has led to the wide variety of optical and microwave/ millimeter wave devices that the III-V technology offers. The full extent of all the options from the III-Vs has not yet been fully explored. The f_T (current Gain bandwidth in GHz) and f_{MAX} (Maximum frequency for power gain in GHz) of the III-V transistors exceeded those of any Silicon transistor until advent of the Silicon-Germanium HBT.

The Silicon-Germanium HBT device is a double heterojunction bipolar Transistor (DHBT) achieved by growing the base layer from an alloy of Silicon and Germanium. Silicon and Germanium are not lattice matched and thus there is a limit on the amount of Germanium that can be included in the base layer and on the thickness of that base. A 10 % mole fraction of Ge has produced sufficient heterojunction at both sides of the base to raise base doping and thus imitate a key aspect of the GaAs HBT. Base Resistance is still generally above 5000 ohms per square compared to the 200 ohms per square for GaAs. Higher Germanium contents have been used with consequently lower base resistance but these devices remain in doubt because of stability problems. The Current Gain Bandwidth f_T and the maximum frequency for power gain f_{MAX} of SiGe DHBT are compared with the GaAs and InP HBTs in Fig.2. A key aspect of Fig. 2 is that, with a thin base (~400 Angstroms) the SiGe HBT provides f_T values comparable to GaAs HBT and a f_{MAX} that is quite adequate for applications up to 10 GHz. Fig.2 illustrates that the contribution of the heterojunction is to provide a higher f_{MAX} while using a thinner base layer. The f_T *Vb product of the SiGe HBT is a less than one third that of the GaAs HBT[4].

IMPACT OF SiGe HBT

SiGe HBTs achieve their peak f_T at high current densities (>10e5 A/cm^2) but very low currents primarily because the emitter sizes are very small by III-V HBT standards. Devices reported with high f_T over 70 GHz have an emitter width only 0.4 micron. Reduced dimensions mean low power and that, very often, is of prime importance.

The impact on the III-V market will be that many GaAs IC applications may be taken over by SiGe. This is most probable for those applications that call for high speed but low voltage swing such as digital ICs in the Fiber–Optics communication systems which now reach for 10 Gb/s rates (OC192). The compatibility of SiGe with the BiCMOS process is a significant aid for this event. Systems up to 2.5 GB/s are being designed to use one–chip solutions employing BiCMOS SiGe devices. The OC192 systems are being studied for the same possibilities

In radio systems the first decade of the new century will see the coming of the "software radio". This is the system where the signals are converted to the digital domain as close to the antenna as possible and the system function can be configured by software programming. This will call for the development of Analog to Digital Converters (ADCs) and Digital to Analog Converters (DACs) with 0.1 to 1.0 Gs rates and 10 to 14 bits resolution. These will use over-sampling methods (Σ-Δ), and f_T values of over 75 GHz will be needed. There will also be requirements for Nyquist ADC chips providing 3 Gs rates and 8 to 10 bits resolution. They require high f_T, large voltage swing, linearity and low parasitics. SiGe is a poor candidate to perform these tasks because of low breakdown and limited dynamic range of the SiGe HBT. However, many of the sub 3 GHz RF circuits, with the exception of the power amplifiers, likely will be converted to SiGe. Again the motivation for the change is that lower power operation can be achieved with the SiGe device.

DEVELOPMENT OF THE III-Vs

The GaAs/InP HBT technologies will have to adapt to meet the rising expectations of performance in the decade ahead. III-V technologies have more performance to offer. This extra performance can be extracted by improving device design through scaling and measures aimed at reducing collector capacitance.

Scaling

A striking fact concerning III-V HBT devices is that there has been so little emphasis on lateral scaling. Scaling is the reduction of device feature sizes. Vertical scaling would involve layer design changes. Lateral scaling is exemplified by the reduction of emitter widths. SiGe standard widths must be no more than 0.5 µm because of the very high base resistance. GaAs standard emitter widths are generally about 2.0 µm. Reducing lateral dimensions at the emitter and collector will reduce extrinsic capacitances and resistances, thus raising f_T and f_{MAX}.

To this time III-V HBT offered performance so far ahead of competition that scaling was not attempted. Additionally, the reliability of HBT depends on the ledge of the wide band gap material that covers the intrinsic base–emitter junction edge. Shrinking the emitter width did not pay off until the availability of InGaP as a substitute for the AlGaAs emitter material. With the new emitter material the virtual ledge length could be reduced from 1 µm to below 0.3µm, and very small III-V HBTs retaining very high current gain became possible. In our laboratory Zampardi has demonstrated [5] III-V HBT with 0.8 µm emitter width. Fig.3 illustrates how a scaled (reduced dimension) III-V HBT can offer the same choice as the SiGe, i.e., higher f_T or unchanged f_T but at lower power using much smaller devices.

Measures to Reduce Base to Collector Capacitance

To further lift the figures of merit for III-V HBTs (InP), Rodwell at UCSB has reduced the Cbc by removing the original substrate and the sub-collector N+ layer[6,7]. In so doing they have also solved one of the most crucial problems for the HBTs : that of maintaining low thermal resistance and temperature uniformity in arrays of devices such as a 2500 transistor ADC. The HBTs are mounted collector-up on Copper heat sinks that are plated onto the emitter side of the wafer subsequent to emitter and base formation and before removal of the original substrate. The collectors are formed by a Schottky diode stripe which avoids all the usual extrinsic capacitance. The base-collector area has been reduced to approximately the base emitter intrinsic area. This reduction of Cbc is very effective in raising the f_{MAX} to unprecedented frequency. The figures of merit achieved by this group using 0.4 μm by 6 μm emitters and collectors (scaling) has exceeded 200 GHz for f_T and 1000GHz for f_{MAX} at a current density of 2.5e5 A/cm^2. For a much lesser current and lower power the same performance as before (f_T ~100 GHz) would be available.

Cost Reductions

Current conventional wisdom holds that III-Vs will always be markedly more expensive than Silicon. This could be changing. Current costs at a SiGe foundry run to about 22 to 25 cents per square millimeter. Fig.5 shows the really encouraging news that with an increase in GaAs wafer size to 150 mm, the cost of processing ion implanted MESFETS is predicted (by Raytheon [8]) to fall to less than 10 cents, and the cost of processing epitaxially based PHEMT and HBT to fall to less than 30 cents. This very good news confirms that advantages of large wafer size brought to Silicon will also apply to III-Vs.

Conclusions

As we enter the year 2000 the III-V technologies have been established as a $9 B industry – no longer the device of the future. Seventy-five percent of the business is in the Opto-electronics area for which the materials properties of the III-Vs make them so wonderfully suited. That business will continue to grow, reaching to over 7 $B by 2003. The applications of III-Vs microwave/mmWave circuits above 10 GHz is a key aspect to opening the rebirth of radio relay as a carrier of broad bandwidths to the home. This radio broadband distribution industry will grow and with it the applications of PHEMT from both GaAs and InP to frequencies at first in the sub 50 GHz. Eventually applications above 50 GHz will become numerous, possibly led by development of low-cost auto radars to provide safer highways.

The most interesting developments will concern the technologies used for very high speed digital circuits such as ADCs and DACs, which will populate the software radio or the high speed digital that will form the backbone of the fiber optic information highway. Here there is stiff competition from SiGe. However, III-Vs will greatly improve to levels well beyond their present perceived limits. This will happen through such measures as scaling for lowering power without sacrificing speed and by lowering costs through the use of larger fabrication centers working on wafers 150 mm in diameter.

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Table1 High Speed GaAs and InP transistors

DEVICE	APPLICATION
MESFET	Lower frequency LNA , **Digital ICs for Fiber Optics**, Sub 10 GHz Power Amplifiers
PHEMT GaAs & InP	LNAs, Power Amplifiers , VCOs MMICs at 10 GHz and above Millimeter wave LNAs, Millimeter wave PAs
HBT GaAs	**Cellular Power Amlifiers** up to 5 GHz, High Speed Digital circuits, ADC & DACs, DDS , Power Amplifiers
HBT InP	Fiber Optic ICs, very high speed DDS, ADC, DAC, Power Amplifiers

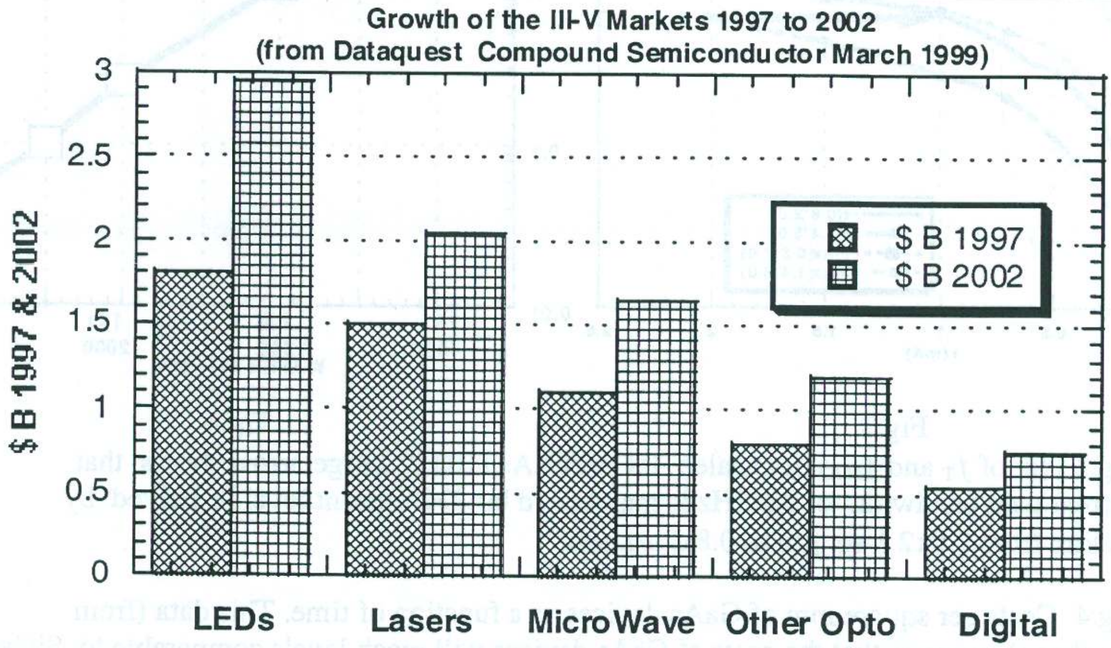


Fig.1 Projected growth of the total III-V market place 1997 to 2002

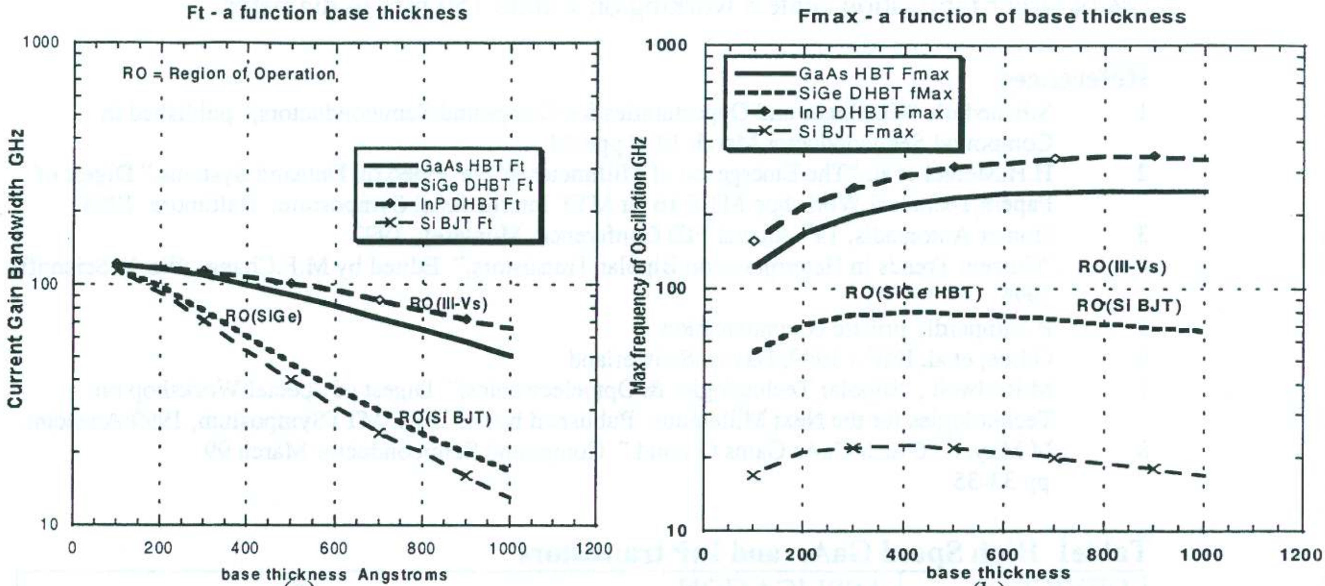
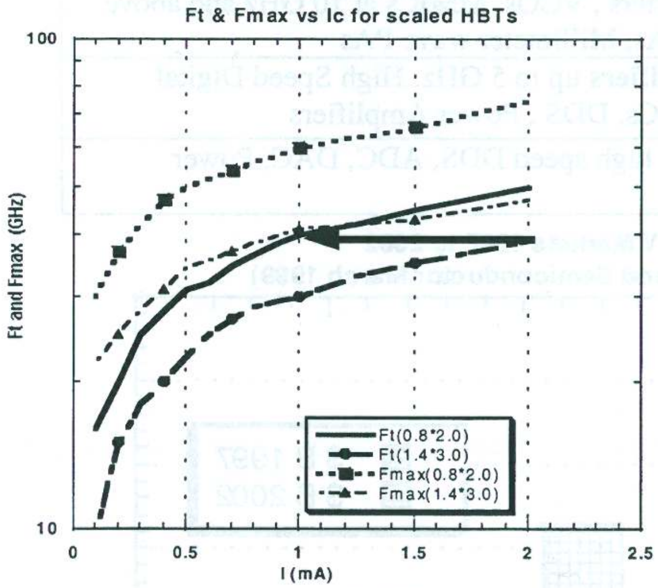


Figure 2 A comparison of the Figures of Merit (a) f_t and (b)f_{max} for the Silicon , Silicon-Germanium and III-V systems GaAs and InP. Independent variable is base width



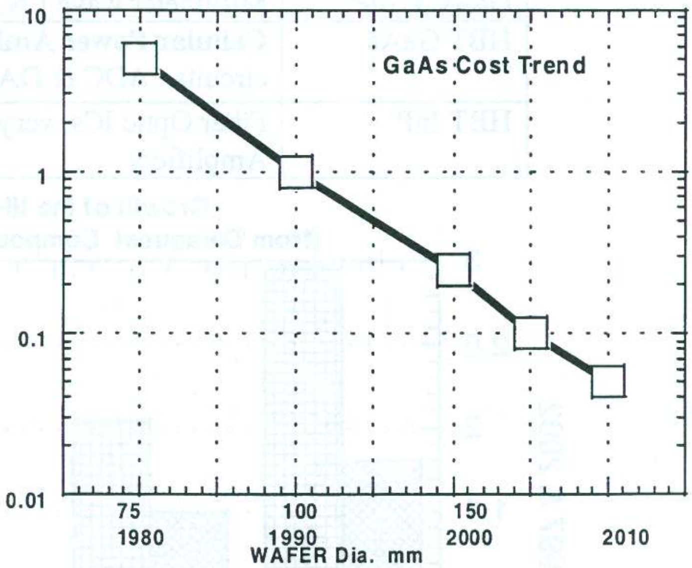


Fig.3

Fig.4

Fig.3 Plot of f_T and f_{MAX} for scaled InGaP/GaAs HBTs. Large arrow shows that current gain bandwidth of 38 GHz is maintained but DC current level is halved by scaling from 2.0x2.1 sq. μm to 0.8x2 sq. μm

Fig.4 Costs per square mm of GaAs devices as a function of time. This data (from Raytheon) suggests that the costs of GaAs devices will reach levels comparable to SiGe BiCMOS foundry costs in the early years of the next decade.