The Future of Compound Semiconductors

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Abstract — The compound semiconductor industry, which showed great promise in the 90's, struggled with the disappointment of over supply and commoditization in the "post bubble" period and lost share to improving performance of silicon solutions. Our industry is now re-emerging as a critical technology for achieving the promise of ubiquitous wireless connectivity.

While MESFET technology dominated industry volume ten years ago, it now plays an inferior role to HBT and pHEMT. New technologies, such as E/D pHEMT and BiHEMT, are emerging as the future workhorses. These technologies provide greater functionality and performance than their predecessors. At the same time, GaN technology for RF applications has moved from experimental to early commercialization.

As our industry matures we are seeing changes in how compound semiconductors are taken to market. High performance packaging is making inroads where MMIC die have been the historical choice. Low-cost modules have become the preferred solution for high volume RF applications. The overall availability of compound semiconductors is consolidating as the supply and demand ratio comes back into balance. It is an exciting time for compound semiconductor development.

Index Terms — GaAs, InP, GaN, RF, WiFi, WCDMA. Microwave, Cellular

I. Introduction

The "good old days" may be back again. From 2001 through 2005 the compound semiconductor industry, was burdened with excess capacity and commoditized products. Prior to 2001 and at the peak of the bubble period compound semiconductor technologies were in high demand and represented one of the best technology investments available. Investment in capacity had reached a staggering level. The market capitalization of the major compound semiconductor companies rose meteorically in 2000 only to fall at a similar rate post bubble.

What will it take to turn the tide? The sea-change may already have started. Several major trends are underway. First, with the transition of communications from voice to the combination of voice and data the GaAs content in most new phones is more than doubling. A typical GSM phone has approximately one to one and a half dollars of GaAs content. Due to the multi-mode and multi-band nature of many next generation (3G) phones the content has increased to five to six dollars. The overall complexity of the RF section of most handsets has increased significantly as well. This added complexity is reversing the commoditization trend of compound semiconductors thus bringing value back into RF products.

The promise of large volume production that fueled the capacity overinvestment during the 1990s has finally reached a balance. Utilization rates of most of the major manufacturers have reached levels between 75% and 100%. Capacity is being added again, this time in a thoughtful and controlled manner. Approximately 50% of the worldwide equipment capacity is managed by three major suppliers.

The question now is: has the tide turned? What is the future for our industry and what are the keys to making the future a success? There are many positive trends in the overall industry but innovation is central to them all. Innovation remains critical to the success of our industry. This paper will explore some of the current trends in technology and highlight areas where innovation can increase momentum.

Compound semiconductors include a wide variety of materials, some of the most common being GaAs, AlGaAs, InGaP, InP, SiC, and GaN. They exist in the marketplace because of the unique benefits their material properties offer. GaAs and its ternary derivatives represent the largest production volume of devices within the compound semiconductor industry. Fig 1 displays the Energy gap (E_g) and cutoff wavelengths (λ) of a variety of semiconductor materials.

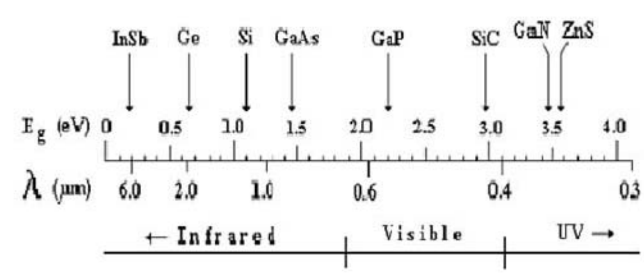

Fig 1 Semiconductor Properties

The large unit volume cellular handset market is the major driver of GaAs manufacturing capacity. The compound semiconductor market, at approximately $3.0 billion, represents only about one percent of a silicon dominated semiconductor market.

Silicon is a cost effective material with adequate performance characteristics that can be produced nearly defect free in very high volume at relatively low cost. Silicon dioxide is an excellent insulator and is easily incorporated into the manufacturing process.

GaAs devices, as compared to silicon, offer advantages in the following areas:

- Bandgap & breakdown field
- Saturation velocity
- Electron mobility
- Semi-insulating substrate

The higher bandgap and breakdown fields of GaAs are compatible with higher supply voltages and higher breakdown voltage than silicon for a given set of feature sizes. This translates into improved output power density and efficiency. A higher saturation velocity gives GaAs an advantage with regard to F_t, F_{max}, and channel current for similar feature sizes. This translates to higher gain, higher available current swing, higher output power, and better noise figure. High electron mobility, about five times greater than silicon, inherently results in lower parasitic resistance improving output power, efficiency and noise figure. The semi-insulating substrate is one of the biggest advantages of GaAs for RF circuits verses the conductive substrate of silicon. On silicon, losses from circuit interconnects and passive devices are increased significantly as compared to GaAs. Passive integration and loss-sensitive design are critical to RF circuits. Silicon has higher thermal conductivity and lower manufacturing cost, two advantages over compound semiconductor devices.

III. CURRENT MARKET

After the introduction of cellular phones in the early 1980s, portable communications became the largest market for GaAs technology. The GaAs market is currently over $3.0 billion and growing to exceed $5.0 billion by 2011 as forecasted by Strategy Analytics [1]. Leading suppliers, including captive, merchant and foundry supply, are shown in Fig 2.

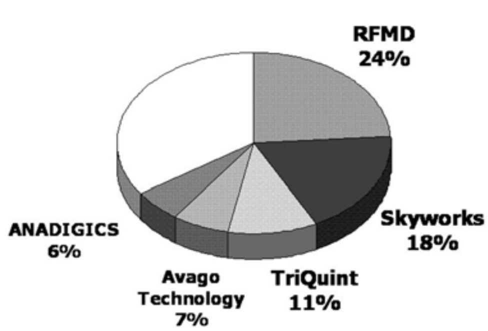

Fig 2 – 2006 GaAs Market [1]

Personal voice and data applications are seen to represent approximately 70% of that market.

IV. CELLULAR PHONES

Since the 1990s, cellular phones have become smaller, less expensive, thinner, and have increased in functionality. Semiconductor integration of more features, lower cost, and improved performance has enabled the success of cell phones. GaAs technologies, starting with MESFET and migrating to HBT and pHEMT devices, have found a solid home in the RF section of the cell phone as the best technology to maximize performance and battery life.

Phones are becoming more complex. New generations incorporate multi-mode (2.5G and 3G) and multi-band (800MHz through 2.6GHz) functionality. This increased complexity creates a demand multiplier for GaAs technologies. A GSM or CDMA 2000 phone has a relatively simple power amplifier module. The module, which is typically laminate based, may contain one or more power amplifier die, several surface-mount passive device components, and for GSM, a controller IC, typically designed on CMOS or SiGe. A simple stand-alone PA represents $0.35 - $0.80 of content in a phone, depending upon the standard (Fig 3).

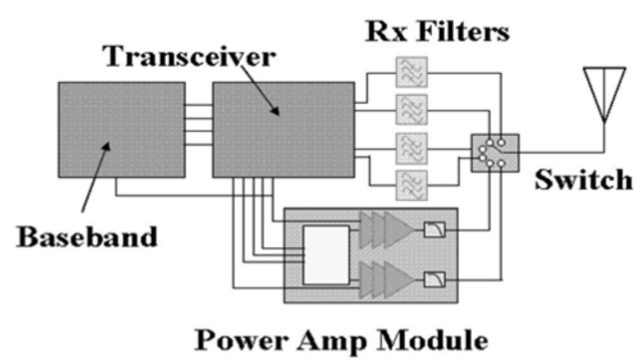

Fig 3 – GSM/GPRS/EDGE Phone

Current design of cellular phone RF sections is moving to higher integration modules, where RF suppliers design more of the front-end functionality into a single package. In addition, the introduction of WCDMA (3G) for mobile broadband access forces a multi-mode design. To be compatible with the ubiquitous GSM/GPRS/EDGE networks around the world as well as the expanding footprint for WCDMA, both RF front ends must be designed into the handset. This presents a mechanical challenge and a complex RF design challenge. Most cellular phone manufacturers have looked to the major compound semiconductor suppliers to provide a complete solution in highly integrated modules (Fig. 4). The example shown represents a seven band, multi mode handset. This includes a quad band GSM/GPRS/EDGE transmit module (2.5G) and three transmit modules to cover bands for WCDMA (3G).

These high-end smart phones will likely also include Class 1 Bluetooth for extended range and WiFi and/or WiMax capability for added flexibility. The baseband and transceiver functions integrate to a single chip radio. The trend has relative value of the RF section in the handset increasing as compared to the silicon content.

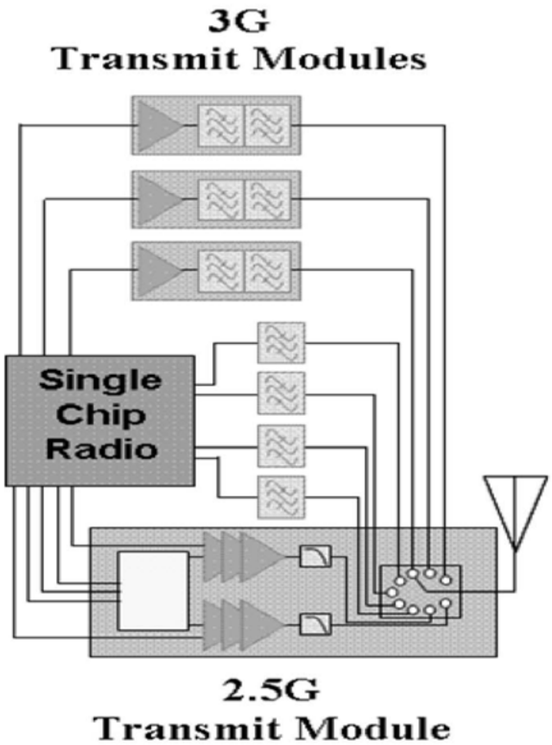

Fig 4 – GSM/GPRS/EDGE/WCDMA Phone

Phone manufacturers are eager for innovation to keep their products shrinking in size and part count. In the RF section, multiple technologies are needed that don't lend themselves to monolithic integration. This drives the need for a module solution. On the receive side of the RF section, the LNA and mixer have been integrated into the transceiver. Mixed signal CMOS technology performance has improved sufficiently to meet the performance requirements for these functions. Direct conversion designs have removed the need for intermediate frequency (IF) filters previously used in super-heterodyne solutions. RF-receive bandpass filters are still typically required. Current 3G design incorporates Tx filters as well but improved duplexer design may eventually displace the stand alone Tx filter. The Rx filters are migrating to integrated filter bank modules or being integrated into a receive module with the transceiver.

The transmit side of the RF section is fertile ground for compound semiconductors. Transmit modules, combining much of the front end content, are displacing discrete solutions and now represent 49% of the overall handset RF demand. A GSM/GPRS/EDGE phone incorporates an extremely fast and very low-loss transmit/receive switch to perform the duplexing function. The phone is either in a transmit mode or a receive mode but never both at the same time. This Rx/Tx switch function was traditionally served by PIN (P-type Intrinsic N-type) diodes, but with the growing dominance of quad-band and multi-band phones to cover the licensed frequency spectrums around the globe, the pHEMT switch has emerged as the low loss, low current-drain solution. Integrating this switch function with the decoding intelligence required, the Tx filters, and the HBT power amplifiers provides a complete transmit solution. TriQuint Semiconductor is a leader in this form factor with a 6 mm x 6 mm highly integrated solution (Fig. 5).

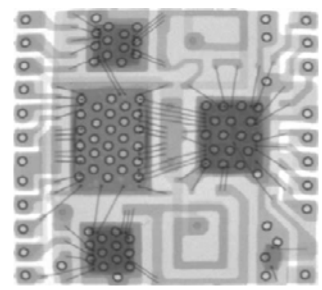

Fig 5 – X-ray of a TriQuint Semiconductor 6 mm x 6 mm Transmit Module (TQMxx4002)

V. WIFI - WIMAX

WiFi has become one of the larger market opportunities for GaAs. Hot spots are available in hotels, coffee shops, and airports. Private enterprise and local municipalities have invested in public access networks. In some cases the networks are fee-based while others are either designed for free public access, supported by advertising, or are *ad hoc* networks sponsored by advocacy groups.

The WiFi market has developed quickly from single band to dual band solutions. As the market moved from 2.4 GHz to dual band 2.4 GHz / 5 GHz, GaAs power amplifiers began displacing silicon or silicon germanium solutions. Just as in the cellular phone industry, the inherent properties of GaAs enabled better performance in RF.

The RF section in WiFi is following the same path as cellular. Early solutions were based on discrete components while contemporary solutions are migrating to modules. WiFi also has a standards change that will drive new design architectures. The standard known as 802.11n or MultipleInput-Multiple-Output (MIMO) creates the opportunity to double or triple the GaAs content per unit. The concept behind MIMO is to have two or three RF data paths in parallel, working together. The advantages include increased data transfer rates and more reliable configurations of dedicated bandwidth for sensitive applications.

Figure 6 is an example of a highly integrated TriQuint design for an 802.11n solution. The design incorporates LNA, switch, and PA monolithically. The interconnect used is a copper stud bump as opposed to the standard wirebond.

Copper bumps offer several design advantages including lower cost, smaller size, improved thermal transfer, and decreased manufacturing variation. Figure 7 is a photograph of the device "flipped" and incorporated into a 6mm x 8mm laminate module with a diplexer and several chip capacitors. MIMO will enable data intensive applications, such as high quality video, to be distributed throughout the home with high resistance to interference or disruption.

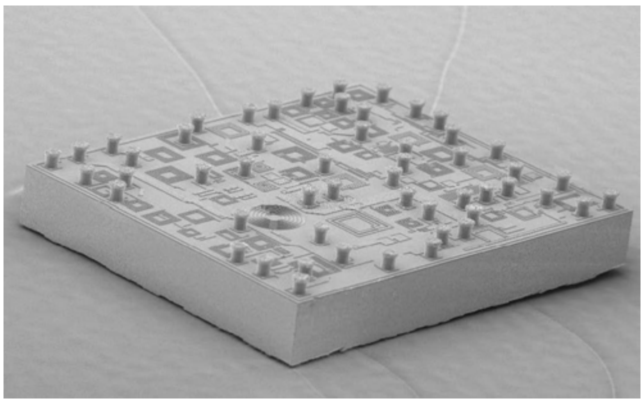

Fig 6 – 802.11n Die on E/D pHEMT

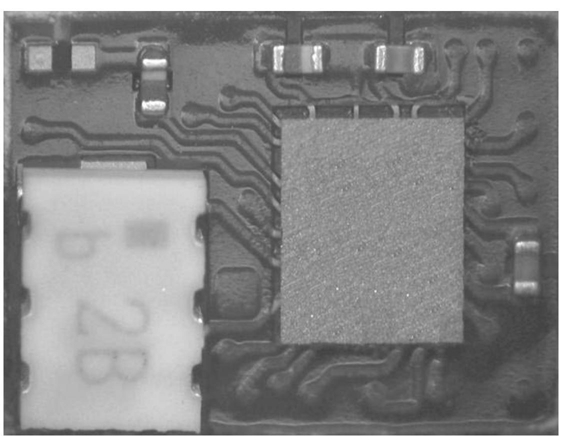

Fig 7 – 802.11n Flip Chip Module (6 mm x 8 mm)

WiMax provides a cost effective wide area broadband network that can compliment, and in some cases extend, 3G capability for data-intensive transfers. The frequency bands and power levels indicate GaAs, and possibly GaN, will be the right technology choices for WiMax. The price point for this application may be prohibitive to GaN for some time. In future applications it is likely the two standards, WiFi and WiMAX, will be operated on the same hardware platform with the chipsets and RF sections optimized to handle both.

VI. OTHER APPLICATIONS

Approximately 30% of the compound semiconductor market is attributed to applications other than handsets and WiFi/WiMax. These applications serve a variety of markets including military, optical, infrastructure, cable, terrestrial microwave links, automotive, satellite, professional two-way radio, VSAT, and others.

The market today for point-to-point microwave radio links operating in the 6 – 40 GHz range for cellular base station backhaul is growing. These links expand personal communications infrastructure into areas where optical backhaul is not available, or problematic due to difficult terrain. Product design for this application is following the established path of integration as multi-function chips replace components and discrete devices.

The defense industry has long exploited the merits of III-V compounds to meet the demanding mission-critical requirements of their applications. The combination of sophisticated communications systems and powerful radar systems creates a market demand for leading edge technology. High power, high efficiency, high linearity, low noise figure, and low phase noise drive state-of-the-art requirements.

Safety and security in the automotive market are creating demand for products based on GaAs technology. Automotive radar systems are being deployed on high-end vehicles today supporting adaptive cruise control and parking assistance. Future systems will enable pre-crash detection and deployment of safety aids. Saving fractions of a second in reaction time will translate into saving lives.

VII. CONCLUSION

Design of RF subsystems is following a roadmap moving from discrete component design to multi-function devices and integrated low cost modules. Large volume applications such as handsets and WIFI are leading the way with the introduction of new standards such as 3G and WiMax. E/D pHEMT, BiHEMT, and GaN technologies are bringing performance and innovative cost effectiveness to new designs. As communication systems increase in complexity, the design opportunities for compound semiconductors is expanding.

ACKNOWLEDGEMENT

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REFERENCES

[1] Asif Anwar, "GaAs Device and Material Market Trends" Strategy Analytics April 2007. Adjusted to include foundry revenue.