Commercialization of Group III Nitrides-on-Silicon Technologies

by
Ian Peiyuan Seetoh

Bachelor of Engineering (Chemical)
National University of Singapore, 2009

SUBMITTED TO THE DEPARTMENT OF MATERIAL SCIENCE AND ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING IN MATERIALS SCIENCE AND ENGINEERING

AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SEPTEMBER 2010

Signature redacted

Signature of Author: ....
Department of Materials Science and Engineering
July 28, 2010

Signature redacted

Certified by: ....
Eugene A. Fitzgerald
Merton C. Flemings – SMA Professor of Materials Science and Engineering
Thesis Main Supervisor

Signature redacted

Certified by: ....
Soo-Jin Chua
Professor of Electrical and Computer Engineering, National University of Singapore
Thesis Co-supervisor

Signature redacted

Accepted by: ....
Christine Ortiz
Chair, Departmental Committee on Graduate Students

Commercialization of Group III Nitrides-on-Silicon Technologies

by
Ian Peiyuan Seetoh

Bachelor of Engineering (Chemical)
National University of Singapore, 2009

Submitted to the Department of Material Science and Engineering on July 28, 2010, in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Materials Science and Engineering

Abstract

While group III nitride materials have been commercialized for many years, there is recent interest in growing these materials on silicon substrates as a cost effective alternative to more expensive sapphire and silicon carbide technologies. Therefore, it is necessary to determine how group III nitride-on-silicon technologies can be positioned in way for them to be effective in their respective applications, thereby enabling their commercialization. This thesis is a systematic evaluation of the epitaxial growth on silicon carbide, sapphire and silicon substrates, focusing on their lattice-mismatches, thermal expansion mismatches, and thermal conductivity. The subsequent analysis of important commercial applications determined that GaN-on-Si technology is ready for commercialization in the near future. These applications include the InGaN/GaN white light emitting diode and the blue laser diode, as well as the AlGaN/GaN high electron mobility transistor, each with its own unique requirements for the technology and the implementation. It was recommended that start-up firms interested in commercializing GaN-on-Si technology focus on the growth of GaN on silicon substrates and engage device manufacturers proactively. InN and In-rich nitrides can complement maturing GaN and Ga-rich nitrides technologies, resulting in new applications and products in future. While the growth of InN films is currently very challenging, it is believed that the experience and revenue obtained from the commercialization of GaN-on-Si technology can benefit InN-on-Si technology, speeding up the latter's commercialization. A brief business strategy aimed at translating the findings into a feasible approach for commercialization is also provided.

Thesis Supervisor: Eugene A. Fitzgerald
Title: Merton C. Flemings – SMA Professor of Materials Science and Engineering

Acknowledgements

The author would like to express his gratitude to a few people who have made the completion of this thesis possible.

Firstly, he would like to thank Professor Eugene Fitzgerald for his guidance and inspiration. He was able to provide unique insights deriving from his wealth of experience in innovation and entrepreneurship and was always enthusiastic about sharing his knowledge with students.

He would also like to thank Prof Soo-Jin Chua from the National University of Singapore who provided guidance and motivation in Singapore. His experience and expertise in the field of group III nitrides provided the author with many useful ideas.

Finally, the author would also like to thank his fellow classmates for all the support and fun during the course of his graduate studies.

Table of Contents

1. Introduction

The commercialization of the first blue InGaN light emitting diodes (LEDs) by Shuji Nakamura from Nichia Chemical Industries Limited in 1993 [1] and the recent entry of white LEDs into the general lighting industry sparked immense interest in the growth and fabrication of group III nitride materials. As demand for Blu-Ray technology rises with the popularity of high-definition video, InGaN blue lasers will also be in high demand. In addition, as wireless communication moves into higher frequency bandwidths demanding higher-power devices, AlGaN/GaN HEMTs will be increasingly important.

Group III nitrides (III-N) refer to GaN, InN, AlN, and their respective alloys. The III-N material system spans a very large range of bandgap energies, from the infrared (2 μm) to the ultraviolet (2 nm) regimes (figure 1). Therefore, this alloy system is capable of producing many useful applications in optoelectronics. Importantly, III-N materials are able to emit blue and near-ultraviolet light, in regimes not normally covered by the group III arsenide/phosphide systems.

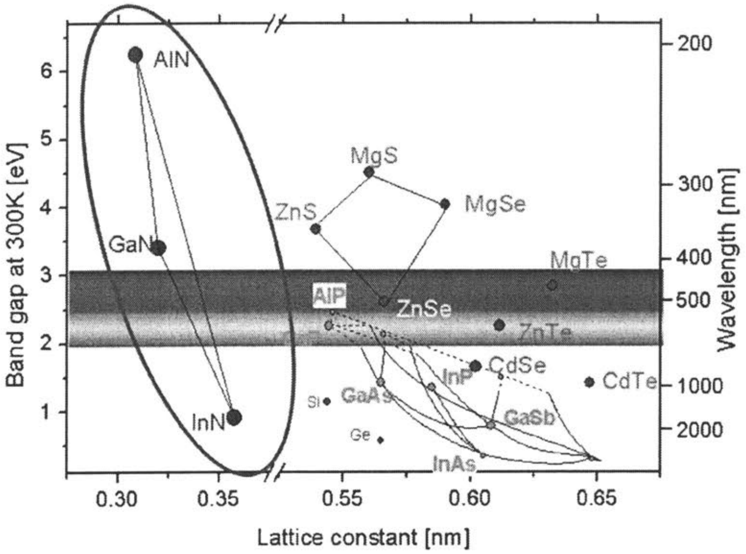


Figure 1: Plot of bandgap energy vs. lattice constant for III-N materials. Source: http://www-opto.e-technik.uni-ulm.de/lehre/cs/III_V_map_a.jpg

Blue and green InGaN LEDs are already widely used in indicators and traffic signaling. InGaN/GaN LEDs can be packaged with phosphors that can convert part of the blue light into red light, which can blend with the unconverted blue light to produce white light. In the lucrative general lighting industry, 'white LEDs' already outperform incandescent bulbs in both cost and performance. They are currently comparable to compact fluorescent lamps (CFL) in performance, but have much higher unit costs which hinder sales. Nevertheless, white LEDs are expected to outperform and outsell CFLs by 2025, based on progressive reductions in production costs [2, 3].

Apart from LEDS, InGaN can also be used to make laser diodes for the production of blue lasers [4, 5]. In optical storage disk applications, blue lasers have a smaller wavelength (405 nm) than red lasers (650 nm), and therefore have smaller spot sizes due to reduced diffraction. Therefore, InGaN blue lasers can replace red lasers in optical data storage/reading. The smaller spot sizes of blue lasers can result in smaller pit sizes in a data disc. This means that more data can be packed into a single disc. The transition from DVD (red laser) to Blu-ray disc (blue laser) technologies is motivated by this benefit.

Besides optoelectronics, III-N materials also have important applications in electronics. AlGaN/GaN high electron mobility transistors (HEMTs) have been successfully commercialized as RF devices. AlGaN has a larger bandgap than GaN. In AlGaN/GaN heterostructures, an electron well forms in the GaN region just below the heterojunction (figures 2 and 3), which results in a dense 2D electron gas (2DEG). The 2DEG can be used for transistor operations under source-drain biases. As the 2DEG flows in undoped material, it is free from ionized impurity scattering and can have very high mobilities. Since AlGaN and GaN have larger bandgap energies than Si and GaAs, they are especially useful for high-power and high-frequency operations [6, 7].

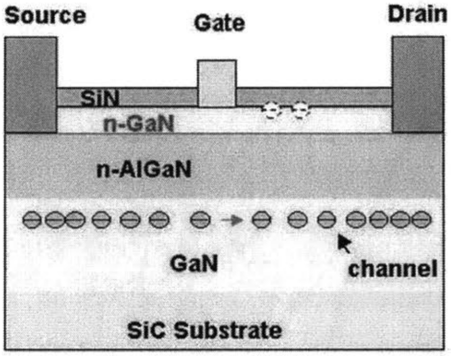


Figure 2: Schematic diagram of an AlGaN/GaN HEMT. Source: Fujitsu website: http://news.soft32.com/fujitsu's-technology-for-gallium-nitride-hemt_4558.html

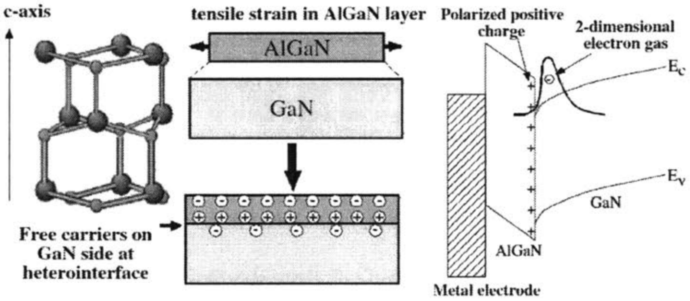


Figure 3: AlGaN/GaN heterostructure and its band diagram. As the AlGaN layer is under strain, free carriers are accumulated at the heterointerface owing to the piezoelectric effect caused by the strain and a spontaneous polarization effect along the c-axis. [6]

While most of the current III-N technologies and applications are based on the epitaxial growth of III-N materials on sapphire and silicon carbide substrates, there is a recent surge of interest in the use of silicon as an alternative substrate material. The objective of this thesis is to evaluate whether III-N on silicon technologies are feasible and how to implement these technologies in a commercially-viable way.

2. Substrates for epitaxial growth of III-N

A crucial aspect of III-N technology is the epitaxial growth of high quality nitride films. There are no AlN and InN wafers available as substrates for epitaxy. GaN wafers are available at poor qualities and prohibitive prices, which limit their adoption in most applications [3]. Therefore, other substrate materials, which are lattice-mismatched with most III-N materials, should be considered for epitaxial growth. Silicon carbide and sapphire wafers are already being used by LED and RF electronics manufacturers, while the silicon (111) wafers are just beginning to be adopted industrially. The growth process is typically achieved by metal organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE).

Lattice-mismatch between the III-N material and the substrate directly influences the formation of dislocations in the grown epilayer. In heteroepitaxy, there is a critical thickness [8, 9] to which the strained film can grow coherently without the formation of dislocations. When the thickness of the epilayer exceeds the critical thickness, the epilayer becomes incoherent and undergoes strain relaxation by forming dislocations, which can adversely affect device performance. The critical thickness decreases with increasing lattice-mismatch. In addition, lattice mismatch also causes lattice strain in the epilayer which can affect its electronic properties and also cause wafer bowing during growth.

Silicon carbide and sapphire wafers usually require a procedure to reduce their surface roughness. For sapphire, the wafers can be heated at $1000^{o}C$ with hydrogen, followed by nitridation with ammonia (MOCVD or MBE) or nitrogen plasmas (MBE), to form a very thin (few nm) layer of AlN, which can promote subsequent nucleation of the III-N material [10]. For silicon carbide, the surface is oxidized to form a silicon oxide layer which is subsequently etched to obtain a smooth surface [10]. In the case of silicon substrates, the native amorphous silicon oxide layer has to be removed, usually by HF etching [10].

After surface preparation, a buffer layer is typically grown. The purpose of the buffer layer is to reduce lattice-mismatch, control excessive strain arising from thermal expansion mismatch, and/or also to promote nucleation of the desired III-N layer. As GaN and InN have poor wettability with sapphire, silicon carbide, and silicon substrates, an AlN or AlGaN buffer layer is typically grown to promote nucleation [11-16]. Due to large lattice mismatches with AlN (see table 2), incoherent growth occurs immediately, resulting in columnar AlN grains. The subsequent growth of III-N typically results in the vertical growth and lateral coalescence of the columnar grains to form a columnar film structure with vertical threading dislocations (figure 4).

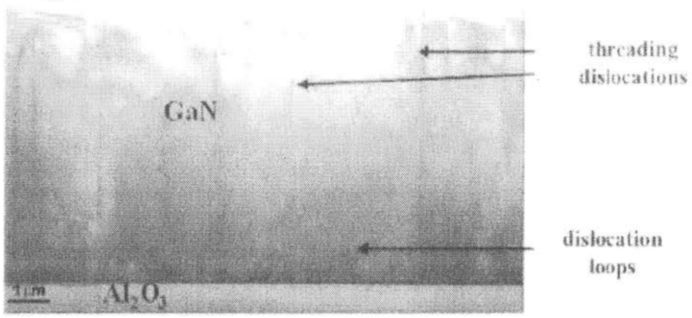


Figure 4: A typical cross-section TEM image of GaN grown on a sapphire substrate. [2, 17]

The size of a wafer is important in high throughput manufacturing. Larger wafer sizes mean that more devices can be fabricated in a single production run, resulting in lower unit costs. The price of a wafer affects the pricing of the resultant product. The quality of the substrate material also has important implications for processing. Poor quality substrate materials often require additional pretreatment steps and higher costs.

After the high-temperature (600 – 1200 °C) growth process is completed, the wafer is cooled to room temperature. If the substrate material contracts thermally at a different rate from the grown epilayer, thermal stress will occur. The grown epilayer will experience thermal expansion-related tensile or compressive strain after cooling if its coefficient of thermal expansion is larger or smaller respectively than that of the substrate material. The grown epilayer cracks easily under excessive tension, which is an important issue in the growth of GaN on silicon substrates.

The strain resulting from lattice and thermal expansion mismatches can result in the bowing of the wafer. Net tensile strain results in concave bowing, while net compressive strain results in convex bowing. A very important effect of bowing is the lifting of parts of the wafer above the heating platform in a typical growth reactor (figure 5) [18]. This results in a non-uniform temperature distribution across the wafer. The temperature variance increases with substrates of lower thermal conductivity, as the substrate material is incapable of conducting heat energy quickly across the temperature gradients. With the projected use of larger-sized wafers in future [3], the bowing will be more significant together with an increase in temperature variance [18]. The temperature variance results in variances in film quality and alloy composition (e.g. $In_xGa_{1-x}N$) across the wafer, which can be detrimental to manufacturing yields. Wafer bowing can be reduced with the use of thicker wafers, but this option may not be feasible with expensive substrate materials (e.g. sapphire and silicon carbide).

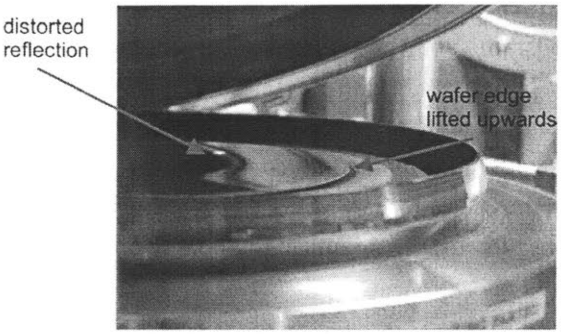


Figure 5: View on a 150 mm a-plane sapphire wafer in an opened MOCVD reactor at 650 °C. The strong bowing can be seen best in the wavy reflection on the wafer but also by the significantly lifted wafer edge. [18]

With these parameters in mind, we shall proceed with an evaluation of the use of silicon carbide, sapphire, and silicon substrates for III-N growth. Information about these substrate materials and their epitaxial relationship with III-N materials is compiled in tables 1 and 2 to facilitate our discussion.

Table 1: Comparison of possible wafers/substrates for III-N epitaxy

	Silicon (111)	c-plane Sapphire	c-plane 6H SiC	GaN-on-Sapphire	Single crystal GaN
Typical defect densities (cm^{-2})	< 1	10^3	10^3	10^6 - 10^9	10^5
Price (US$)*	30	62	995	475 (50 mm)	1295 (10 mm)

*Price of comparable 100 mm-diameter wafers in 2010, except for GaN-on-sapphire (50 mm-diameter) and Single crystal GaN (10 mm x 10 mm). These wafers were marketed for use in laboratories.
Information obtained from MTI Corporation's website: http://www.mtixtl.com/index.aspx

Table 2: Crystalline and thermal properties of group III nitrides and relevant substrates [19, 20]

	GaN	**AlN**	**InN**	**Si (111)**	**6H SiC**	**Sapphire**
Crystal Stucture	Wurtzite	Wurtzite	Wurtzite	Diamond	Hexagonal	Hexagonal
Energy Gap (eV)	3.4	6.2	0.7	1.1	3.0	9.9
Lattice Constants (Å)						
a	3.189	3.112	3.538	5.43/√2	3.081	4.758/√3
c	5.186	4.982	5.703	-	15.117	12.980
Lattice mismatch (%)*						
Si (111)	**20.4**	**23.4**	**8.5**			
6H SiC	**-3.4**	**-1.0**	**-12.9**			
Sapphire	**-13.9**	**-11.7**	**-22.4**			
Thermal Conductivity ($Wcm^{-1}K^{-1}$)	1.30	2.85	0.45	**1.50**	**4.90**	**0.41**
Thermal expansion, linear (10^6 K^{-1})						
α_a	5.6	4.2	3.8	3.6	4.2	7.5
Thermal expansion mismatch (%)**						
Si (111)	**35.6**	**14.3**	**5.3**			
6H SiC	**24.9**	**0.0**	**-10.5**			
Sapphire	**-34.2**	**-78.6**	**-97.4**			

***Lattice mismatch = $(a_{substrate}-a_{film})/a_{film}$. Positive values indicate that the III-nitride is under tensile lattice strain.**

****Thermal expansion mismatch = $-(\alpha_{a,substrate}-\alpha_{a,film})/\alpha_{a,film}$. Positive values indicate that the III-nitride film is under thermal tensile strain after cooling**

2.1. Silicon carbide substrates

A quick look at the lattice constants and thermal expansion coefficients of the materials suggests that silicon carbide is the most appropriate substrate for III-N growth. In terms of lattice and thermal expansion matching, silicon carbide matches best with GaN and AlN, and matches with InN better than sapphire. It also has the highest thermal conductivity, which can be useful in heat dissipation, contributing to its adoption in most AlGaN/GaN HEMT devices. The use of silicon carbide for III-N growth has accelerated in recent years with improvements in the quality of the substrates [14, 21].

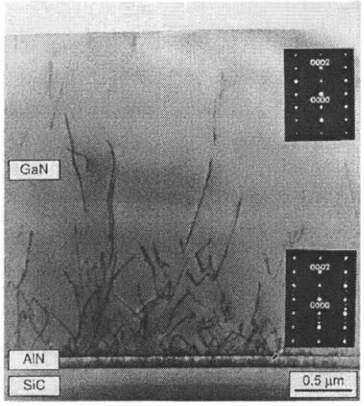


Figure 6: Cross-sectional TEM of a 2.7 µm GaN (0001) film deposited at 950 °C and 90 Torr via MOCVD on a high-temperature (1100 °C) monocrystalline AlN buffer layer predeposited on a 6H SiC (0001) substrate. [14]

As SiC does not form a melt, it is more difficult to fabricate high-quality SiC wafers than Si and GaAs wafers. SiC wafers are typically grown by physical vapor transport or chemical vapor deposition [22]. The early wafers suffer extensively from micropipe defects which are screw dislocations that extend through the thickness of the wafers, resulting in adverse effects on subsequent device performance [10, 23]. Although wafers with little or no micropipe defects are now available, they typically command premium prices. SiC wafers also have low angle defect grain boundaries that contribute to leakage currents and failure in devices.

In addition, the relatively higher costs of vapor-phase synthesis result in the cost of silicon carbide wafers being more than ten times higher than those of sapphire and silicon (see table 1), which are typically synthesized by cheaper crystal-melt processes. Currently, silicon carbide substrates are typically used as very small 2-inch wafers, which result in very low throughput production as very few devices can be fabricated per wafer, adding further costs to production.

2.2. Sapphire substrates

Currently, c-axis oriented sapphire is the substrate material-of-choice for III-N growth for optoelectronic applications [15, 16]. The lattice-mismatch is reduced by the natural 30° rotation of the c-plane of the nitrides relative to the c-plane of the sapphire substrates [10]. In terms of lattice matching, sapphire performs midway between silicon and silicon carbide for GaN and AlN, and has the worst lattice matching with InN. It also suffers from poor thermal properties, having the largest thermal expansion mismatches and lowest thermal conductivity. While current InGaN/GaN LEDs are mostly produced on sapphire substrates, most commercial AlGaN/GaN HEMTs are fabricated on SiC due to the need for good heat dissipation of the high-power devices by using substrates of high thermal conductivity.

Where lattice strain is concerned, materials tend to crack more easily under tension than under compression. Since the nitride layer is under compression after growth on sapphire, the effects of thermal expansion mismatch are not particularly severe. Currently, the effects of bowing and non-uniform temperature distributions are not pressing issues as most growth processes are performed on very small 2- to 4-inch wafers. However, these will be important considerations as manufacturers attempt to scale-up production with larger 8-inch wafers in future.

2.3. Silicon substrates

Silicon wafers are available in large sizes, in very high purity, and at very low prices compared to other substrates. The lattice mismatch between silicon and III-N materials can be reduced by using the (111) plane for growth. The effects of bowing on temperature uniformity are not severe for silicon as silicon conducts heat fairly well and better than sapphire [18].

Silicon (111) has the best lattice and thermal expansion matching with InN, compared to sapphire and silicon carbide. Currently, the growth of InN or indium-rich group III nitrides is very challenging due to reasons that will be explained later. However, if the relevant technical difficulties are overcome in future, there can be widespread applications for these materials and silicon can be an excellent material choice as a substrate.

The growth of GaN or AlN on silicon is particularly challenging. The lattice and thermal expansion mismatches for these materials are particularly high. Moreover, the direction of these mismatches causes the resultant nitride film to experience a lot of tensile stress after growth, which if left unmanaged, can easily result in cracked films. Furthermore, the silicon material can react with the nitrogen source during growth, forming a layer of amorphous silicon nitride [10]. This amorphous layer can be detrimental to the subsequent epitaxial growth process. For LED applications, the silicon material can absorb some light away from the LED, resulting in reduced light output.

Although the lattice-mismatch of GaN with Si (111) is significantly higher than with sapphire and SiC substrates, GaN-on-Si (111) films generally do not suffer from significantly higher dislocation densities. As the lattice-mismatch goes beyond 2%, the dislocation densities of the incoherent films generally do not increase much with further increases in lattice-mismatch. Therefore, GaN-on-Si (111), GaN-on-sapphire, and GaN-on-SiC films have fairly constant dislocation densities of 10^9 cm^{-2}, despite having a wide range of lattice mismatch of magnitudes 3 – 20 % [19].

For the growth of GaN on silicon substrates, multiple (> 3) alternate buffer layers of AlN-GaN [11, 18, 24, 25] are usually required to help introduce compressive strain in order to prevent cracking (figure 7). The formation of the amorphous silicon nitride layer is usually avoided by exposing the substrate to the III source to form a monolayer of III-precursors on the surface, before introducing the N source into the reaction chamber. Light absorption by the silicon substrate can be reduced by using reflective surfaces such as the Si/SiO_2 interface in a nano-SOI substrate (figure 8) [11].

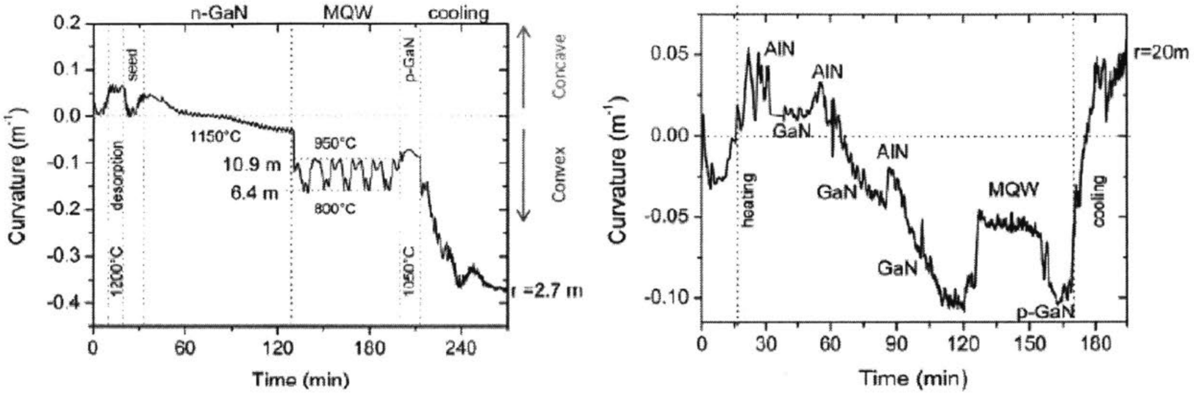
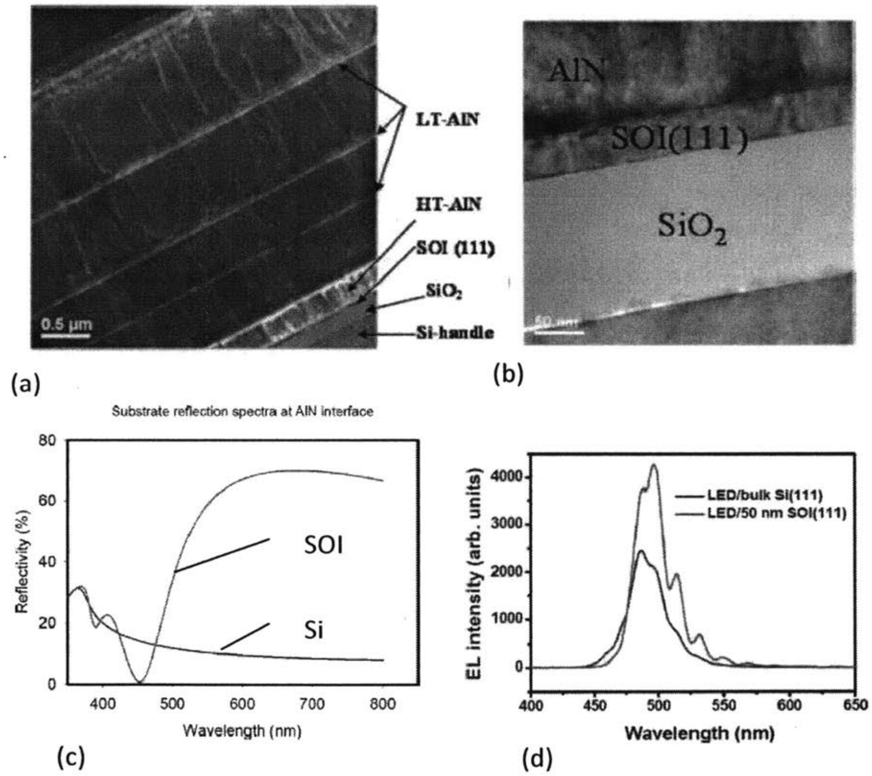


Figure 7: In situ curvature measurements during the MOCVD growth of an LED structure on 2-inch sapphire (left) and silicon (right) substrates. Upon cooling after growth, the epilayers on sapphire experience residual compressive strain (convex bowing), while the epilayers on the silicon (111) substrate experience residual tensile strain (concave bowing). The tensile strain on silicon substrates is reduced by adding a series of AlN/GaN buffer layers. [18]



(a) (b) (c) (d)

Figure 8: (a) Cross-section TEM of GaN grown on SOI. Three low temperature (LT) AlN interlayers are grown between GaN for strain compensation. (b) XTEM of 50 nm SOI (111)/150 nm buried oxide substrate. (c) Calculated internal reflection spectra of substrates as seen by light incident from the AlN layer. (d) Electroluminescence (EL) spectra of InGaN/GaN quantum well LEDs grown on 50 nm SOI(111) and bulk Si (111) at 7 mA. [11]

3. Commercial applications

3.1. White LEDs for general lighting applications

Electrical lighting is indispensible to everyone's life, with an estimated 30 billion light bulbs on earth consuming 2,650 TWh of energy per year or 19% of the total electricity generated globally [2]. Given the concerns over global warming and CO_2 production, together with the recent drive towards greener technologies, the energy-efficient and environmentally-friendly white LEDs are attractive as alternatives to incandescent light bulbs and fluorescent lamps for general lighting purposes. White LEDs are much more energy-efficient than incandescent bulbs and do not contain toxic chemicals like mercury which is found inside fluorescent lamps.

LEDs have been routinely used in signaling and indicator applications for many years. General lighting applications typically involve higher flux (> 1000 lm) and require higher efficiencies (> 100 lm/W) [2]. Compact fluorescent lamps (CFLs) can operate at these specifications and are rapidly replacing incandescent lamps in the general lighting market [26]. While newer high-brightness white LEDs are able to operate at these efficiencies and have much longer lifetimes, their adoption is hindered by their high unit costs. For an operating period of 60,000 hours, assuming similar light outputs per bulb, we need 1 LED, 8 CFLs, or 80 incandescent lamps based on their respective lifetimes (table 3). The high unit cost of $80 per LED, compared to $3 per CFL and $0.25 per incandescent lamp can deter the most consumers from purchasing LEDs. Even with the advantages of high electrical efficiency and device lifetime, the total cost of LED lighting is only slightly lower than that of CFL.

Table 3: Operational life cost comparison between incandescent lamps, compact fluorescent lamps (CFL), and LEDs, assuming similar light outputs per bulb. [26]

CHARACTERISTIC	INCANDESCENT	CFL	LED
1. Life (hour)	750	7500	60,000
2. Number of bulbs	80	8	1
3. Cost of bulbs	$20.00	$24.00	$80.00
4. Watts consumed	100	20	9
5. Electrical operating cost	$800.00	$120.00	$54.00
6. Total cost	$820.00	$144.00	$134.00

The state-of-the-art commercial white LEDs are typically InGaN/GaN multiple quantum well LEDs grown and fabricated on sapphire or silicon carbide substrates. The device operates in forward-bias where charge carriers are injected into the nm-thick quantum well layers and recombine to emit light. Carrier confinement in the InGaN quantum wells by the larger bandgap GaN barrier layers enables higher recombination efficiencies compared to conventional *p-n* diodes. The emitted blue light is passed through a phosphor layer which results in the emission of white light. The high unit cost of these LEDs relative to CFLs has motivated many research groups to fabricate InGaN/GaN LEDs on silicon substrates [11, 13, 18, 24, 25, 27, 28] over the last five years. In 2009, Azzurro Semiconductors licensed its GaN-on-Si technology to Osram for further development into LEDs, in a step that brings the technology closer to commercialization [29]. Azzurro Semiconductors is a spin-off from Alois Krost's research team at the Otto-von-Guericke University, Magdeburg, Germany.

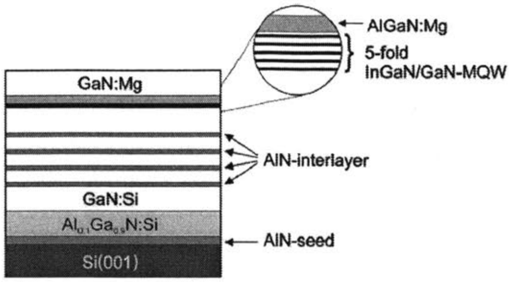


Figure 9: Schematic structure of an InGaN/GaN multiple quantum well (MQW) LED on a silicon substrate. *p*-type doping is achieved with Mg (GaN:Mg) and *n*-type doping is achieved by Si (GaN:Si). [24]

In the 2009 Solid-State Lighting Manufacturing Roadmap [3], the packaged LED device costs about 40% of an LED and was targeted for reduction to about 5% by 2015 (figure 10). A switch to cheaper substrate technologies like silicon would appear to be very appealing. However, the cost analysis in the same report also indicated that 80% of the manufacturing cost of an LED device is associated with back end processes like die packaging and phosphor deposition, emphasizing a preference to reduce costs in these areas. This suggests that GaN-on-Si technologies, which impact wafer processing, epitaxy, and substrate portions of the cost analysis, may not be particularly attractive at this moment, but may be important in the longer term (e.g. 3-5 years later) as the bottleneck problems associated with backend processing are resolved. However, if the GaN-on-Si epitaxial process is scalable to large 200 mm Si wafers with uniform yields, the increase in throughput can be useful in reducing the current costs of backend processes.

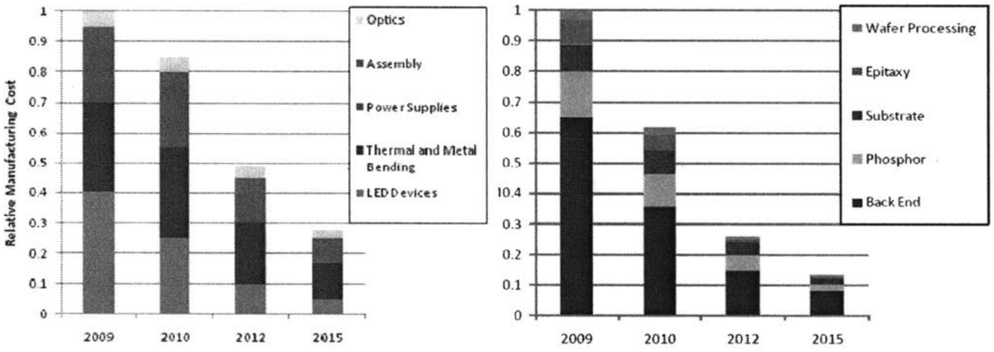


Figure 10: Projected manufacturing cost tracks of LED luminaires (left) and packaged LED devices (right). [3]

As mentioned earlier in Section 2.3, the growth of GaN on silicon would require more complex multiple AlN/GaN buffer layers in order to account for lattice and thermal expansion mismatches, resulting in increased costs associated with epitaxy. Therefore, for silicon to be cost-effective relative to sapphire and silicon carbide, large diameter (≥ 200 mm) wafers should be adopted to reduce epitaxy costs by leveraging on high throughput production. However, the use large wafers will result in wafer bowing being more pronounced, affecting product yields.

In summary, while significant progress has been made in recent research on high-brightness GaN-on-Si LEDs, LED manufacturers may not be very eager to adopt these technologies now as they are currently more concerned with lowering costs associated with backend processes and phosphor deposition. However, GaN-on-Si technology may provide significant cost advantages in future. To achieve this, large-diameter Si substrates must be utilized while the resultant GaN-on-Si epilayers must have uniform qualities and the LED devices must be able to perform at high efficiencies (> 100 lm/W).

3.2. Blue laser diodes

The commercialization of the blue laser diode in the late 1990s [1] brought along a host of new applications including high density optical storage and other high resolution applications in laser printing, optical scanning, and optical lithography [4]. Of all these applications, high density optical storage has proved to be the most promising, based on its developments over the last few years.

For optical storage discs, their storage density is controlled by the spot size of the recording/reading laser beam. The resolution of the spot size is diffraction-limited to the order of the wavelength of the laser. Therefore, the replacement of red lasers (for DVDs) by blue lasers (for Blu-ray discs) can result in optical storage discs that have smaller pits and higher pit densities, resulting in up to four times more data being packed into a single disc [4]. The Blu-ray system has a large recording capacity of 27 GB and a high-speed transfer rate of 38 MB/s, compared to the DVD system which has a capacity of 4.7 GB and transfer rate of 11 MB/s.

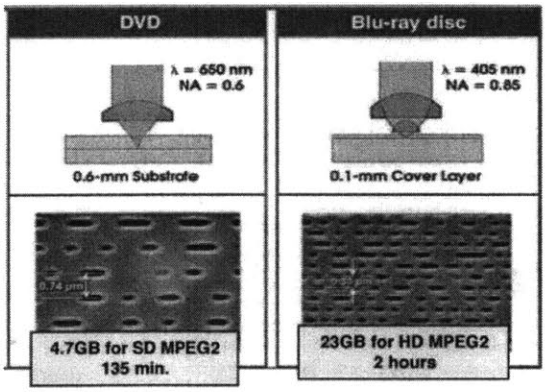


Figure 11: Comparison of the sizes of laser beam spot and storage pits from DVD and Blu-ray systems. [4]

In the US, the sale of Blu-ray discs and players rose by 67% in 2009 to $1.5 billion, while the number of households with Blu-ray disc players increased by 76% to 17 million over the same period [30]. In future, 3D video may be available in our living rooms, driving up further demand for high-density optical storage. In 2010, the Hollywood 3D movie "Avatar" sold 2.7 million Blu-ray discs over just four days in North America, setting a new sales record despite TV screens being unable to display 3D graphics then [31]. With the increasing popularity of high resolution HDTVs, the demand for high-definition video will mean that sales of Blu-ray discs and Blu-ray players will continue to grow, resulting in great opportunities for blue laser diodes.

Currently, epitaxial GaN grown on silicon, sapphire, or silicon carbide substrates have dislocation densities in the order of 10^9 cm^{-2} [19]. While this level of material quality is adequate for LEDs, blue laser diodes require higher-quality epitaxial GaN layers and are typically fabricated on epitaxial lateral overgrowth (ELO) substrates [32] or free-standing GaN bulk substrates. GaN ELO substrates are usually made by starting with an epitaxial GaN layer grown on a substrate like sapphire or silicon. A dielectric layer (e.g. SiO_2 or SiN_x) is then deposited on the epitaxial GaN layer and patterned into stripes to form a growth mask. In the subsequent regrowth process, GaN grows out of the opening of the mask and coalesces laterally over the mask to form an ELO substrate [17]. This process results in high-quality epitaxial GaN forming at the region above the mask which lowers the overall dislocation density to 10^6 cm^{-2}, enabling the commercialization of blue laser diodes with continuous lasing lifetimes of above 10,000 h [17, 32].

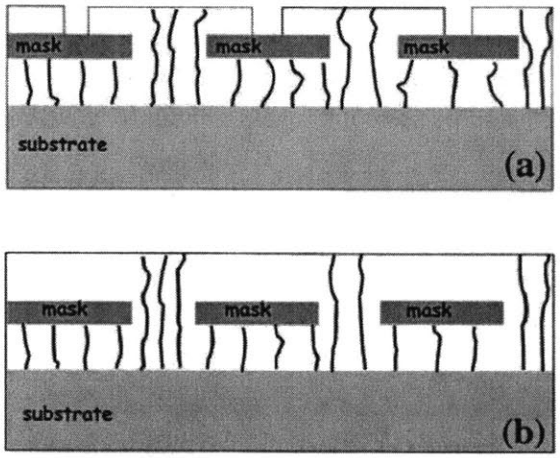


Figure 12: Typical ELO growth process. (a) Lateral growth and (b) Coalescence of regrown GaN. [17]

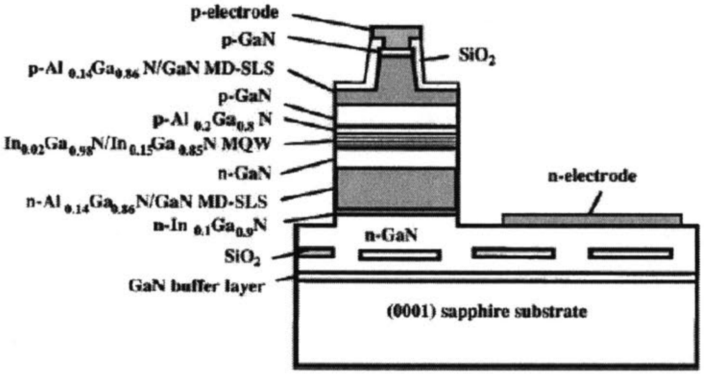


Figure 13: Structure of an InGaN multiple quantum well laser diode with AlGaN/GaN modulation-doped strained-layer superlattices (MD-SLS) as cladding layers. The structure is fabricated on an ELO GaN-on-sapphire substrate. [33]

An important step in the manufacture of laser diodes is the smooth cleaving of the laser chips after fabrication to expose smooth mirror-like faces. Therefore, the cleavability relationship (figure 14) between the substrate and epilayer is very important. Between SiC, sapphire (Al_2O_3), and silicon, SiC appears to be the best option in terms of cleavability, followed by silicon (111) [32]. The natural 30° rotation of GaN relative to sapphire can result in difficulties in cleaving. Techniques like laser lift-off

(Section 4.1) may be required to remove the GaN epilayer from the sapphire before cleaving, contributing additional process costs.

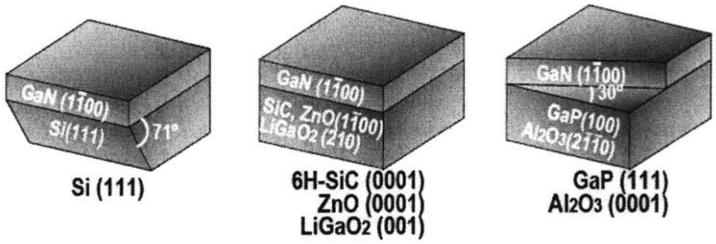


Figure 14: Cleavability relationship between GaN epitaxial film and substrate. [32]

For GaN-on-Si technology to be useful in blue lasers, the GaN film must be of a high quality with dislocation densities around 10^6 cm^{-2} or better. ELO techniques have been successfully applied on silicon [34, 35]. These demonstrations rely on anodized aluminum oxide templates for patterning, which employs a solution-based technique that is cost effective and yet readily scalable for large wafer sizes. These ELO GaN-on-Si substrates have reduced dislocation densities in the order of $10^7 - 10^8$ cm^{-2}. A further reduction in dislocation densities would certainly be helpful for the adoption of these specialized GaN-on-Si technologies by laser diode manufacturers.

3.3. RF Devices

Currently, wireless frequencies range in the microwave region from several 100 MHz to several GHz. High-power devices (> 100 W) are already being used in applications like those found in broadcasting stations and communication satellites. As wireless communication frequencies increase in future due to increased information traffic, high-power devices will be in greater demand. [6] At higher frequencies, transmission distances decrease along with increases in circuit losses. Therefore, higher-power RF devices are necessary to secure communication reliability when transmitting using higher frequencies over the same spatial distance. High-power devices can also mean smaller equipment sizes at wireless facilities, resulting in cost savings.

Compared to Si and GaAs, GaN has larger bonding energies and smaller molecular masses which contribute to larger phonon energies, resulting in them being more resistant to lattice scattering and having a higher saturation drift velocity [6]. GaN also benefit from higher breakdown fields, lower intrinsic carrier concentrations, and lower thermal current leakage at junctions due to its large bandgap.

Table 4: Important material parameters of wide bandgap semiconductor materials for high-power applications [6]

Material	E_g (eV)	ε	μ_n ($cm^2 V^{-1} s^{-1}$)	E_c (10^6 V/cm)	v_{sat} (10^7 cm/s)	κ ($W cm^{-1} K^{-1}$)	Band type
Si	1.1	11.8	1350	0.3	1.0	1.5	I
GaAs	1.4	12.8	8500	0.4	2.0	0.5	D
c-GaN	3.27	9.9	1000	1	2.5	1.3*	D
h-GaN	3.39	9.0	900	3.3	2.5	1.3	D
3C–SiC	2.2	9.6	900	1.2	2.0	4.5	I
6H–SiC	3.0	9.7	370^a, 50^c	2.4	2.0	4.5	I
4H–SiC	3.26	10	720^a, 650^c	2.0	2.0	4.5	I
AlN	6.1	8.7	1100	11.7	1.8	2.5	D
Diamond	5.45	5.5	1900	5.6	2.7	20	I

a: along *a*-axis, c: along *c*-axis, *: estimate

E_g: bandgap energy, ε: relative dielectric constant, μ_n: electron mobility, E_c: breakdown electric field, v_{sat}: saturated drift velocity of electron, κ: thermal conductivity

Compared to other high-power RF devices like SiC MESFETs, AlGaN/GaN HEMTs have the advantage of a 2DEG flowing in an intrinsic material where the electrons have very high mobility as they do not suffer from impurity scattering. As the polar AlGaN/GaN material is grown in the [0001] direction, spontaneous polarization along the growth direction and the piezoelectric polarization due to the strain at the heterointerface can generate sheet carrier densities of 10^{13} cm^{-2}, typically an order of magnitude higher than non-polar AlGaAs/GaAs 2DEGs [6, 36, 37]. This compensates the reportedly lower carrier mobility of GaN in high-current operation. The higher electron mobility of AlGaN/GaN HEMTs allows these devices to operate at very high frequencies that can exceed 100 GHz [38-41]. Currently, due to its high thermal conductivity which is especially useful in the heat dissipation of high-power devices, SiC substrates are typically used in the manufacturing of AlGaN/GaN HEMTs.

Cree Inc. is a leading manufacturer of SiC wafers and SiC electronic devices. The company has also been very successful in fabricating AlGaN/GaN HEMT devices on their SiC substrates. A list of selected RF devices manufactured by Cree was examined.

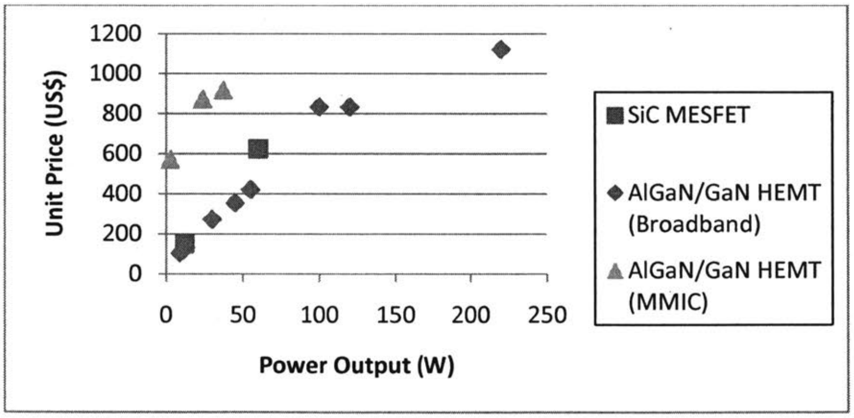


Figure 15: Prices of Cree's RF devices as a function of power output. (See appendix for more information)

From figure 15, the price of Cree's RF devices increases linearly with output power, emphasizing the earlier discussion on the value of high-power devices for high-frequency RF applications. SiC MESFETs appear to be similarly priced as the broadband AlGaN/GaN HEMTs. Monolithic microwave integrated circuit (MMIC) AlGaN/GaN HEMTs are priced at about US$500 higher than corresponding broadband devices of the same power output. For broadband applications, the cheapest device cost US$101.91 and operates at 2 GHz while producing a relatively low power output of 9 W. A linear regression of the data estimates that the price of broadband devices increases with output power at a rate of US$5/W.

Nitronex Corp. specializes in the growth of GaN on silicon substrates and the subsequent use of the GaN-on-Si substrate for fabrication of HEMT devices. Compared to SiC wafers, silicon wafers are available at lower cost and at greater purity. Silicon wafers are also available in large diameters (> 200 mm) compared to typically small SiC wafers (50 – 100 mm), resulting higher throughput production and reduced unit costs. Unfortunately, the price of Nitronex's products cannot be obtained directly from the Nitronex website for comparison with Cree products.

The power and frequency of RF devices from Cree and Nitronex are compared (figure 16), together with silicon RF products from Polyfet. By a general analysis of the power vs. test frequency values of these products, we can observe the ecology of the present RF device market. Silicon-based lateral diffused metal oxide semiconductor (LDMOS) and vertical diffused metal oxide semiconductor (VDMOS) dominate low-frequency (< 1.5 GHz) RF applications. The sheer variety of the products in this narrow frequency range is also testament to the maturity of these technologies. Given the low cost and high-power performances of silicon RF devices at these frequencies, III-V RF devices tend to differentiate themselves by targeting higher frequencies.

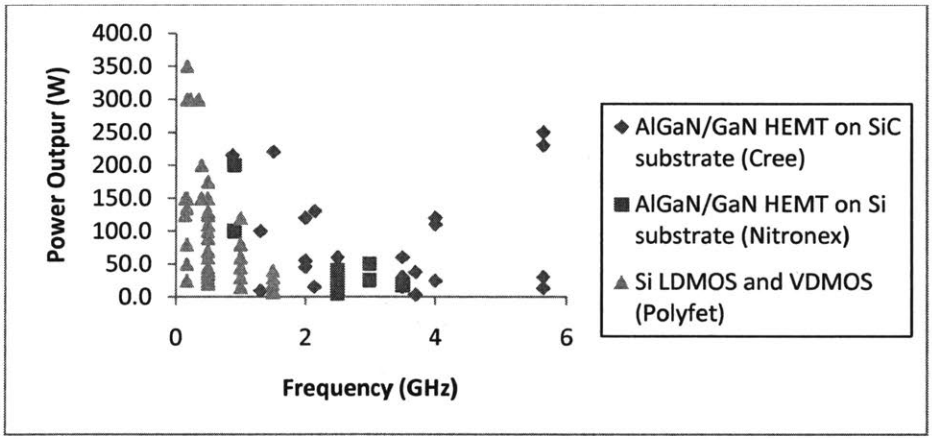


Figure 16: Comparison of AlGaN/GaN HEMTs with Si RF devices. (See appendix for more information)

GaAs pseudomorphic HEMTs (pHEMTs) operate with a 2DEG in a thin pseudomorphic InGaAs layer between AlGaAs and GaAs. The InGaAs layer has a large conduction band offset with AlGaAs which allows for high electron densities. Electron mobility is also higher in InGaAs than in GaAs. These design features allow GaAs pHEMTs to be very useful at high frequency operation beyond 3 GHz. GaAs pHEMTs also benefit from the use for GaAs wafers which are cheaper and larger then SiC wafers. However, their small bandgap energy limits the capacity for high-power operation. A selection of GaAs pHEMTs (not shown in figure 16) from RF Micro Devices Inc. that are designed as power switches for military and space applications can operate at frequencies up to 20 GHz but with limited power outputs below 50 W (see Appendix).

While Si and GaAs devices dominate high-power/low frequency and low-power/high frequency applications respectively, AlGaN/GaN HEMTs find a niche in high-power/high-frequency applications. This is reflected by the distribution of the Cree's products in the power output vs. frequency plot. As a relatively young company (founded in 1999), the range of Nitronex's products is rather limited compared to Cree. Nevertheless, their GaN-on-Si HEMTs are able to outperform silicon devices while being on par with the lower-frequency range of Cree's products. Nitronex's inability to commercialize a product to compete with Cree's higher-power/higher-frequency products could be due to poorer heat dissipation by the silicon substrates.

Apart from RF devices, GaN is also poised to be important power management devices in future. In a study by the market research firm iSuppli Corp. in 2010, the market for GaN power management semiconductors can reach US$183.6 million in revenue by 2013. This is an astonishing figure considering that the market is virtually non-existent at the moment. According to iSuppli, this can be made possible by progressive cost reduction of GaN technology through means like GaN-on-Si technology. It was estimated that by 2013, the cost of GaN power devices can be low enough for these high-power and efficient devices to be adopted in portable electronic products like smart phones and mobile computers, replacing conventional silicon power devices. [42]

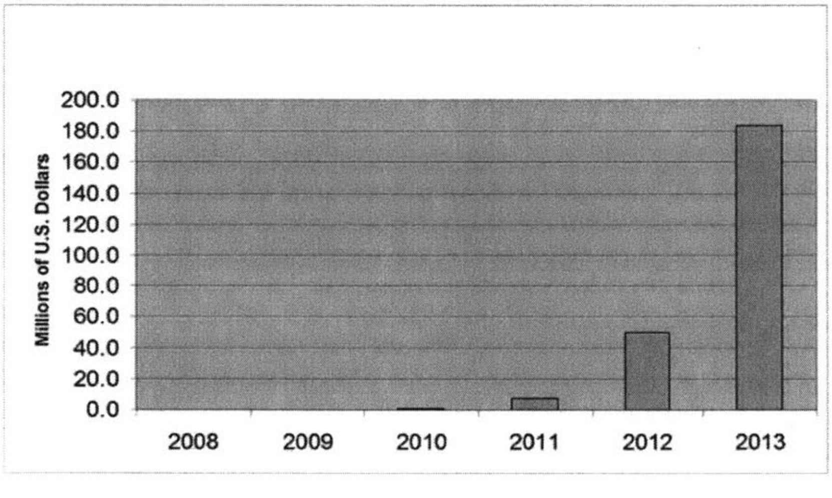


Figure 17: Global gallium nitride power management semiconductor revenue forecast. Source: iSuppli Corp., retrieved via EDN website at [42].

In summary, AlGaN/GaN HEMTs can be very useful in high-power/high-frequency devices. These devices can be very useful in applications found in wireless base stations and satellite communication. They are also expected to be important as power management devices in portable electronics. It was demonstrated by Nitronex that silicon-based AlGaN/GaN HEMTs match up with silicon carbide-based AlGaN/GaN HEMTs, with the former expected to be cheaper due to cheaper silicon substrates. It is a motivation for silicon-based AlGaN/GaN HEMTs to push towards higher-output power/higher-frequency performances.

3.4. Key findings from market analysis

We have performed a review of the white LED, blue laser diode, and the III-N HEMT markets. Here is a summary of our findings and recommendations:

Table 5: Key findings from the analysis of white LED, blue laser diode, and III-N HEMT markets

Device Type	InGaN/GaN LEDs	InGaN/GaN laser diodes	AlGaN/GaN HEMTs
Application	White LEDs for general lighting	Blue laser diodes (405 nm) in Blu-Ray players	RF devices for wireless applications
State-of-the-art substrates	GaN-on-sapphire GaN-on-SiC	ELO GaN-on-sapphire Bulk GaN substrates	GaN-on-SiC
Possible impact of GaN-on-Si technologies	Not important at this moment, unless able to obtain consistent yields with large diameter (200mm) wafers, which can help reduce backend costs. Will be very useful after 3-5 years.	Can offer significant cost savings by replacing expensive bulk GaN substrates.	Offer cost savings. More useful if applied for high-power (> 100W) and high-frequency (> 3 GHz) devices.
Typical GaN dislocation densities	10^{9} cm^{-2}	10^{6} cm^{-2}	10^{9} cm^{-2}
Possible GaN-on-Si substrates	GaN on planar Si substrates	ELO GaN on patterned Si substrates	GaN on planar semi-insulating Si substrates

4. Implementation issues

Our analysis of III-N applications in white LEDs, blue laser diodes, and RF devices appeared to conclude that GaN-on-Si technology can be very useful under various scenarios. Earlier in Section 2, we observed that GaN-on-Si technologies are approaching maturity, with successful growth being performed by many groups around the world. For these laboratory results to be truly meaningful, we need to translate them into useful commercial products. This section seeks to outline an approach for these technologies to be implemented in the marketplace.

4.1. Supply chain analysis

A possible supply chain for group III nitrides-on-silicon technologies begins with the substrate material (silicon wafers), followed by the growth of the III-N material, which is then used to fabricate devices like LEDs, HEMTs, and laser diodes. The devices are then packaged before being shipped to distributors and customers for sale.

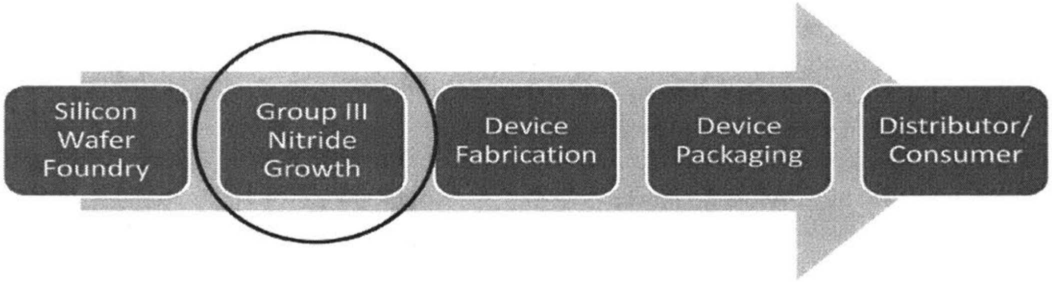


Figure 18: Expected supply chain for the implementation of group III nitride-on-silicon technologies

Where do we fit in this supply chain? We can decide based on certain assumptions:

1) A typical university-linked startup
2) Limited funds for expensive production equipment and many employees
3) Strong technical knowledge in growth of group III nitrides on silicon

We can discount 'silicon wafer foundry' as silicon wafers are already very cheap and widely available and therefore it is not necessary for us to produce them in-house. Device fabrication is likely to be the most capital intensive of the various entities in the supply chain, involving many expensive thin-film processing equipment. Since our core competency is in III-N growth on silicon, it is more prudent for us to focus on this stage of the supply chain. Specifically, we should focus on providing GaN-on-Si technology for the device manufacturers, like Philips Lumileds as GaN is currently in high demand. Furthermore, we should look for device manufacturers who do not manufacture their own substrates, so that they will be more receptive to our technology.

Our technology faces competition from other GaN-on-silicon technologies and bulk GaN substrates. Nitronex makes AlGaN/GaN HEMTs for RF applications on their GaN-on-silicon wafers, while Azzurro licensed their technology to Osram in 2009 for further research into GaN-based LEDs using 150 mm silicon wafers [29]. These two privately-held companies are only established recently and have yet to establish monopolies in the marketplace. Therefore, there are still plenty of opportunities available in the marketplace for us to take advantage of. As Nitronex is currently focused on RF devices and Azzurro only beginning to produce GaN-on-Si wafers in 2010, we can differentiate ourselves from the competition by customizing our GaN-on-Si technologies in close cooperation with LED, laser diode, and RF device manufacturers.

Bulk GaN substrates meeting practical size, cost, and quality requirements are not presently available for LED manufacturers, [3] while most AlGaN/GaN HEMTs are based on SiC substrates . While the use of bulk GaN substrates in the manufacture of LEDs lowers epitaxy and back-end costs due to simpler buffer layers and improved uniformity and yields, the substrates cost ten times higher than even SiC, resulting in the overall costs increasing by a factor of three (figure 19). Bulk GaN substrates are currently adopted by some blue laser diode manufacturers along with ELO GaN substrates due to their demand for good-quality substrate materials.

Most bulk GaN substrates are fabricated by hydride vapor phase epitaxy (HVPE). The HVPE process starts with the reaction between gaseous HCl and liquid Ga to form GaCl gas. The gaseous GaCl then reacts with gaseous NH_3 on a substrate (e.g. sapphire) to form GaN crystals. A unique feature of this technique is that some of the normally vertical threading dislocations bend to create loops during growth. As a result, the surface dislocation density can be reduced to 10^6 cm^{-2} for thick (300 μm) GaN layers [2, 43].The GaN epilayer can be removed from sapphire substrates by a laser lift-off process (figure 20) [43]. In this process, a Nd:YAG (355 nm) laser pulse is passed through the sapphire substrate. Sapphire is transparent to this wavelength but GaN crystals at the interface absorb the radiation and decompose into gaseous Ga and nitrogen, resulting in separated bulk GaN substrates. The adoption of this technology is currently limited by the very small wafer sizes (50 mm) and their high prices.

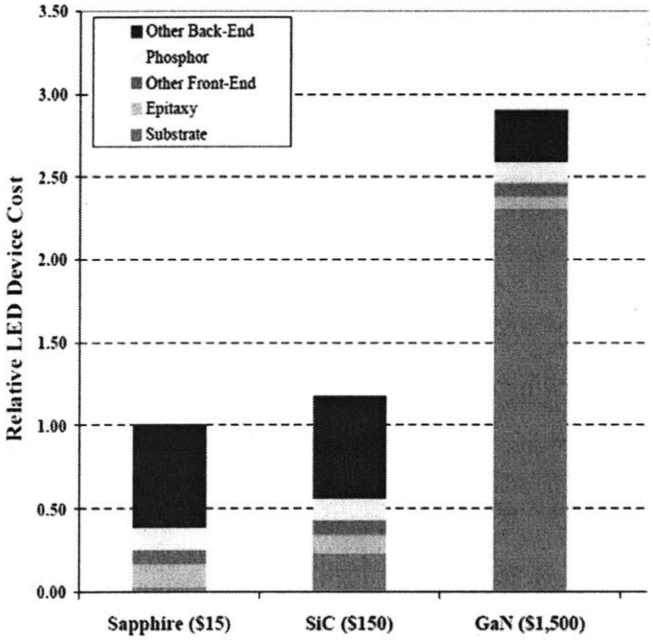


Figure 19: Impact of substrate selection on relative costs of main process steps of a final packaged white LED device. [3]

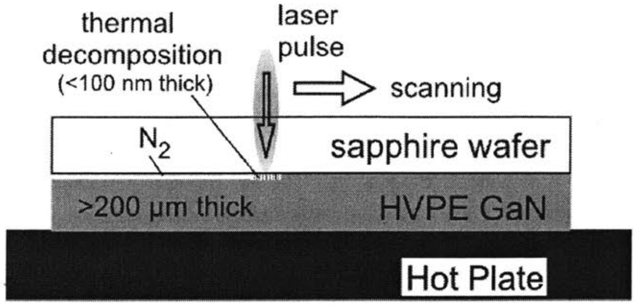
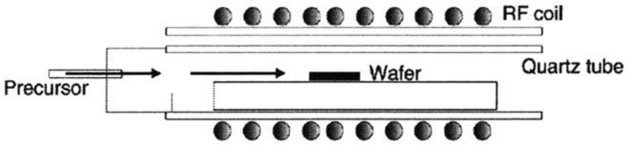


Figure 20: Schematic diagram of a laser lift-off process for separating bulk GaN crystals from the sapphire substrate after HVPE growth. [43]

4.2. Material growth

Metal organic chemical vapor deposition (MOCVD) is currently the most popular growth process for III-N materials. In this process, the gaseous organic precursors are passed over a heated substrate and react chemically to form a semiconducting layer. The process is very well developed over the years as it is routinely used for the growth of other III-V compound semiconductors for optoelectronics and electronics devices. Typical deposition rates for GaN (1-10 µm/min) are usually higher than those of other processes like molecular beam epitaxy, which can be important in productivity. MOCVD also enables precise control over the deposition of nanometer-thickness films (e.g. for quantum wells), in which HVPE struggles to achieve. A drawback of this technique is carbon impurities from the organic precursors which may affect the electronic properties of the resultant semiconductor material. The key parameters that require optimization usually include the substrate temperature, V/III ratio of precursors, and the chamber pressure.



$Ga(CH_3)_3$ (v) + NH_3 → GaN (s) + $3CH_4$ (v) (l)

•AlN or InN obtained by replacing Ga with Al or In

Figure 21: Schematic diagram of an MOCVD system. [19]

Another important material growth method is molecular beam epitaxy (MBE), which is the most popular method for III-N growth after MOCVD. This technique involves the reaction of molecular, atomic, or ionized beams of constituent elements on a heated substrate. Ga, Al, and In sources originate from effusion cells, while the nitrogen source can be from ammonia or from an RF-plasma source of nitrogen. This method typically involves lower deposition temperatures (600°C for GaN) than for MOCVD (> 1000°C for GaN). However, this process requires an ultra-high vacuum condition (10^{-11} mbar), which can be costly to build. Also, its growth rates for GaN (1 µm/h) are much lower than MOCVD. The cost of an MBE system is higher than a comparable MOCVD system because the ultra-high vacuum conditions result in a lot of stainless steel volume for a given rate of material production. The required distance from the sources for good uniformity combined with the vacuum requirement means that the physical size of an MBE machine is large, and it gets uncontrollably large as we try to deposit on multiple wafers that are large and require excellent uniformity. Thus, the scaling of an MBE machine results in a drastic scaling of costs.

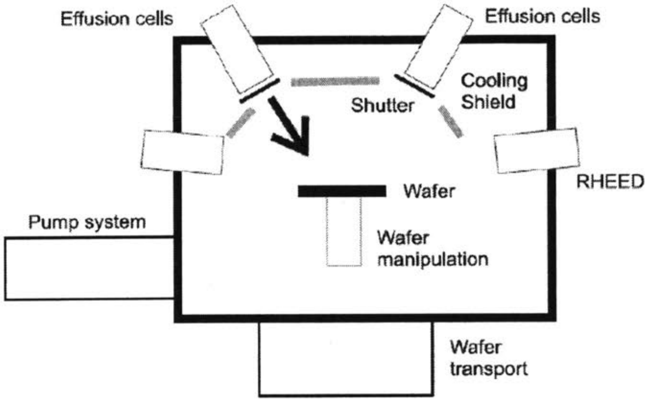


Figure 22: Schematic diagram of an MBE system. [19]

MOCVD is adopted in the manufacture of most InGaN/GaN LEDs and laser diodes, while both MOCVD and MBE are used to make AlGaN/GaN HEMTs. MBE allows for precise control of the interface between heterostructures, which is very important in HEMT devices and can outweigh the drawbacks of slow deposition rates and high costs. In our scenario, we are more interested in the cost-effective growth GaN epilayers on silicon than in fabricating devices. Therefore, the MOCVD system should be adopted for our business.

As a startup organization with limited capital, it is very difficult to acquire production equipment. An MOCVD reactor system costs $2 million, excluding the clean-room facilities. Therefore, it is more feasible for us to go 'fab-less' by minimizing capital investment in production equipment. Given our assumed affiliation with a university, we can initially use the university's lab facilities to produce samples for our potential customers. Based on their responses, we can decide whether to produce GaN-on-Si wafers or license our technology to device manufacturers.

If we decide to go into production, we can rent production facilities from affiliated research institutes to perform pilot plant studies or to begin small-scale production. Subsequently, we can partner silicon wafer companies in cost-sharing and revenue-sharing deals for larger-scale production. An alternative to production would be to license the patented technologies to device manufacturers. This strategy minimizes capital investment, provides quick revenue, and frees resources that can be channeled towards developing 'longer-term' technologies for future commercialization (e.g. InN-on-silicon). A drawback of this option is that it may be difficult to ensure that the company that we are licensing to actually performs the implementation process in production.

4.3. Patents

Given the promising commercial opportunities offered by group III nitrides-on-silicon technologies, many groups have published relevant patents, especially for GaN-on-Si growth techniques. There are many different ways in which we can integrate GaN with silicon. A patent search (table 10 in appendix) was performed here, focusing on the buffer layer, as it is an important technology component that is commonly addressed.

The growth of an AlN buffer is particularly popular among many groups [44-46]. Aluminum nitride can be used to reduce lattice mismatch and promote the nucleation of GaN on silicon. A major difficulty in the growth of an AlN buffer is to prevent or control the formation of amorphous silicon nitride as the heated silicon surface is exposed to a nitrogen source. This is normally overcome by exposing the silicon surface to an aluminum source initially to form monolayers of aluminum on the surface [44]. The nitrogen source is then added to react with the aluminum layer to form AlN without forming silicon nitride. Alternatively, silicon nitride can be grown on purpose, but at elevated temperatures to form a single-crystal silicon nitride buffer for further material growth [46, 47]. MOCVD growth of GaN was also performed on silicon substrates using a variety of designs including AlGaN/GaN transition layers [48], superlattices [49], and ELO-style patterned substrates [50, 51]. Other buffer layers include silicon carbide [52] and boron phosphide [53].

This review exercise demonstrates that the GaN-on-Si technology is a very crowded field, especially for techniques related to AlN or AlGaN buffer layers. Given the wealth of knowledge already available in literature and patent databases, it is advantageous for prospective entrepreneurs to possess some earlier-patented buffer-layer technologies, from which they can subsequently build 'vertical patents' that encompass more complex designs like devices to facilitate the commercialization process. Otherwise, it is advised that they look into less-crowded fields like InN and In-rich nitrides, which can be very important for the long term.

4.4. Implementing GaN-on-Si technologies

Based on our analysis of the supply chain, material growth techniques, and a selection of related patents, we can now formulate a possible approach towards implementing GaN-on-Si technologies based on the following key points:

- Commercialize GaN-on-Si substrates
- Leverage on university facilities or rent fabrication facilities to produce samples for potential customers (device manufacturers)
- Decide whether to produce or license
- Use MOCVD for production
- Design products aimed at minimizing cost, while conforming to quality standards demanded by respective applications
- 'Fab-less' production, especially at early stages of commercialization
- Expand existing broad patents to include devices

5. InN and In-rich nitrides for future applications

5.1. Difficulties with MOCVD growth of InN films

Currently, it is very difficult to grow good-quality films of InN or indium-rich nitrides (e.g. $In_xGa_{1-x}N$, x > 0.2) especially with MOCVD [54-57]. In the MOCVD growth of InN, the growth temperature is typically at 450 – 550 °C to prevent the dissociation of InN. Considering that GaN is typically grown at around 1000°C, these are very low growth temperatures that limit the diffusivity of adatoms, resulting in numerous defects and voids in the material. The low growth temperatures are also believed to hinder the thermal decomposition of NH_3, resulting in very slow growth rates of 0.1 – 0.3 μm/h, compared to 1 – 2 μm/h in MBE systems.

While silicon (111) substrates have the lowest lattice-mismatch and very low thermal expansion-mismatch with InN, they have high surface energies that result in poor wettability of InN. Direct growth of InN on silicon often results in rough films with large grains (figure 24) [58]. Although InN films grown on nitrided sapphire are of a poorer quality (based on XRD measurements) than those grown on silicon, they have higher electron mobilities (figure 23), possibly due to increased diffusion along grain boundaries [58].

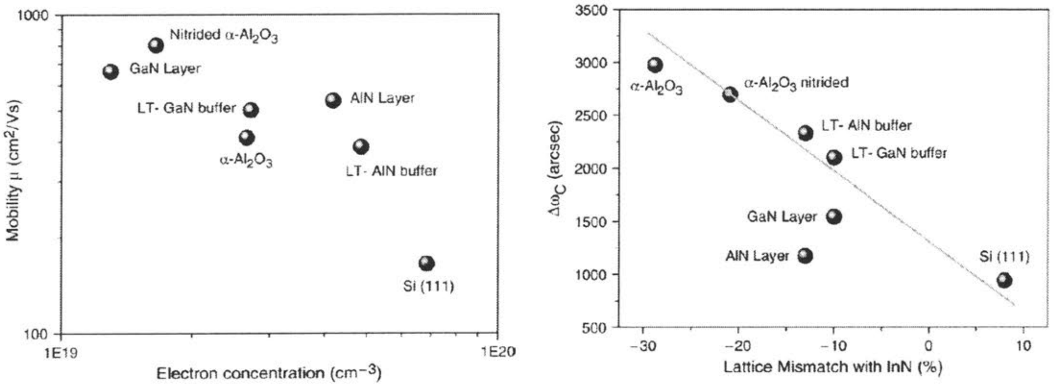


Figure 23: Room temperature electron mobility of InN grown on various substrates (left). Full width at half maximum $\Delta\omega_c$ of XRD rocking curve at the InN (0002) peak as a function of lattice mismatch of the various substrates (right). [58]

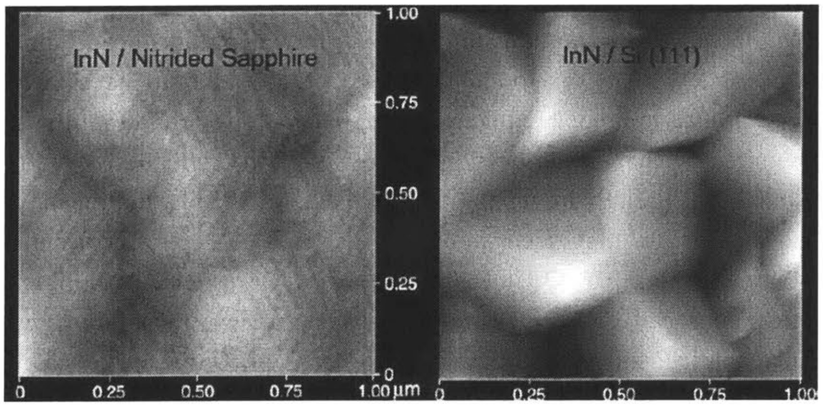


Figure 24: Morphology of InN grown on lightly-nitrided sapphire and Si (111) substrates measured by AFM(1 μm x 1 μm). [58]

While GaN is typically grown in hydrogen ambient, InN is typically grown in nitrogen ambient. At the same time, it was observed that the MOCVD growth rate of indium nitride increases with reducing V/III ratios (figure 26) [58]. As the reaction of ammonia on the substrate surface produces hydrogen gas as a by-product, it is likely that hydrogen could be involved in an etching reaction with InN, resulting in reduced growth rates. Maleyre et. al. [58] managed to increase growth rates to 0.4 µm/h by reducing the V/III ratio to 5000. They also found that indium droplets would be formed due to the dissociation of InN if they were to decrease the V/III ratio further.

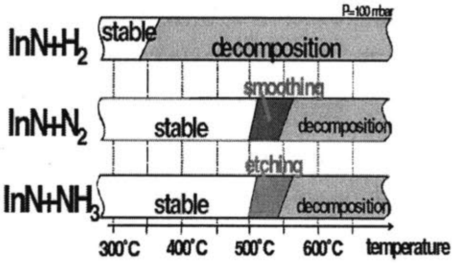


Figure 25: Thermal stability of MOCVD-grown InN at 100 mbar with various ambient gases: hydrogen (top), nitrogen (middle), and 25% nitrogen-75% ammonia (bottom). [59]

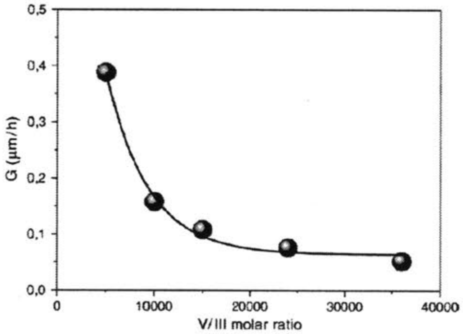


Figure 26: MOCVD growth rate of InN films for V/III ratios from 5,000 to 36,000. [58]

Having a high growth rate makes it easier to realize thicker films. InN and In-rich InGaN films are *n*-type as grown, with free electron concentrations ranging from mid 10^{17} to high 10^{20} cm^{-3} [60]. To enable *p*-doping, it is desirable for MOCVD-grown films to have their free electron concentrations reduced from 10^{18} cm^{-3} to 10^{17} cm^{-3} or lower. It was found that thicker films tend to have lower free electron concentrations and higher electron mobility (figure 27) [61]. It was also found that the electron mobility of most InN films is limited by charged dislocation scattering related to high dislocation densities (10^{10} cm^{-2}) and hydrogen impurities [62]. Hydrogen impurities can be reduced by thermal annealing, resulting in substantial improvements to the electron mobility and free electron concentration to levels comparable to MBE-grown films [61]. As InN films grown via GaN or AlN buffers have columnar structures, their dislocations can be better-controlled by increasing the lateral growth rate of the columns, encouraging coalescence and resulting in smoother films. One way to achieve this is to add organo-halide compounds such as $CBrCl_3$ during MOCVD growth (figure 28) [63].

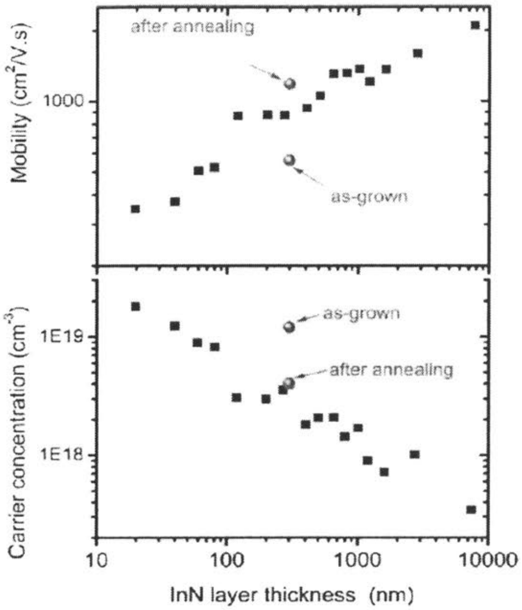


Figure 27: Room temperature Hall mobility and carrier concentration of InN layers grown by MBE (■) and MOCVD (●) as a function of the film thickness. Improvements in carrier mobility and concentration were achieved by thermal annealing in nitrogen for 1 h at 500 °C after growth. [61]

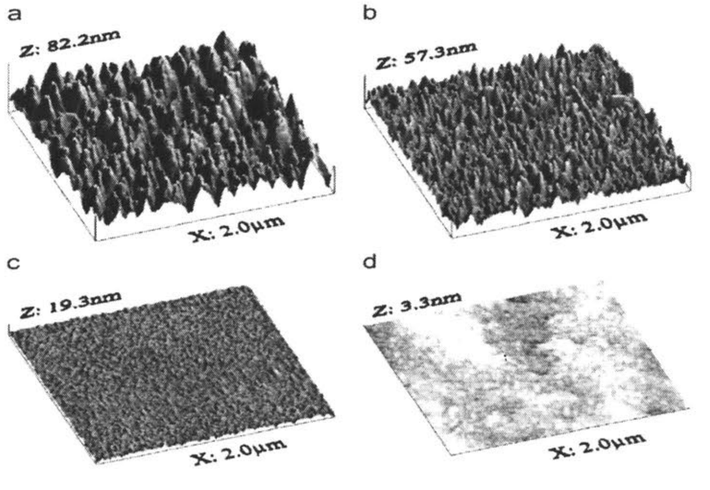


Figure 28: 2 x 2 μm2 AFM images of InN epilayer surfaces grown at 450 °C by MOCVD on GaN-on-sapphire substrates with increasing added $CBrCl_3$ in the gas phase. (a) $CBrCl_3$/TMIn = 0, rms roughness = 40 nm. (b) $CBrCl_3$/TMIn = 0.02, rms roughness = 25 nm. (c) $CBrCl_3$/TMIn = 0.04, rms roughness = 6.8 nm. (d) $CBrCl_3$/TMIn = 9.28, rms roughness = 1.6 nm. [63]

p-doped (usually by Mg) InN films have very high surface electron concentrations due to the high electron affinity of InN. The amphoteric defect model by Walukiewicz [64] describes a Fermi stabilization energy E_{FS} that could be used to pin the Fermi level of doped materials whose properties are controlled by defects. It was found that the Fermi stabilization energy of InN is well above the conduction band edge (figure 29), resulting in large surface electron accumulation [60, 65, 66]. The high concentration of electrons on the surface has resulted in unique results in *p*-type doping, in which the surface electrons can form a surface inversion layer followed by a depletion region in a *p*-bulk material (figure 30), resembling a native n^+/p junction [66]. While conventional Hall measurements may not be able to detect the bulk holes in a *p*-doped sample due to the surface electrons, a combination of sheet conductivity and electrolyte capacitance-voltage measurements can obtain information about bulk hole mobility and concentration [67].

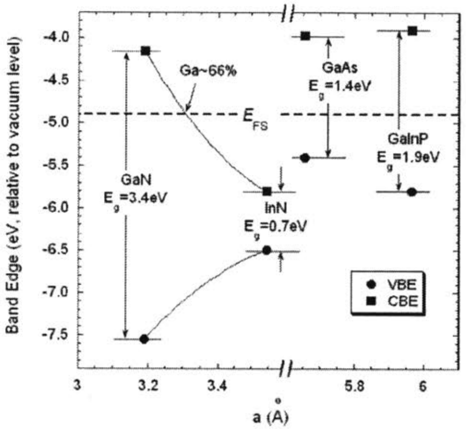


Figure 29: Position of the valence band maxima and conduction band minima for InGaN alloys, GaAs, and $Ga_{0.5}In_{0.5}P$. The Fermi stabilization energy (E_{FS}) at E_{vac} (energy relative to vacuum) = -4.9 eV is also shown. Note the high electron affinity (5.8 eV) of InN, which is larger than most semiconductors. [60]

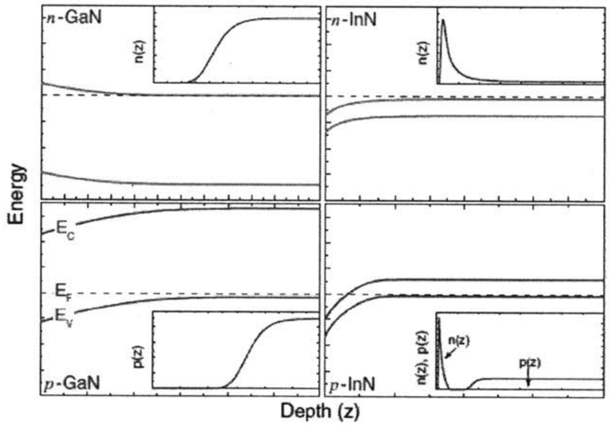


Figure 30: A schematic representation of the band bending relative to the Fermi level, EF, and corresponding electron (n(z)) and hole (*p*(z)) concentration variation (shown inset) in the near-surface region in n- and p-type GaN an InN. [68]

5.2. Potential applications of InN and In-rich nitrides

So far, the commercialization of InN and In-rich nitrides has been limited by difficulties with epitaxial growth. As the above-mentioned problems of i) high dislocation density, ii) slow growth rates, iii) low electron mobility, iv) high free electron concentration, and v) difficulties with *p*-doping are solved with improved epitaxial techniques and possibly with the novel use of nanostructures [69, 70], these narrow bandgap materials can be integrated with wider-bandgap GaN and AlGaN materials to create a new range of useful devices [57].

Future high-efficiency solar cells can be fabricated using tandem III-N layers with Si that capture a wide portion of solar radiation [71, 72]. A two-junction tandem solar cell can have materials with bandgaps of 1.1 eV (Si) and 1.8 eV ($In_{0.46}Ga_{0.54}N$), which is close to the combination that can theoretically result in maximum energy conversion for two-junction tandem solar cells [73]. Another benefit of this combination is that the conduction band of $In_{0.46}Ga_{0.54}N$ has the same energy relative to vacuum as the valence band of Si (figure 31), meaning that it is possible to form a low resistance Ohmic junction at the *n*-$In_{0.46}Ga_{0.54}N$/*p*-Si interface without the need for heavy doping. It was predicted that the efficiency of polycrystalline silicon solar cells can be increased by more than 50% (from 17% to 27%) by growing a tandem $In_{0.46}Ga_{0.54}N$ layer on it [73]. In addition, $In_{0.4}Ga_{0.6}N$ was shown to be more resistant to radiation damage than GaAs (figure 32), implying that InGaN-based solar cells can be a potential replacement for GaAs-based solar cells for satellite and space applications in future [57, 60].

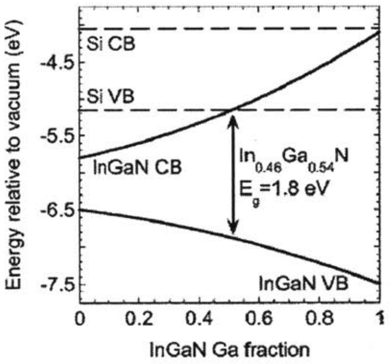


Figure 31: Energy diagram showing the conduction and valence bands of InGaN as a function of alloy composition. The conduction and valence bands of Si are shown for comparison. At an alloy composition of $In_{0.46}Ga_{0.54}N$, the bottom of the InGaN conduction band and the top of the Si valence band have the same energy relative to the vacuum. [71]

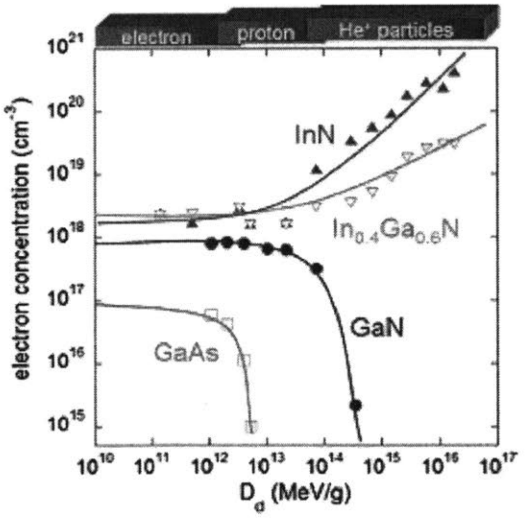


Figure 32: Changes in electron concentration when III-N materials are irradiated with high-energy particles. GaAs is also included for comparison. D_d = displacement damage dose. [57, 60]

Besides solar cells, indium-rich InGaN can be used to make red LEDs and integrated with blue and green gallium-rich InGaN LEDs to directly produce white light without power losses associated with phosphor conversion. One approach was demonstrated by using two sets of multiple quantum wells (MQWs) [74], with the lower set of $In_{0.35}Ga_{0.65}N$ MQWs emitting yellow light (430 nm) and the upper set of $In_{0.2}Ga_{0.8}N$ MQWs emitting blue light (570 nm). The blending of the two colors produced cool white light without the need for phosphor conversion (figure 33). Also, $InN/In_{0.7}Ga_{0.3}N$ MQWs was used for emission near 1.55 μm, suggesting future potential in fibre-optics communication [75]. In addition, InN is a potential replacement for ZnTe and InAs for terahertz generation [76]. Furthermore, AlGaN/GaN pseudomorphic HEMTs (pHEMTs) can be made with the growth of good quality pseudomorphic InGaN layer in the 2DEG region. As InGaN has higher electron mobilities than GaN, the resultant device can be expected to perform at even higher frequencies and switching speeds.

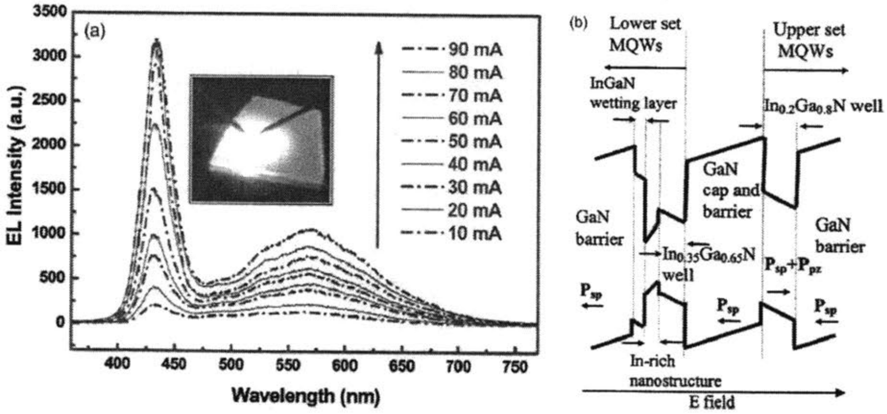


Figure 33: (a) Electroluminescence spectra at various injection currents of LEDs with two sets of multiple quantum wells. The inset shows cool white emission at an injection current of 40 mA. (b) Energy band of the LEDs. [74]

6. Commercialization Strategy

The preceding analysis on substrate materials, current and future commercial applications, and implementation issues related to supply chain management, material growth, and patents, have resulted in a variety of findings for group III nitrides-on-silicon technologies. What we need now is an action plan to provide a direction for commercialization.

A successful innovation process requires continuous interaction between the inventors and the supply chain partners. Since GaN-on-Si technologies are ready for commercialization, interested entrepreneurs should seize the opportunity to engage the industry before the market gets saturated. As mentioned in Section 4.3, some existing broad patents would be useful as starting points in a rather crowded research field. We have identified GaN-on-Si substrates as potential products, with an option of producing them or licensing the technology to device manufacturers. 'Fabless' production options described in Section 4.2 are recommended to enable quick and inexpensive production of samples for potential customers, whose responses would be crucial in deciding whether production or licensing would be applicable.

The interaction with customers will lead to better product design for commercially lucrative applications. Revenue generated from sales or licensing fees can be reinvested into longer-term InN-on-Si technologies and/or used to extend operations to include device fabrication. As the development of InN-on-Si technologies can result in environmentally-friendly applications like high-efficiency LEDs and solar cells, the relevant fundamental research conducted with universities can benefit from the current hype on 'clean energy' and obtain research funding from Government agencies. The continuous development and refinement of GaN-on-Si technologies can result in useful knowledge that can speed up the innovation and commercialization of InN-on-Si technologies.

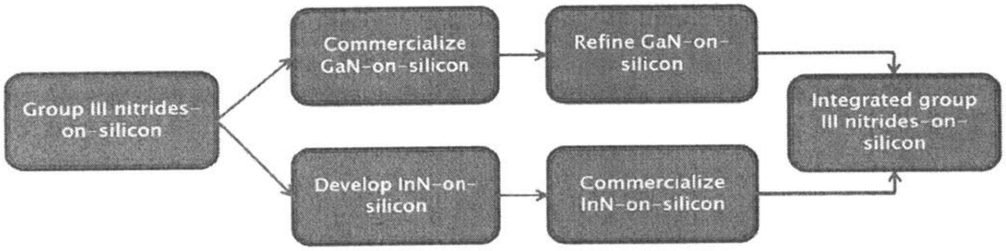


Figure 34: Flow chart of a possible business plan for the commercialization of group III nitrides-on-silicon technologies.

Lastly, GaN-on-Si and InN-on-Si technologies can be converged, resulting in innovative products and solutions based on the wide-ranging properties of the $In_xGa_{1-x}N$ alloy system. At the same time, AlN can be used for more applications other than as epitaxial buffers and potential barriers. The $Al_xIn_{1-x}N$ system can be exploited in future for further emerging applications. At this late stage, the company can be positioned as a specialist in the integrated design and manufacture of materials and devices that leverage on the properties on the entire III-N alloy system.

7. Conclusion

The analysis of group III nitrides-on-silicon technologies began with a comparison of silicon carbide, sapphire, and silicon substrate materials with respect to the epitaxial growth of III-N materials. It was found that despite silicon being an attractive substrate due to its low price, high purity, and large sizes, they often require the design and growth of complex buffer layers to account for its large thermal expansion mismatch with GaN.

In the market analysis, GaN-on-Si technology was positioned as a cost-effective alternative to competing GaN-on-sapphire and GaN-on-SiC technologies. It was found that GaN-on-Si technologies will be more effective in reducing the costs of white InGaN/GaN LEDs after 3-5 years. GaN-on-Si technologies can also be applied in making blue InGaN/GaN laser diodes, provided they can produce GaN epilayers with low dislocation densities ($< 10^6$ cm^{-2}). Lastly, GaN-on-Si technology can also be used to make AlGaN/GaN HEMTs that can perform in high-frequency/high-power operations.

An analysis of the supply chain resulted in an initial focus on material growth of GaN-on-Si substrates for device manufacturers. MOCVD growth was preferred to MBE and a 'fabless' production approach was recommended. Due to the crowded field, it may be difficult to develop new patents protecting new GaN-on-Si technology and further intellectual property protection by expanding existing broad patents to include a selection of devices may be necessary.

Lastly, we proposed an active approach towards commercialization, encouraging continuous interaction between the supply chain entities. This interaction can result in successful commercialization of GaN-on-Si technologies and the experience can benefit InN-on-Si technologies. Further positive developments in these fields can result in further commercialization of many new III-N products, resulting in the successful integration and commercialization of III-N materials and devices on silicon platforms.

Reference

1. Nakamura, S., S. Pearton, and G. Fasol, *The Blue Laser Diode*. 2000: Springer.
2. Mottier, P., *LEDs for Lighting Applications*. 2009: Wiley.
3. *Solid-State Lighting Research and Development: Manufacturing Roadmap*. 2009, U.S. Department of Energy.
4. Bergh, A.A. *Blue laser diode (LD) and light emitting diode (LED) applications*. in *5th International Symposium on Blue Laser and Light Emitting Diodes, 15-19 March 2004*. 2004. Germany: Wiley-VCH.
5. Lutgen, S., et al. *Progress of blue and green InGaN laser diodes*. in *Novel In-Plane Semiconductor Lasers IX, 25-28 Jan. 2010*. 2010. USA: SPIE - The International Society for Optical Engineering.
6. Okumura, H., *Present status and future prospect of widegap semiconductor high-power devices.* Japanese Journal of Applied Physics Part 1-Regular Papers Brief Communications & Review Papers, 2006. **45**(10A): p. 7565-7586.
7. Ueda, T., et al., *GaN transistors for power switching and millimeter-wave applications.* International Journal of High Speed Electronics and Systems, 2009. **19**: p. 145-52.
8. Matthews, J.W. and A.E. Blakeslee, *Defects in epitaxial multilayers. III. Preparation of almost perfect multilayers.* Journal of Crystal Growth, 1976. **32**: p. 265-73.
9. Matthews, J.W., A.E. Blakeslee, and S. Mader, *Use of misfit strain to remove dislocations from epitaxial thin films.* Thin Solid Films, 1976. **33**: p. 253-66.
10. Liu, L. and J.H. Edgar, *Substrates for gallium nitride epitaxy.* Materials Science & Engineering R-Reports, 2002. **37**(3): p. 61-127.
11. Tripathy, S., et al., *GaN-based microdisk light emitting diodes on (111)-oriented nanosilicon-on-insulator templates.* Journal of Applied Physics, 2008. **104**(5): p. 7.
12. Nakamura, A., et al., *Effects of sapphire substrate misorientation on the GaN-based light emitting diode grown by metalorganic vapour phase epitaxy*, in *Physica Status Solidi C - Current Topics in Solid State Physics, Vol 5, No 6*, T. Palacios and D. Jena, Editors. 2008. p. 2007-2009.
13. Zhu, D., et al., *GaN-based LEDs grown on 6-inch diameter Si (111) substrates by MOVPE.* Proceedings of SPIE - The International Society for Optical Engineering, 2009. **7231**: p. 11.
14. Weeks, T.W., Jr., et al., *GaN thin films deposited via organometallic vapor phase epitaxy on (6H)-SiC(0001) using high-temperature monocrystalline AlN buffer layers.* Applied Physics Letters, 1995. **67**. p. 401-3.
15. Nakamura, S., *The roles of structural imperfections in InGaN-based blue light-emitting diodes and laser diodes.* Science, 1998. **281**. p. 956-61.
16. Amano, H., et al., *Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer.* Applied Physics Letters, 1986. **48**. p. 353-5.

17. Vennegues, P., et al., *Reduction mechanisms for defect densities in GaN using one- or two-step epitaxial lateral overgrowth methods.* Journal of Applied Physics, 2000. **87**: p. 4175-4175.

18. Dadgar, A., et al., *Epitaxy of GaN LEDs on large substrates: Si or sapphire?* Proceedings of SPIE - The International Society for Optical Engineering, 2006. **6355**: p. 8.

19. Quay, R., *Gallium Nitride Electronics*. Springer Series in Materials Science and Engineering. 2008, Germany: Springer.

20. Michael E. Levinshtein, S.L.R., Michael S. Shur, *Properties of Advanced Semiconductor Materials - GaN, AlN, InN, BN, SiC, SiGe*. 2001, Canada: Wiley.

21. Arulkumaran, S., et al., *Electrical characteristics of AlGaN/GaN HEMTs on 4-in diameter sapphire substrate.* IEEE Electron Device Letters, 2003. **24.** p. 497-9.

22. Willander, M., et al., *Silicon carbide and diamond for high temperature device applications.* Journal of Materials Science-Materials in Electronics, 2006. **17**(1): p. 1-25.

23. Madar, R., *Materials science - Silicon carbide in contention.* Nature, 2004. **430**(7003): p. 974-975.

24. Schulze, F., et al., *Metalorganic vapor phase epitaxy grown InGaN/GaN light-emitting diodes on Si(001) substrate.* Applied Physics Letters, 2006. **88**(12).

25. Reiher, F., et al., *InGaN/GaN light-emitting diodes on Si(110) substrates grown by metal-organic vapour phase epitaxy.* Journal of Physics D-Applied Physics, 2009. **42**(5): p. 4.

26. Held, G., *Introduction to Light Emitting Diode Technology and Applications*. 2009: CRC Press.

27. Fenwick, W.E., et al., *Development of new substrate technologies for GaN LEDs: Atomic layer deposition transition layers on silicon and ZnO.* Light-Emitting DiodeProceedings of SPIE - The International Society for Optical Engineering, 2009. **7231**: p. 9.

28. Wakui, M., et al., *GaN-LED grown on SI substrate by MBE/MOCVD and monolithic fabrication of a light distribution variable device.* TRANSDUCERS 2009 - 15th International Conference on Solid-State Sensors, Actuators and Microsystems, 2009: p. 4.

29. http://www.ledsmagazine.com/news/6/11/16. *Azzurro transfers GaN-on-Si technology to Osram*. 2009.

30. http://www.blu-ray.com/news/?id=4009, *DEG: Consumers Spent $1.5 Billion on Blu-ray in 2009*. 2009.

31. http://www.variety.com/article/VR1118018252.html?categoryId=3762&cs=1, *'Avatar' shatters DVD and Blu-ray records*. 2010.

32. Matsuoka, T. *Nitride-semiconductor technologies for blue lasers*. in *Optomechatronic Micro/Nano Devices and Components, December 5, 2005 - December 7, 2005*. 2005. Sappora, Japan: SPIE.

33. Nakamura, S., et al., *Present status of InGaN/GaN/AlGaN-based laser diodes.* Journal of Crystal Growth, 1998. **189**: p. 820-825.

34. Zang, K.Y., et al., *Nanoheteroepitaxy of GaN on a nanopore array of Si(111) surface.* Thin Solid Films, 2007. **515**. p. 4505-4508.

35. Zang, K.Y. and S.J. Chua, *Orders of magnitude reduction in dislocation density in GaN grown on Si (111) by nano lateral epitaxial overgrowth*, in *Physica Status Solidi C - Current Topics in Solid State Physics, Vol 5, No 6*, T. Palacios and D. Jena, Editors. 2008, Wiley-V C H Verlag Gmbh: Weinheim. p. 1585-1588.

36. Asbeck, P.M., et al., *Piezoelectric charge densities in AlGaN/GaN HFETs.* Electronics Letters, 1997. **33**(14): p. 1230-1231.

37. Ambacher, O., et al., *Pyroelectric properties of Al(In)GaN/GaN hetero- and quantum well structures.* Journal of Physics-Condensed Matter, 2002. **14**(13): p. 3399-3434.

38. Higashiwaki, M. and T. Matsui, *AlGaN/GaN heterostructure field-effect transistors with current gain cut-off frequency of 152 GHz on sapphire substrates.* Japanese Journal of Applied Physics Part 2-Letters & Express Letters, 2005. **44**(16-19): p. L475-L478.

39. Inoue, T., et al., *30-GHz-band over 5-W power performance of short-channel AlGaN/GaN heterojunction FETs.* Ieee Transactions on Microwave Theory and Techniques, 2005. **53**(1): p. 74-80.

40. Kumar, V., et al., *AlGaN/GaN HEMTs on SiC with f(T) of over 120-GHz.* IEEE Electron Device Letters, 2002. **23**(8): p. 455-457.

41. Micovic, M., et al., *GaN/AlGaN high electron mobility transistors with f(tau) of 110GHz.* Electronics Letters, 2000. **36**(4): p. 358-359.

42. Mutschler, A.S. *Gallium nitride power management chips poised for impressive growth, iSuppli says*. 2010 [cited 2010; Available from: http://www.edn.com/article/457654-Gallium_nitride_power_management_chips_poised_for_impressive_growth_iSuppli_says.php.

43. Kelly, M.K., et al., *Large free-standing GaN substrates by hydride vapor phase epitaxy and laser-induced liftoff.* Japanese Journal of Applied Physics Part 2-Letters, 1999. **38**(3A): p. L217-L219.

44. Temkin, H. and S.A. Nikishin, *Method of epitaxial growth of high quality nitride layers on silicon substrates (US Patent Number: 6391748)*. 2002, Texas Tech University.

45. Weeks, T.W. and K.J. Linthicum, *Gallium nitride material devices and methods of forming the same (US Patent Number: 7233028)*. 2007, Nitronex Corporation.

46. Gwo, S., *Method of growing nitride semiconductor heterostructures on silicon substrate (US Patent Number: 7012016)*. 2006.

47. Solomon, G.S., D.J. Miller, and T. Ueda, *Detached and Inverted Epitaxial Regrowth & Methods (US Patent Number: 6176925)*. 2001, CBL Technologies Inc, Matsushita Electronics Corporation.

48. Zhang, X. and S.J. Chua, *Method of fabricating group-III nitride-based semiconductor device (US Patent Number: 6524932)*. 2003, National University of Singapore.

49. Chen, P., et al., *Method and structure for fabricating III-V nitride layers on silicon substrates (US Patent Application: 11/344472)*. 2006, Agency for Science, Technology and Research (Singapore).

50. Holger Jürgensen, A.K., Armin Dadgar, *Method for depositing III-V semiconductor layers on a non-III-V substrate*. 2006, Aixtron AG.

51. Chua, S.J., Y. Wang, and K. Zang, *Nano-air-bridged lateral overgrowth of GaN semiconductor layer (US Patent Application: 11/434399)*. 2006.

52. Linthicum, K.J., et al., *Method of fabricating gallium nitride microelectronic layers on silicon layers (US Patent Number: 6602764)*. 2003, North Carolina State University.

53. Terashima, K., et al., *Method of growing group III nitride semiconductor crystal layer and semiconductor device incorporating group III nitride semiconductor crystal layer (US Patent Number: 6069021)*. 2000, Showa Denko KK.

54. Bhuiyan, A.G., A. Hashimoto, and A. Yamamoto, *Indium nitride (InN): A review on growth, characterization, and properties*. Journal of Applied Physics, 2003. **94**(5): p. 2779-2808.

55. Butcher, K.S.A. and T.L. Tansley, *InN, latest development and a review of the band-gap controversy*. Superlattices and Microstructures, 2005. **38**(1): p. 1-37.

56. Walukiewicz, W., *Narrow band gap group III-nitride alloys*. Physica E-Low-Dimensional Systems & Nanostructures, 2004. **20**(3-4): p. 300-307.

57. Wu, J.Q., *When group-III nitrides go infrared: New properties and perspectives*. Journal of Applied Physics, 2009. **106**(1).

58. Maleyre, B., et al., *Growth of InN layers by MOVPE using different substrates*. Superlattices and Microstructures, 2004. **36**(4-6): p. 517-526.

59. Drago, M., P. Vogt, and W. Richter, *MOVPE growth of InN with ammonia on sapphire*. Physica Status Solidi a-Applications and Materials Science, 2006. **203**(1): p. 116-126.

60. Li, S.X., et al., *Fermi-level stabilization energy in group III nitrides*. Physical Review B, 2005. **71**(16).

61. Ruffenach, S., et al., *Recent advances in the MOVPE growth of indium nitride*. Physica Status Solidi a-Applications and Materials Science, 2010. **207**(1): p. 9-18.

62. Wang, K.A., et al., *Effect of dislocation scattering on the transport properties of InN grown on GaN substrates by molecular beam epitaxy*. Applied Physics Letters, 2006. **89**(16).

63. Briot, O., et al., *Growth of InN films and nanostructures by MOVPE*. Journal of Crystal Growth, 2009. **311**(10): p. 2761-2766.

64. Walukiewicz, W., *Intrinsic limitations to the doping of wide-gap semiconductors*. Physica B-Condensed Matter, 2001. **302**: p. 123-134.

65. Mahboob, I., et al., *Intrinsic electron accumulation at clean InN surfaces*. Physical Review Letters, 2004. **92**(3).

66. Yim, J.W.L., et al., *Effects of surface states on electrical characteristics of InN and In1-xGaxN*. Physical Review B, 2007. **76**(4).

67. Wang, X.Q., et al., *Hole mobility in Mg-doped p-type InN films*. Applied Physics Letters, 2008. **92**(13).

68. King, P.D.C., et al., *Surface electronic properties of n- and p-type InGaN alloys*. Physica Status Solidi B-Basic Solid State Physics, 2008. **245**(5): p. 881-883.

69. Chattopadhyay, S., et al., *One-Dimensional Group III-Nitrides: Growth, Properties, and Applications in Nanosensing and Nano-Optoelectronics*. Critical Reviews in Solid State and Materials Sciences, 2009. **34**(3-4): p. 224-279.

70. Kuykendall, T., et al., *Complete composition tunability of InGaN nanowires using a combinatorial approach.* Nature Materials, 2007. **6**(12): p. 951-956.

71. Hsu, L. and W. Walukiewicz, *Modeling of InGaN/Si tandem solar cells.* Journal of Applied Physics, 2008. **104**. p. 024507 (7 pp.).

72. Reichertz, L.A., et al., *Demonstration of a III-nitride/silicon tandem solar cell.* Applied Physics Express, 2009. **2**. p. 122202 (3 pp.).

73. Kurtz, S.R., P. Faine, and J.M. Olson, *Modeling of two-junction, series-connected tandem solar cells using top-cell thickness as an adjustable parameter.* Journal of Applied Physics, 1990. **68**. p. 1890-5.

74. Soh, C.B., et al., *Cool white III-nitride light emitting diodes based on phosphor-free indium-rich InGaN nanostructures.* Applied Physics Letters, 2008. **92**(26).

75. Che, S.B., et al., *Fabrication and properties of coherent-structure In-polarity InN/In0.7Ga0.3N multiquantum wells emitting at around 1.55 mu m.* Journal of Applied Physics, 2007. **102**(8).

76. Mu, X.D., et al., *Resonant terahertz generation from InN thin films.* Optics Letters, 2007. **32**(11): p. 1423-1425.

77. Piner, E.L., J.C. Roberts, and P. Rajagopal, *Gallium nitride material devices and methods of forming the same (US Patent Number: 7339205)*. 2008, Nitronex Corporation.

78. Berishev, I. and A. Bensaoula, *Group III Nitride Field Emitters (US Patent Number: 6218771)*. 2001, University of Housten.

Appendix

Table 6: Specifications of RF products from Cree Inc. Source: http://www.cree.com/products/wireless.asp

Device Type	Applications	Manufacturer Part Number	Frequency Range (GHz)	Test Frequency (GHz)	Test V_{DS} (V)	Power output @P_{sat} (W)	Gain @P_{sat} (dB)	Price (US$)
SiC MESFET	Broadband/General Purpose	CRF24010FE	DC-2.7	2	48	12	15	150.00
		CRF24060FE	DC-2.7	1.5	48	60	13	623.70
GaN HEMT on SiC		CGH40120F	DC-4.0	1.3	28	120	19	831.53
		CGH40180PP	DC-2.5	1.3	28	220	19	1120.44
		CGH40006P	DC-6.0	2	28	9	13	101.91
		CGH40090PP	DC-4.0	2	28	100	12.5	831.53
		CGH40045F	DC-4.0	2.5	28	55	14	419.25
		CGH40035F	DC-4.0	3.5	28	45	14	352.77
		CGH40010F	DC-6.0	3.7	28	12.5	14.5	127.39
		CGH40025F	DC-6.0	3.7	28	30	13	270.64
	MMIC	CMPA0060002F	0.02 - 6.0	4	28	3	10	573.09
		CMPA2560025F	2.5 - 6.0	4	28	37.5	14	919.61
		CMPA0060025F	0.02 - 6.0	4	50	24	11.8	873.63
	3G, LTE and WiMAX	CGH09120F	UHF - 2.5	0.87	28	120	21.5	Unavailable at website
		CGH21120F	1.8 - 2.3	2.15	28	110	15	
		CGH21240F	1.8 - 2.3	2.14	28	215	15	
		CGH25120F	2.3 - 2.7	2.5	28	130	12.5	
		CGH27015	2.3 – 2.9	2.5	28	15	15	
		CGH27030F	2.3 - 2.7	2.5	28	30	14.5	
		CGH27060F	2.3 - 2.7	2.5	28	60	13	
		CGH35015	3.3 - 3.9	3.5	28	15	12	
		CGH35030F	3.3 - 3.9	3.5	28	30	11.5	

		CGH35060F	3.3 - 3.9	3.5	28	60	11.5	
		CGH55015F1/P1	4.9 - 5.8	5.65	28	15	11	
		CGH55030F1/P1	4.9 - 5.8	5.65	28	30	10	
	C-Band	CGH55015F2/P2	4.5-6.0	5.65	28	13	12.5	Unavailable at website
		CGH55030F2/P2	4.5-6.0	5.65	28	30	11	
	S-Band	CGH31240	2.7 - 3.1	2.9	28	230	10.5	Unavailable at website
		CGH35240F	2.9 - 3.5	3.3	28	250	11.4	

Table 7: Specifications of RF products from Nitronex Corp. Source: http://www.nitronex.com/products.html.

Device Type	Applications	Manufacturer Part Number	Frequency Range (GHz)	Test Frequency (GHz)	Test V_{DS} (V)	Power output @P_{sat} (W)	Gain @P_{sat} (dB)
GaN HEMT on Si	Broadband/General Purpose	NPTB00004	DC-6.0	2.5	28	5.1	15.5
		NPT25015	DC-3.0	2.5	28	25	14
		NPT35015	DC-6.0	3.5	28	18	11
		NPTB00025	DC-4.0	3	28	25	13.5
		NPTB00050	DC-4.0	3	28	50	11.5
		NPT1004	DC-4.0	2.5	28	40	13.5
		NPT1010	DC-2.0	0.9	28	100	18.7
		NPT1007	DC-1.2	0.9	28	200	18.3
	3G, LTE and WiMAX	NPT25100	1.8-2.7	2.5	32	90	16.5
		NPT35050A	3.3-3.8	3.5	32	65	12.5

Table 8: Specifications of RF products from Polyfet. Source: http://www.polyfet.com.

Device Type	Manufacturer Part Number	Test Frequency (GHz)	Test V_{DS} (V)	Power output @P_{sat} (W)
Si LDMOS	LC801	0.5	28	20
	L88016	0.5	28	30
	LP701	0.5	28	35
	LC401	0.5	28	60
	LP702	0.5	28	70
	LK701	0.5	28	70
	LK702	0.5	28	90
	LX501	0.5	28	100
	LZ402	0.5	28	125
	LB401	0.5	28	130
	LR401	0.5	28	130
	LB501	0.5	28	175
	LR501	0.5	28	175
	LP801	1	28	15
	LQ801	1	28	30
	LP802	1	28	30
	LX802	1	28	30
	LX803	1	28	45
	LK802	1	28	45
	LX401	1	28	60
	LB803	1	28	80
	LR804	1	28	120
	LP601	1.5	28	7
	LQ601	1.5	28	12
	LK602	1.5	28	20

	LB603	1.5	28	30
	LR604	1.5	28	40
	LR301	0.35	28	300
Si VDMOS	SA701	0.175	28	25
	SA702	0.175	28	50
	SM703	0.175	28	80
	ST703	0.175	28	80
	SM704	0.15	28	125
	ST704	0.15	28	125
	SM705	0.15	28	150
	SM706	0.175	28	135
	SM401	0.175	28	135
	SV401	0.175	28	150
	SR704	0.175	28	300
	SR401	0.175	28	300
	SX501	0.175	28	350
	SR706	0.225	28	300
	SR704U	0.4	28	150
	SR705	0.4	28	200
	SC701	0.5	28	20
	SP701	0.5	28	25
	SP702	0.5	28	40
	SQ701	0.5	28	45
	SK701	0.5	28	45
	SK702	0.5	28	90
	SD702	0.5	28	90
	SH702	0.5	28	90
	SD703	0.5	28	110
	SH703	0.5	28	130
	SR703	0.5	28	150

Table 9: Specifications of RF products from RF Micro Devices Inc. Source: http://www.rfmd.com

Device Type	Manufacturer Part Number	Test Frequency (GHz)	Power output @1dB (W)
GaAs pHEMT	FMS2023	20	0.25
	FMS2024	20	0.25
	FMS2027	20	0.13
	FMS2029	20	0.40
	RFSW2040D	25	39.81
	RFSW2041D	25	39.81
	RFSW2042D	20	2.51
	RFSW2043D	20	10.00
	RFSW2044D	25	39.81
	RFSW2045D	2	2.00

Table 10: Selected patents on GaN-on-Si buffer layer technologies

Patent Number	Year	Inventors	Assignees	Patent Name	Summary of Relevant Claims
7339205	2008	E L Piner, J C Roberts, P Rajagopal	Nitronex Corporation	Gallium nitride material devices and methods of forming the same. Reference [77]	• Silicon and silicon carbide substrates. • Growth of AlN, GaN, and AlGaN.
7233028	2007	T W Weeks, K J Linthicum	Nitronex Corporation	Gallium nitride material devices and methods of forming the same. Reference [45]	• Growth on graded AlGaN buffer. • Devices: LED, photodetector, transistor. • Specific electrical contacts. • Fabrication on silicon, sapphire, and silicon carbide substrates

7078318	2006	Holger Jürgensen, Alois Krost, Armin Dadgar	Aixtron AG	Method for depositing III-V semiconductor layers on a non-III-V substrate. Reference [50]	• Broad claims for growth of III-V materials on Si substrate • Broad claims for deposition techniques with MOCVD and MBE • Broad claims for a variety of patterned materials used for ELO growth
7012016	2006	S. Gwo		Method of growing nitride semiconductor heterostructures on silicon substrate. Reference [46]	• Growth of single-crystal silicon nitride buffer, followed by AlN buffer. • Subsequent growth group-III nitrides.
6602764	2003	K J Linthicum, T Gehrke, R F Davis, D B Thomson, K M Tracy	North Carolina State University	Method of fabricating gallium nitride microelectronic layers on silicon layers. Reference [52]	• Growth by converting the surface of Si (111) to 3C SiC through chemical reaction with carbon precursor (ethylene). • Includes the use of SIMOX SOI. • Includes use of MOCVD.
6524932	2003	X Zhang, S J Chua	National University of Singapore	Method of fabricating group-III nitride-based semiconductor device. Reference [48]	• Growth via amorphous silicon and multi-layered buffer • Recrystallization of amorphous and polycrystalline layers with subsequent high temperature steps
6391748	2002	H Temkin, S A Nikishin	Texas Tech University	Method of epitaxial growth of high quality nitride layers on silicon substrates. Reference [44]	• Growth of AlN buffer on Si (111) using MBE at precise temperatures. • Growth of SiNx controlled and minimized.
6218771	2001	I Berishev, A Bensaoula	University of Housten	Group III Nitride Field Emitters. Reference [78]	• Growth on Si (111). • Field emission device

6176925	2001	G S Solomon, D J Miller, T Ueda	CBL Technologies Inc, Matsushita Electronics Corporation	Detached and Inverted Epitaxial Regrowth & Methods. Reference [47]	• 2 step growth process of III-N, resulting in a layer of liquid metal between III-N and substrate. • MOCVD and HVPE. • Heavily n-doped III-N
6069021	2000	K Terashima, S Nishimura, T Tsuzaki, T Udagawa	Showa Denko KK	Method of growing group III nitride semiconductor crystal layer and semiconductor device incorporating group III nitride semiconductor crystal layer. Reference [53]	• Growth using two boron phosphide buffers, each grown at different temperatures. • Subsequent growth of InAlGaN
11/434399*	2006	S J Chua, Y Wang, K Zang		Nano-air-bridged lateral overgrowth of GaN semiconductor layer. Reference [51]	• Growth over substrate patterned with nanopores, forming nanovoids • Nanovoids help reduce dislocation densities at the surface
11/344472*	2006	P Chen, S J Chua, Z Miao, S Tripathy	Agency for Science, Technology and Research (Singapore)	Method and structure for fabricating III-V nitride layers on silicon substrates. Reference [49]	• Growth via a transition structure and a superlattice structure • Transition structure: Series of AlGaN/AlN/GaN • Superlattice structure: >5 periods of alternating AlGaN/GaN

*Patent pending