Challenges and Opportunities in the III-V Industry: A Quarter Century View

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Abstract

Over the past 25 years, advances in epitaxial growth technology have been one of the key contributors to the rapid growth of the III-V industry. GaAs HBT power amplifiers and pHEMT switches have been at the forefront of the wireless revolution that continues today. Over the past several years, GaAs BiHEMT technology has emerged as a means to monolithically integrate functionality of GaAs HBT power amplifiers with high-performance pHEMT RF switches. Challenges to grow such structures are significant due to the large number of epilayers and the impact of HBT growth over the underlying pHEMT layers. In addition, new wireless standards impose more stringent linearity requirements and ever tightening spec windows. To achieve high yield and reproducibility for a large volume of wafers, sophisticated in-situ monitoring and post-growth characterization are necessary. This presentation will review the emergence of GaAs HBT for wireless communications, address the current challenges and landscape faced by a high-volume epitaxial wafer foundry, and provide insights into future directions for materials-driven advances in the III-V industry.

INTRODUCTION

Since the 1980's, compound semiconductor material systems such as GaAs, InP, and GaN have provided the foundation for many of the technologies we rely upon for daily use. Mobile communications, solid state lighting, solar cells, and our communications infrastructure are examples that depend upon these materials. Because nearly all of the compound semiconductor devices utilize epitaxial materials, epitaxial wafer suppliers are an integral part in today's compound semiconductor industry.

Kopin Corporation, a spin-off from the Massachusetts Institute of Technology, has a long history of epitaxial growth technology. While at MIT, future Kopin team members were working on Wafer Engineering, which combines different semiconductor materials together without lattice rejection, and fabricating devices to study the results of these semiconductor combinations. When Kopin was formed in 1985, it licensed 30 patents from MIT. Kopin first worked on solar cells, providing high efficiency cells to space programs. Although the MOCVD growth process was not mature then, Kopin focused on MOCVD because we believed its potential as the most flexible platform for combining various compounds together. A few years later, Kopin began a commercial epitaxial wafer supply business, providing hundreds of products to dozens of companies.

In the early 1990s, Qualcomm was in need of a new power amplifier technology because silicon-based power amplifiers could not meet the linearity requirement of the CDMA standard. Qualcomm reached out to Kopin and Rockwell Science Center to develop a power amplifier for CDMA. Kopin and Rockwell formed a partnership wherein Kopin was responsible for developing the HBT wafers and Rockwell Science Center for the design, processing, packaging and testing of the power amplifier circuit. The Kopin and Rockwell team delivered GaAs HBT power amplifiers to Qualcomm, enabling the CDMA commercial service.

Kopin became the first company to mass produce HBT transistor wafers in 1995. In 1997, Conexant (a spin-off company from Rockwell Science Center and predecessor of Skyworks Solutions) started shipping power amplifier ICs at a rate of 1000 units per month. In 1998, the number was increased to 1.5 million units per month, and it has grown exponentially ever since. Today Kopin is the premier epitaxial wafer supplier, having shipped more than 1 million HBT, BiFET and BiHEMT wafers. Serving primarily for the wireless communications industry, Kopin's GaAs transistor products have been incorporated into billions of mobile devices.

Every component in smart phones and other wireless devices must enable the devices to have smaller footprints, higher speed, better signal quality, higher efficiency, lower cost and worldwide usage. Everyone in the food chain must keep up in the march. Throughout the past quarter century, these market trends have been ongoing and have not stopped. Kopin has followed this trend by moving the growth platform, growth process, and quality system in sync with the changes.

HBT

The GaAs HBT is an ideal device for wireless handset power amplifiers. It has excellent linearity, high RF efficiency, high breakdown voltage and requires only a single power supply. Compared to Si, the size of the amplifier is smaller for a given output power and requires a simpler process with much less stringent feature sizes.

The epitaxial process is one of the most fundamental and most important steps in the HBT manufacturing process. The entire transistor structure is grown during the epitaxial step. If the material thicknesses, compositions, and interface qualities are not correct, the device characteristics will not be correct, and there is very little that the circuit processing can do to compensate for the deficiencies.

As a result, the epitaxial wafer provider must maintain the specified transistor performance, not just the layer structures. Kopin was the first company to introduce the quick-lot process which entails fabricating large area devices on a sample wafer (out of a batch of wafers), measuring the device characteristics and correlating them with other growth parameters to ensure the transistor characteristics meet the customer's needs. The whole industry is still relying upon this method.

BiFET

As the functionality, performance, and size requirements for power amplifiers become more demanding, there is a growing need for a combined structure of HBT and FET within the same epitaxial wafer. One implementation is to grow an FET on top of an HBT, which is typically called a BiFET. The top FET is normally used in a biasing circuit for the power amplifier made with HBTs. The epi grower has to maintain not only the performance of the HBT but also the FET properties. The BiFET is now widely used for power amplifier circuits.

BiHEMT

Another combined structure implementation is to grow an HBT over a pHEMT, which is commonly referred to as a BiHEMT. It is possible to monolithically integrate RF switches made with pHEMTs and power amplifiers made with HBTs. Challenges to grow such structures are significant because of the large number of epilayers (up to 30) and the impact of HBT growth on the underlying pHEMT layers. To achieve high yield and reproducibility for a large volume of wafers, sophisticated in-situ monitoring and post-growth characterization are critical.

CHALLENGES FOR EPI WAFER SUPPLIER

Role of Epi Wafer Supplier

The role of an epi wafer supplier has evolved over time from a simple foundry service provider to a partner relationship with customers. In the beginning, a customer provided a specification for layer thicknesses and doping, and the epi supplier built wafers to the specification. Since every circuit manufacturer has its own proprietary structures with differentiable characteristics, from very early on we have formulated a strict silo system to safeguard and protect the intellectual properties of each customer. Early HBT structures consisted of five or six layers only, but newer device structures became much more complicated with many more layers and graded interfaces and doping. As device designs became increasingly more complex and performance requirements tighter, the simple supplier-customer relationship no longer sufficed to meet the needs.

Instead of having two parties with distinct knowledge sets, it became necessary for the epitaxial wafer provider to understand device fabrication, and for the wafer processing company to learn the fundamentals of epitaxy. By reciprocating knowledge, both parties benefitted. The companies that have followed this model are the companies which are successful and thriving in this challenging marketplace.

Kopin adds value by focusing our epitaxial engineering and material science knowledge into recommendations for new designs or process optimization. Kopin's deep understanding of device physics as related to epitaxial layers and structures has been increasingly more important as the marketplace is undergoing a rapid change in performance requirement. It is important to understand that the epitaxial structure Kopin grows is different based on the wireless standard and the customer's manufacturing process. Minor changes in a layer thickness, doping, or composition, can have a significant impact on device efficiency, power, or manufacturing yield. By working together with our customers, we strive to maximize benefits, and minimize defects which affect yield.

Ultimately, it is the epitaxial wafer supplier's job to ensure they have the correct tools, enough capacity and a deep knowledge set to meet the growing demands from customers. Kopin has invested heavily in new production equipment, statistical process controls, new in-situ diagnostic techniques and equipment, and an engineering staff to effectively combine them all together. This formula ensures we can serve the needs of our customers today, and into the future.

Tighter Specifications

To satisfy the customers' expectations, epi suppliers must provide a consistent product which enables customers to develop and improve their production process in order to create high quality products with high yield rates. Customers cannot achieve and sustain product yields in the high 90's if epitaxial quality is a contributor to yield losses. It is no longer acceptable to provide a product which merely meets specifications. Customers expect products to meet their ever increasing "target" performance and not just stay within historical control limits. Intra-wafer uniformity and wafer-to-wafer reproducibility targets that were once considered good in previous years are now frequently considered too variable for high yield device processing. Every one of Kopin wafers must meet these new stringent requirements.

In addition to top performance, customers demand a declining price curve and reliable supply for the products they need. The epitaxial supplier must proactively improve and maintain operational efficiencies. This is accomplished in several ways.

Large Volume

It is easy to recognize that large increases in volume have led to significantly reduced cost for producing epitaxial wafers, while providing improvements in performance, reproducibility, and reliability. A large portion of the cost structure is rooted in initial startup costs such as purchase of epitaxial reactors, facilitizing the building, developing the epitaxial process, and getting the process qualified by customers. From very early on, Kopin has partnered with one major epi reactor maker to design and improve reactor characteristics for increased uptime, yield, and production stability. We also installed the same size systems, similar to Southwest Airlines. This business and operation model with standardization is a key to efficient operation. As the epi reactor handles more wafers per run and is more automated, labor has become a relatively smaller fraction of the cost. As is typical for semiconductor industry, the cost is lower as the reactors are more fully utilized.

Substrate and Raw Materials

As volume reduces the fixed and labor cost per wafer, the substrate and other materials become an increasing portion of the cost. In addition, consistency of raw materials is critical to ensure repeatable epitaxial processes and avoid any unknown variables. 6" semi-insulating GaAs substrates are now the dominant substrates utilized for wireless components. This wafer size gradually replaced the 4", with broad incorporation within the past 5 years. For an MOCVD based company such as Kopin, various metal-organic precursors and gas sources are utilized as the starting materials for the epitaxial process. To ensure cost-effective and reliable supply, long-term contracts and supply agreements are needed.

Smart Epi

Because the velocity of wafers in the production line is high, a small hiccup can result in a very significant loss for high-volume, high-yield power amplifier manufacturers. Therefore, an advanced manufacturing technology coupled with a very stringent quality system must be in place. This is especially true as epitaxial structures become more complex. As a result, it has become necessary to monitor and control the growth processes of *every wafer in every run in real time* to guarantee the quality and performance of devices.

Kopin has developed such a system (which we named "Smart Epi") and implemented it in high-volume production of epi wafers, which we believe is the first in industry. Smart Epi is comprised of an in-situ monitoring system and proprietary data analysis and acquisition software. The in-situ monitoring system provides information on thickness, doping, growth temperature, and uniformity for each and every wafer as it is grown. Our proprietary software analyzes a tremendous amount of data coming from the monitoring system, provides the key information in real time for engineers to monitor, and stores the necessary data in our database for statistical process control and records.

Kopin has implemented the Smart Epi in every reactor now, and we are using it in every run for every structure. It has proven to be extremely valuable to control the production of epi wafers, especially for very complicated structures such as BiHEMT with as many as thirty layers having various doping levels, thicknesses and alloy compositions.

We believe the Smart Epi combined with our pre- and post-production quality control processes provides our customers the necessary assurances for the quality of our products. There is growing evidence that using only the quick-lot method, historically used in the industry to confirm wafer quality, is no longer sufficient for guaranteeing the strict quality requirements of complex transistor structures because it provides incomplete and delayed feedback from a limited sampling. Smart Epi provides state of the art quality control of all production wafers and provides better operational efficiency. It is a huge advance in epi manufacturing technology.

Close Communication with Customers

Direct and detailed communications with customers related to performance expectations and any fab-related questions are mandatory. Once high volume production starts, any out-of-control parameters can lead to a significant yield loss, decreased productivity, and an aggregate higher production cost. Kopin views the information exchange

between our customers and our engineers/scientists as the key factor in maintaining good process control. Many of our customers are able to provide near real-time feedback on the key performance metrics in their production lines. Kopin utilizes this information on a daily basis to ensure we are delivering the exact product our customers rely upon. Kopin's Smart Epi and quick-lot process results are correlated with the device parameters provided by our customers.

Asian Operation

Recently, Kopin has diversified our production base to both a US-based operation and a Taiwan-based operation (KTC). This capability is now providing multiple benefits to our valued customers. We have installed large volume capacity at KTC with identical epi reactors, the same processes and the same quality systems as in the US, and cross-calibrated both facilities. As a result, we are able to dual source many of our products. This provides assurance to our customers that they will always have access to a supply of Kopin wafers should an unexpected disruption occur. Our Taiwan-based organization not only offers cost advantages to our customers but also a more localized manufacturing point for some customers.

New Products and Technology

New products and technology are an exciting opportunity for both the customer and the epitaxial wafer provider. This opportunity allows both parties to benefit from their cumulative experiences and ensures that the new final product is engineered for both maximum performance and lower cost. If capitalized upon correctly, the customer will benefit with a better product with increased yield. This fact is essential to meeting the stringent demands of the consumer marketplace.

NEW DIRECTIONS IN THE MARKETPLACE

Looking forward, compound epitaxial suppliers must have deep technical knowledge of materials and device physics, and a strong financial position to maintain enough capacity to satisfy a rapidly changing and growing industry. It is by no means a stagnant business.

As more smartphones, tablets and other wireless devices are adopted and a 4G network becomes more widely installed, the demand for GaAs-based devices will be ever increasing. Today the demand is being driven by not only an increase in the number of wireless handsets but also the number of GaAs devices per phone. To take advantage of the capabilities 4G networks offer, GaAs devices will require better linearity and higher efficiency, which in turn will require better device design and tighter process control of epi wafers. We will continue to see shifts towards more complicated structures such as BiFET and BiHEMT for increased functionality, smaller package and reduced cost.

With continual demands on increasing capacity, tighter specifications and quality, and ever increasing complexity of structures, it has become extremely important to keep investing and developing to keep ahead. In addition, close supply chain management for substrates and other raw materials is required for cost-effective and reliable supply. Because it is getting very challenging to provide all these features well, there will be only a few viable epi suppliers.

GaN technology offers new capabilities for high power, high efficiency devices. This technology has suitably demonstrated its capabilities and will no doubt serve as the preferred material system for many applications. Kopin has demonstrated world-record level performance in this area, and is optimistic this will grow into a volume business in coming years. We are looking forward to new applications for this technology, which will enable large volume production. As with GaAs-based HBT, BiFET and BiHEMT products, volume production will be essential to lowering the cost.

CONCLUSION

The epi wafer volume for wireless market has grown to a very large number thanks to the exploding wireless devices. Similar to other semiconductor industries, the high capital costs and long lead time to get production equipment qualified have introduced stresses to the industry. Furthermore, the technology is undergoing rapid changes to get more advanced structures for improved performance, smaller size and lower cost because of the demands from newer devices such as smartphones and tablets. We see this trend continuing and even accelerating as wireless communications are now ubiquitous in the world. These severe challenges have reduced the number of viable epi suppliers.

Kopin has serviced the III-V industry with epitaxial wafers for over 25 years. The growth of the company is rooted in the ability to deliver on our customers' expectations and continually evolve to meet future requirements. We view our close partnerships with our customers as the best mechanism to increase their satisfaction with our products and ensure mutual success of our customers and Kopin.

ACRONYMS

HBT: Heterojunction Bipolar Transistor
BiFET: Bipolar Field Effect Transistor
pHEMT: pseudomorphic High Electron Mobility Transistor
BiHEMT: Bipolar – High Electron Mobility Transistor
MOCVD: Metal Organic Chemical Vapor Deposition
CDMA: Code Division Multiple Access