Gallium Nitride (GaN) versus Silicon Carbide (SiC)
In
The High Frequency (RF) and Power Switching Applications

Introduction

Work on wide bandgap materials and devices has been going on for many years. The properties of these materials are very exciting to designers because wide band gap devices promise substantial performance improvements over their silicon based counterparts. Their ability to operate at higher temperatures, higher power densities, higher voltages and higher frequencies make them highly interesting for use in future electronic systems. Two very important wide bandgap materials showing great promise for the future for both switching and RF power applications are Gallium Nitride (GaN) and Silicon Carbide (SiC). There is a great deal of on-going discussion and questions about Gallium Nitride (GaN) versus Silicon Carbide (SiC) material, the semiconductor devices which are possible and which device / material is best suited for various switching and RF power applications. This paper summarizes our understanding of the current landscape and where these technologies are headed. Material properties, device architectures and cost are all important and inter-related. Ultimately, we believe both SiC and GaN will play important roles but each will settle into its own niche.

Material Properties

The characterization of a material as being wide bandgap pertains to the energy required for an electron to jump from the top of the valence band to the bottom of the conduction band within the semiconductor. Materials which require energies typically larger than one or two electron-volts (eV) are referred to as wide bandgap materials. SiC and GaN semiconductors are also commonly referred to as compound semiconductors because they are composed of multiple elements from the periodic table

The table below compares material properties for Silicon (Si), Silicon Carbide (SiC-4H[1]) and Gallium Nitride (GaN). These material properties have a major influence on the fundamental performance characteristics of the devices. Both SiC and GaN have material properties superior to Si for RF and Switching Power devices.

The high critical field of both GaN and SiC compared to Si is a property which allows these devices to operate at higher voltages and lower leakage currents. Higher electron mobility and electron saturation velocity allow for higher frequency of operation. While SiC has higher electron mobility than Si, GaN's electron mobility is higher than SiC meaning that GaN should ultimately be the best device for very high frequencies. Higher thermal conductivity means that the material is superior in conducting heat more efficiently. SiC has higher thermal conductivity than GaN or Si meaning that SiC devices can theoretically operate at higher power densities than either GaN or Si. Higher thermal conductivity combined with wide bandgap and high critical field give SiC semiconductors an advantage when high power is a key desirable device feature.

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[1] The "4H" in SiC-4H refers to the crystal structure of the SiC material

The relatively poor thermal conductivity of GaN makes heat management for GaN devices a challenge for system designers to contend with..

Materials Property	**Si**	**SiC-4H**	**GaN**
Band Gap (eV)	1.1	3.2	3.4
Critical Field 10^6 V/cm	.3	3	3.5
Electron Mobility (cm^2/V-sec)	1450	900	2000
Electron Saturation Velocity (10^6 cm/sec)	10	22	25
Thermal Conductivity (Watts/cm^2 K)	1.5	5	1.3

Table 1: Material Properties

Material Quality

Substantial improvements have been made in material quality for both SiC and GaN over the last several years. Our experience is that SiC is further along than GaN, since GaN substrates have only been produced up to 2 inches in diameter. In either case, the devices of interest for switching and RF power applications require an epitaxial layer of either SiC or GaN to be grown or deposited on a substrate composed of either the same (homoepitaxy) or a different (heteroepitaxy) material.

Homoepitaxial SiC devices are fabricated in a way that is analogous to silicon in that a SiC epi layer is formed on a SiC substrate (Figure 1). The result is a good crystallographic match between the epi and substrate and an electrically and thermally conductive path from the top to the bottom of the wafer. This has implications on the device structures which can be fabricated as well as cost. There are a number of companies producing SiC substrate and epi wafers. Cree has historically held the dominant position but other companies are closing the gap very quickly both in terms of material quality and, just as importantly, cost.

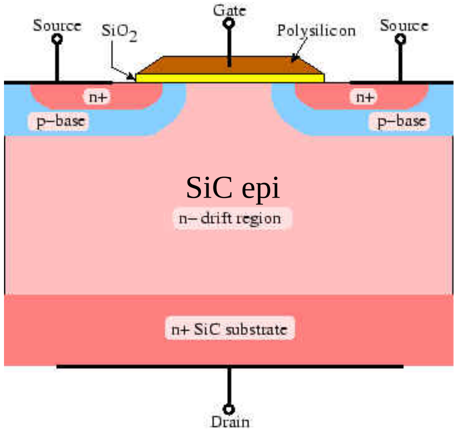


Figure 1: Vertical DMOS SiC MOSFET

GaN substrates are available today and primarily used to manufacture blue laser diodes on 2" wafers which is the current state of the art for this material[2]. A homoepitaxial GaN wafer offers advantages over heteroepitaxy approaches for GaN-based devices; however, production processes for epi ready GaN substrates of high quality (low defect) are still in the early stages and much less mature than SiC. Just as with SiC, there are many inherent challenges that must be addressed when it comes to the growth of bulk single crystal GaN to achieve an epi-ready substrate. Therefore, the common approach today is the heteroepitaxy approach. There are several variations being implemented but for the purposes of switching and RF power applications, the primary choice today for a heteroepitaxial GaN wafer is GaN epi on a "non-native" SiC substrate. Another combination being used is GaN epi on Si. In both cases there are crystal lattice differences which need to be accounted for, which add additional materials and processing costs.

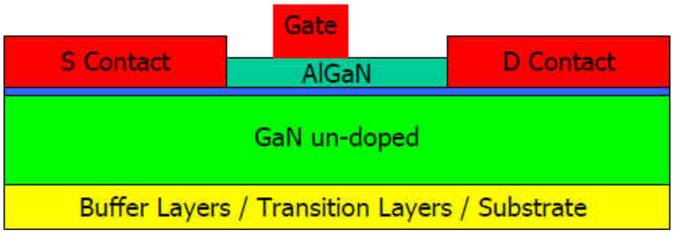
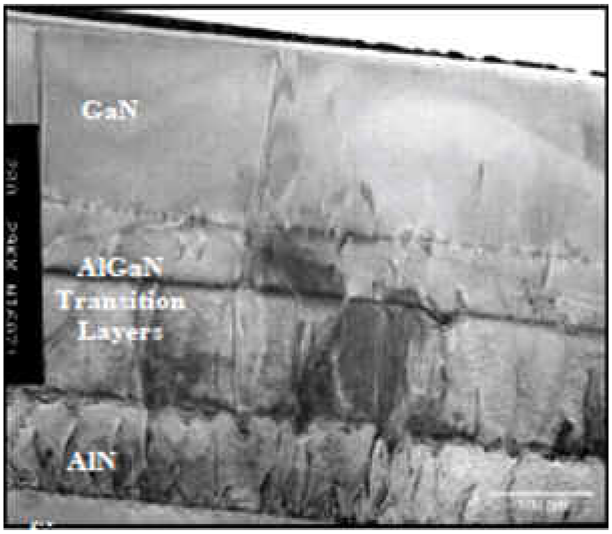


Figure 2: Lateral MOSFET using GaN with transitional layer material to align the lattice using Si or SiC as a substrate

The common approach to accomadating the crystallographic differences is through the use of a buffer layer (Figure 3). Aluminum Nitride (AlN) is one material being used which provides a good material match but is electrically insulating which impacts the types of device structures which can be fabricated. Creation of the buffer layer also adds cost and process complexity. Also these buffer layers combined with the use of non-native substrates result in defects and inherent stress which need to be overcome in order to not adversely affect device performance, yields and reliability



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[2] Orientation Control of Bulk GaN Substrates Grown via Hydride Vapor Phase Epitaxy, Kyma Technologies, Inc.

Figure 3: Cross section of GaN and required buffer layers

State-of-the-art wafer diameters are 3” going to 4” for homoepitaxial SiC and 3” for heteroepitaxy GaN on SiC or Si wafers. In terms of cost, GaN on SiC wafers cost about 20% more than their SiC on SiC counterparts. From a device manufacturing point of view, defectivity for GaN on SiC or GaN on Si wafers is higher than their SiC on SiC counterparts. This is an important consideration because unlike simple diodes or LEDs, power devices are very sensitive to defects. In addition, GaN on Si has a 2 to 1 difference (Figure 4) in the coefficient of thermal expansion (CTE) at the epi interface, which can be an issue during power cycling (another reason why additional layers of material are required to make the device mechanically sound). GaN on silicon wafers promise to be substantially lower cost than either the SiC on SiC or GaN on SiC wafers leading to a great deal of current interest in this combination. A primary question is…. Can the device structures, yields, electrical and thermal performance, reliability and overall benefit to the system cost overthrow the current silicon devices used today?

Substrate	**GaN**	**Si <111>**	**Sapphire (Crystal of Al2O3)**	**SiC 6H**	**Ge <111>**
Lattice Constant (Å)	3.19	3.84	2.75	3.08	4.0
Coefficient of Thermal Expansion (CTE)	5.6	2.6	7.5	4.2	5.9

Figure 4: Lattice constant and CTE of semiconductor starting material

Device Topology

Homoepitaxial SiC has an advantage in that both vertical and lateral devices can be fabricated.

SiC Lateral Devices:

- MESFETs are popular high frequency devices, and enables source vias for high frequency applications as well as integration in the form of Monolithic Microwave Integrated Circuits (MMIC’s). Microsemi is currently developing a MESFET targeted at the S-Band (around 3Ghz) frequency range which may be about the top end in frequency due to gain that can be achieved with homoepitaxial SiC.

SiC Vertical Devices

- Include Schottky diodes, JFETs, SITs, PIN diodes, BJTs, and the Holy Grail for designers who want everything including a normally-off device, the MOSFET. There are a number of companies that offer SiC Schottky diodes with a variety of current and blocking voltage ratings. Microsemi offers Power Modules which incorporate SiC Schottky diodes and has also introduced two RF SITs which operate at VHF (30MHz to 300MHz) and UHF (300MHz to 600MHz) frequencies. Our next generation RF SIT will target the L-Band (1 to 2GHz) frequency range. PIN diodes and BJTs (both switching and RF) are challenged by the need for very precisely controlled doping layers throughout the vertical structure and therefore are not generally production ready at this time because of limitations in available starting material. Some companies have recently announced progress on MOSFETs where the primary challenge is producing a reliable device and scaling up die size for usable currents while maintaining reasonable yields. Our assessment is that they are getting close to production ready, but that full scale production may be a year or two off (Yole Developpement predicts SiC MOSFET mass production in 2014). Several companies are working on JFETs for switching power applications. The challenge is that the most common JFET is a normally "on" structure which designers are reluctant to use as they are used to designing with normally "off" silicon MOSFETs. Clearly, circuit designers do not want a switching device to fail in the "on" position. In order to get around this problem, some companies are developing a Cascode configuration which combine a normally "on" high voltage SiC JFET in series with a low voltage normally "off" Si MOSFET. A drawback of this approach is that the Si MOSFET determines the maximum temperature of the solution. Others have developed normally "off" SiC JFETs which have a threshold voltage of around 1V with a maximum turn on (gate to source) voltage of around 3V. The challenge for these normally "off" JFETs is that designers are still reluctant to use them for fear of spurious signals causing mal-function of the design. Substantive efficiency gains have been demonstrated by both these solutions and there is genuine interest and promise for each.

Heteroepitaxial GaN devices whether on SiC or Si are restricted to lateral device structures at this time due to the buffer layer required to compensate for the lattice mis-match of the materials. There are considerable drawbacks for lateral devices compared to their vertical counterparts including the need for bigger chip sizes and additional topside contacts, etc.

GaN Lateral Devices

- Lateral devices generally require more space than vertical devices. Manufacturing yields are also impacted by larger devices.
- Lateral devices tend to be limited in their operating voltage capability because of the large electric fields which must be sustained across the surface of the device.
- While lateral GaN devices such as Schottky diodes have been demonstrated they have not become practical to manufacture at this time.
- The most common lateral device structure regardless of whether the application is switching or RF power is the HEMT (High Electron Mobility Transistor). RF GaN on SiC HEMTs are being manufactured today for use at very high frequencies such as C and X bands. The primary adopter of these devices are defense systems such as those required for electronic warfare applications. GaN on SiC is the preferred choice because it reigns supreme for RF performance where cost is not the primary factor. RF GaN on Si HEMTs are also being developed. Proponents of these devices are primarily targeting applications like wireless communication which are currently dominated by Si LDMOS devices. The bet is that while the Si based device is not as high performing as the SiC based device, it's performance advantage combined with its future promise of lower cost will trump the incumbent Si LDMOS and GaAs pHEMT in the telecommunication base stations market (3G, 4G, WiMAX).
- Another application space being pursued with the GaN on Si HEMT product is in lower voltage (approximately 200V and lower) switching power electronics. There are a couple companies who are betting that improvements to the starting material

quality, increase in wafer diameter, reduction of wafer costs, improvements in yield coupled with the development of an enhancement mode, normally off device and the higher performance of GaN will win over the current state-of-the-art Si devices. There may also be a RadHard market for these products. However, when you try to apply this concept to higher voltage devices the general consensus is that GaN on Si will lose its steam primarily because of power, and GaN on SiC material will be required to deliver the necessary device performance putting it on a head on collision course with homoepitaxial SiC devices.

Device Topology Summary

Device	Vertical Topology	Lateral Topology
SBD	SiC-4H	GaN
PIN Diode	SiC-4H	GaN
JFET / SIT	SiC-4H	NA
MESFET	NA	SiC-4H, GaN
BJT	SiC-4H	NA
MOSFET	SiC-4H	NA
HEMT	NA	GaN

Figure 5: Semiconductor material vertical and lateral topologies

Summary

Based on the material properties and current device capabilities we expect the following SiC / GaN results.

- Heteroepitaxial GaN on SiC will dominate RF frequency applications above S-Band where performance is paramount such as in Defense applications.
- Heteroepitaxial GaN on Si may find a home as a replacement to the incumbent Si LDMOS and GaAs pHEMT in the telecommunication base stations market (3G, 4G, WiMAX). It depends on several factors:
    - How quickly will cost come down?
    - What performance do these applications really need?
    - What new applications will emerge?
    - What tricks do the incumbent’s still have up their sleeves on device performance and cost?
- Heteroepitaxial GaN on Si HEMTs may displace lower voltage devices in the switching power electronics market (technology being promoted by International Rectifier and EPC). It also depends on several factors, but primarily boils down to whether the performance (including the reluctance associated with a normally “on” device, or normally “off” device with a limited input voltage swing capability) and cost ratio will provide a system benefit a.k.a “value” that will compel designers to adopt it. There may also be opportunities for these devices in the RadHard marketplace.
- Homoepitaxial SiC vertical devices will dominate in switching applications above approximately 600V and especially for higher power applications because:
    - Homoepitaxial SiC will remain lower in cost compared to heteroepitaxial GaN on SiC.

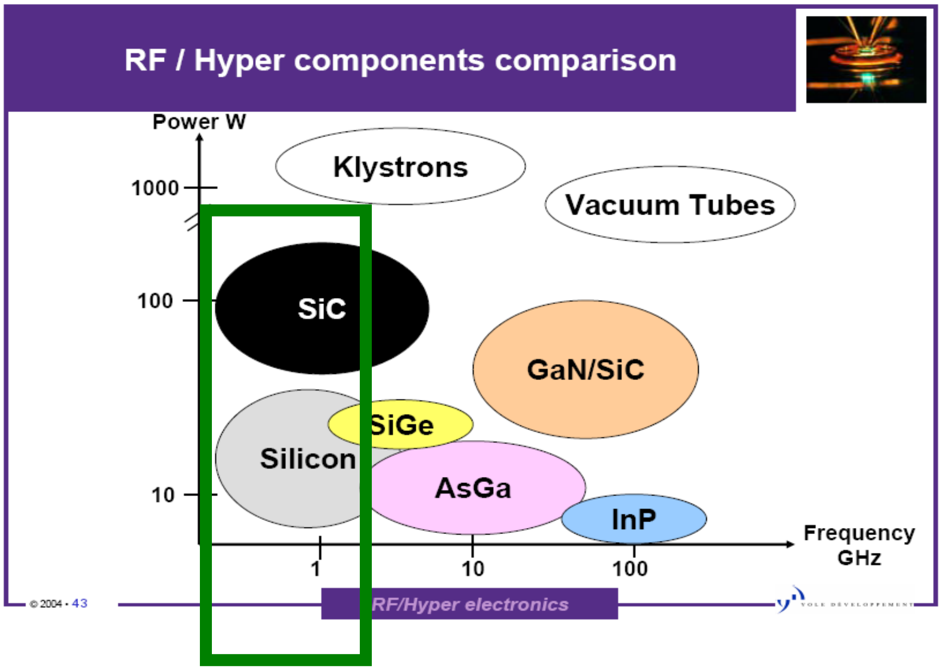
- Homoepitaxial SiC over heteroepitaxial is easier to build up in a more defect free wafer.
- Heteroepitaxial GaN on Si may be lower cost than homoepitaxial SiC and theoretically higher performing than Si devices but suitable high voltage device structures do not exist.
- Heteroepitaxial GaN on Si does not have the higher thermal conductivity that homoepitaxial SiC has so we expect homoepitaxial SiC to win where high temperature operation is the primary parameter of interest.
- Wafer diameters will continue ot increase helping drive down costs.

The gray area seems to be those RF applications in the low MHz to S-Band range of frequencies

- Where high power is required Homoepitaxial SiC wins
- Where medium performance is required there may be a place for Heteroepitaxial GaN on Si
- Cost considerations will always play an important role

Conclusion

There are many interesting devices that can be produced by both materials. We currently see GaN being used for lower power/voltage, high frequency applications and SiC for high power and high voltage switching power applications (Figure 6).



Microsemi Application Space

Figure 6: Semiconductor material power and frequency regions

Cost is similar if SiC substrates are being used. However, if Si is used as a substrate for GaN epi the starting material cost may be less and quite possibly provide a way to get to larger diameter wafers more quickly. One must be aware of increased offsetting costs of added epi layers to compensate for lattice mismatch.

Microsemi is on its current course with SiC because:

- SiC devices fit very well into the markets and applications that we already serve.
- SiC power device technology (devices and materials) is more mature than GaN
- SiC required a lower upfront investment which was more commensurate with the size company we are while allowing us to utilize our existing infrastructure more easily
- Path to profitable growth is shorter with SiC than GaN
- SiC business can be used to fund a GaN effort downstream
- SiC offers the possibility of producing MOSFETs, GaN does not