Wide Bandgap Semiconductor Substrates: Current Status and Future Trends

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Abstract

Wide bandgap semiconductors have expanded the scope of device applications beyond those of silicon and gallium arsenide. Exploitation of wide bandgap semiconductors holds promise for revolutionary improvements in the cost, size, weight and performance of a broad range of military and commercial microelectronic and opto-electronic systems. The inherent material properties of silicon carbide, gallium nitride and aluminum nitride make them ideal candidates for high-power, high-temperature electronics, power amplifiers, switches, and short-wavelength light sources. Gallium nitride based semiconductor technology has provided the fundamental basis for a new class of opto-electronics. New electronic device structures based on silicon carbide and/or gallium nitride have demonstrated remarkable performance and are being considered for next generation military radar and commercial wireless applications. Additionally, silicon carbide devices have been demonstrated that exhibit superior high-efficiency power switching capability, potentially leading to new capabilities in power distribution as well as electric vehicle technology. Critical to the realization of these enabling capabilities are the availability of high quality affordable substrate materials. The Department of Defense has invested heavily in bulk growth research and development of silicon carbide, gallium nitride and more recently aluminum nitride. A synopsis of current capabilities and future challenges for commercialization of these materials will be discussed.

INTRODUCTION

Semiconductor substrates provide the foundation for a multi $100B's electronics industry. Silicon is currently and will remain the material of choice for the foreseeable future due to the low cost, readily availability, and established device technology and infrastructure. If a device can be made with silicon it will. In spite of the phenomenal progress being made with silicon technology it does have its limitations with respect to temperature, frequency operation and voltage blocking capabilities. As gallium arsenide (GaAs) and indium phosphide (InP) technologies provided the basis for the phenomenal growth in the wireless and telecommunications industries during the late 1980s – 1990s, a new class of semiconductors commonly referred to as "wide bandgap semiconductors" holds promise for continued revolutionary improvements in the size, cost, weight and performance of a broad range of military and commercial microelectronic and opto-electronic applications. Silicon carbide (SiC), gallium nitride (GaN) and more recently aluminum nitride (AlN) have emerged as candidate substrate materials that may overcome the performance limitations of silicon, GaAs and InP. SiC is clearly the most developed material of the three due to materials development efforts initiated in the mid-1980's, and the leadership of one company, Cree, Inc. in the maturation of the materials technology.

	4H SiC	**AlN**	**GaN**	**GaAs**	**Si**
Bandgap (eV)	3.26	6.2	3.36	1.42	1.12
Thermal Conductivity (W.cm.K)	4.9	3.4	1.3	0.6	1.3
Breakdown Field (V/cm)	3.5E6	1.8E6	2.0E6	4.0E5	3.0E5
GaN Mismatch (%)	3.3	2.2	0	N/A	18
Size (mm)	75	25	50	150	300
Price ($/in2)	700	>1,000s	>1,000s	<10	~1

Table 1. Key Material Parameters

MANUFACTURING TECHNOLOGY

Bulk crystal growth of wide bandgap semiconductors, namely SiC, GaN and AlN, is unique in that these materials cannot be manufactured in volume using the traditional Czochralski or Bridgeman methods due to the extremely high temperatures and pressures required to melt the materials. A vapor phase transport or epitaxial type of growth process is required. The nature of these processes creates a new set of challenges with respect to controlling thermal gradients, impurities and defect generation. While the state of technological readiness continues to mature, particularly for SiC, numerous advances with respect to boule growth and expansion, defect density and cost will be required.

Silicon Carbide	Gallium Nitride	Aluminum Nitride
1. PVT 2. HT CVD	1. HVPE 2. PVD/HVPE	1. Sublimation

Table 2. Bulk Growth Techniques

Silicon carbide boules are most commonly grown utilizing a Physical Vapor Transport (PVT) process. This process involves evaporating very high purity silicon carbide source material to a high quality seed substrate. The ability to accurately control thermal gradients and reduce electrically active background impurities, namely boron and nitrogen, is critical to obtaining high quality substrates. An additional parameter that must be actively managed when optimizing growth conditions is polytype control. Silicon carbide naturally forms over 200 crystalline structures (polytypes). Only a few of these crystalline structures are of interest for electronic and optical device applications - namely the "4H and 6H" (hexagonal) polytypes. This leads to even further restrictions on the parameters for crystal growth. Current alternatives to PVT include Advanced Physical Vapor Transport (APVT) and High Temperature Chemical Vapor Deposition (HTCVD). The APVT process allows for the introduction, ex-situ or in-situ, of a silicon and/or carbon containing species into the chamber to enhance crystal purity and stoichiometry control. The HTCVD process grows bulk SiC crystals directly from gas-phase precursors. Semi-insulating, either vanadium-doped or intrinsically compensated, and semi-conducting SiC substrates of 4H and 6H polytypes are now commercially available in diameters up to 75mm.

Future Challenges

- Uniform, reproducible electrical properties
- Defect reduction and/or elimination
- Affordability

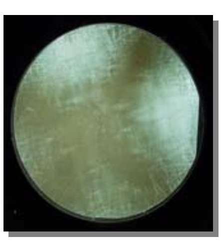

Fig. 1 Cross Polarized Image of 75mm Semi-Insulating SiC Substrate. Provided courtesy of II-VI Inc.

The desire for a lattice-matched substrate currently drives the development of bulk GaN. A native GaN substrate will potentially eliminate the problems of lattice and coefficient of thermal expansion (CTE) mismatch between the epilayers and substrate. Progress in developing bulk GaN single crystals has been slow due to its inherent material characteristics. Gallium nitride has a high equilibrium vapor pressure of nitrogen, decomposes at elevated temperatures and the solubility of nitrogen in gallium is very low. One approach involves growing a thick GaN epitaxial layer on a foreign substrate, after which the substrate is removed [1]. Conductive substrates in diameters up to 50mm are available from multiple sources.

Future Challenges

- Defect reduction
- Uniform and reproducible electrical properties (n/p-type, semi-insulating)
- Diameter expansion
- Affordability

Fig. 2 50mm GaN Substrate. Provided courtesy of Kyma.

Growth of bulk AlN substrates occurs via a sublimation-recondensation process in which very high purity aluminum nitride is sublimed in a nitrogen atmosphere and recondensed on the growing crystal. It is possible, under proper growth conditions, to either spontaneously nucleate single crystal growth or initiate growth utilizing a seed. While the self-seed growth process has been shown to grow high quality single crystals, it doesn't appear to be a viable process for large single crystals. Since AlN substrates are in the very early stages of development prices remain high and quantities are limited. The relative maturity of AlN substrates resembles SiC circa 1991. AlN substrates are currently available from Crystal IS in diameters up to 25mm while plans are in place for demonstrating 50mm single crystal substrates in 2004.

Future Challenges

- Defect reduction
- Diameter expansion
- Affordability
- Demonstrate device benefits

Fig. 2 25mm AlN Substrate. Provided courtesy of Crystal IS.

INDUSTRY CAPABILITIES

As a new technology, there is currently a limited industrial base for wide bandgap semiconductor substrates, relative to that of GaAs or Si. Cree, Inc. (Durham, NC) led the development of the materials, and was the first to offer commercial SiC substrates. They are still the market leaders with respect to technology and market share. Their combined market share for conductive and insulating substrates exceeds 85% [2]. The predominant use for SiC substrates is for commercial LED production while the balance is for development of electronic applications. The field vying for the SiC substrate market is becoming more crowded with no obvious emerging threat to Cree's technological and market leadership. Currently, Cree and II-VI, Inc. (Saxonburg, PA) are the only U.S. companies providing, 4H and 6H respectively, commercial quantities of 75mm semi-insulating SiC substrates in prices ranging from $4000 to over $5000. Dow Corning (Midland, MI) acquired Sterling Semiconductor is currently optimizing SiC wafer products for commercial sales. Internationally, SiXon, Inc (Japan), SICrystal (Erlangen, Germany), and Okmetic (Finland) offer SiC substrates for sale, but have made limited inroads into the commercial market dominance of Cree. Development of 100mm semi-insulating SiC substrates is currently ongoing at several companies. Cree has a 100mm product in development and II-VI has announced it will begin sampling 100mm semi-insulating substrates in mid 2004. The availability of conductive substrates typically leads the development/availability of semi-insulating materials.

The development of bulk GaN is being driven by the desire to overcome the issues associated with the use of non-nitride substrates such as sapphire and SiC. Both of these non-nitride substrates create high concentrations of defects that are believed to significantly diminish device performance. Availability of a native substrate could eliminate many of these issues and enable new classes of devices. The development focus appears to be on conductive substrates suitable for Blue-UV laser diodes. ATMI, Kyma and Sumitomo have all announced success in producing 50mm substrates. Prices remain very high, quantities are limited and quality is still inadequate for large-scale device development and fabrication. Semi-insulating substrates for high power microwave devices are not commercially available but are in development.

Bulk AlN substrates are in the very early stages of development and thus their availability is quite limited. They are currently being used to support a variety of research and development activities. Crystal IS recently announced the availability of 25mm single crystal substrates. Quantities are limited and pricing remains high. However this is expected to improve over time. A number of universities and private companies are also active in AlN bulk growth development.

	SiC	GaN	AlN
US	Bandgap Cree Dow II-VI Intrinsic	ATMI Kyma TDI	Crystal IS
Overseas	Nippon Okmetic SiCrystal Sixon	Sumitomo TopGaN	

Table 3. Commercial SiC, GaN and AlN Substrate Producers

APPLICATIONS

The desirability of wide bandgap semiconductors comes from the unique device performance characteristics enabled by the fundamental electronic materials properties. Devices based on wide bandgap semiconductors have the ability to emit or detect blue, green or UV light, operate at high frequencies with high power density and high efficiency and can withstand high voltages and currents, while operating at higher temperatures than more conventional electronics. Presently, wide bandgap semiconductor technology is the fundamental basis for use of blue and green LEDs, as well as white solid state lighting, in a variety of consumer electronics. This market was enabled by the availability of inexpensive, GaN-based components. Accomplished without the use of a native GaN substrate. The opto-electronics market place will likely be targeted by bulk GaN substrate producers once the commercial availability improves. Aluminum nitride substrates are of particular interest for use as UV sources due their excellent lattice and CTE matching to the active AlGaN layers. For future electronic applications, SiC and GaN transistor technology are well suited for high power microwave amplifiers for use in wireless infrastructure or military radar systems. Due to a very high breakdown voltage, these materials will enable power amplifiers to operate at higher voltages thus increasing the efficiency. The first SiC RF product, a 10W SiC MESFETs, is now commercially available from Cree.

These devices are targeted primarily at wide-bandwidth applications [3]. The availability of SiC-based GaN HEMTs are likely to be years away from introduction due to problems associated with long term reliability, and concerns over variability of performance, and device degradation that is occasionally observed. Once these issues are resolved the future for GaN HEMTs looks bright. For power switching applications SiC Schottky diodes are now available from Cree and Infineon, and are anticipated to be designed into commercial products in the near term.

COMMERCIALIZATION

The ability to fully exploit the properties of wide bandgap semiconductors will require additional improvements in quality, cost and availability of suitable substrates. Silicon carbide appears to be well positioned to address many of the future electronic and opto-electronic applications, and has reached a level of maturity suitable for device commercialization. If and when GaN substrates become commercially available in production quantities they will likely be the exclusive domain of high value blue/uv laser diodes. The future of AlN substrates may be relegated to niche opto-electronic applications unless a compelling business case can presented to support its development for high power microwave applications. To date, the limited availability, and high cost, of high quality GaN and AlN substrates has hindered aggressive device research activities. Unless and until key device demonstrations take place, demonstrating the benefits of these materials for any unique application, it is highly unlikely that a true requirement for the full-scale development of either material can be justified.

Expansion to larger diameters will likely occur as market demands force the conversion. Silicon carbide is poised to take full advantage of the existing 100mm, cost effective infrastructure assuming an application is identified to require such capacity. Demonstration of 100mm substrates has already been shown to be technically feasible with commercial availability projected in mid 2004. Both GaN and AlN substrates must first demonstrate sufficient device performance improvements before significant materials development efforts can be initiated. The key challenge for SiC is to move from an opto-electronics dominated product mix into broader electronics markets, including RF and power device products. Perhaps, in the long term, the largest potential application for SiC is for high voltage power switching applications, where even incremental improvements in device operating efficiencies translate into significant systems cost savings.

CONCLUSIONS

Semiconductor substrates are critical to the electronics and opto-electronics industries. The long-term viability of wide bandgap semiconductors depends heavily on the availability of affordable, large diameter, high-quality substrates. The future challenges faced by these materials are common in nature; the ability to control or eliminate deleterious defects, the ability to scale production processes to obtain economic production, assure reliable device performance and to develop fabrication and characterization methods that ensure affordable, high-quality substrates. Wide bandgap semiconductors can leverage the lessons learned from the deployment of GaAs and InP technology. The foundation exists – the technology, personnel and manufacturing expertise are all in place, which should accelerate the development and wide, spread adoption of wide bandgap semiconductors. The greatest risk is that an early "declaration of technological success" will lead to a failure to continue the steady improvement in materials capabilities.

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