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A Study of Optoelectronic Device Using III Nitride Semiconductors

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Abstract - To realise unique device designs and structures, lift-off procedures have been devised to remove the epitaxial III-nitride thin film from a standard growth substrate, such as sapphire or silicon. To increase device performance, thermal management, and flexibility, among other things, an epitaxial lift-off (ELO) method can be used to transfer the entire film to an arbitrary foreign substrate. Partial ELO techniques, in which only a section of the thin-film is separated from the substrate, can be used to achieve atypical device shapes or geometries, such as apertured, pivoting, and flexible devices, which can be utilised for a wide range of photonic structures or optical cavities. In this study, we take a look back at how far III-nitride technology has come in terms of lift-off techniques and procedures, and then forward to where we think it's headed. As a result of their superior optical and electronic qualities, III-nitride-based gadgets have become ubiquitous and indispensable; by 2026, the global market for these products is expected to reach USD 24.9 billion. Light-emitting diodes (LEDs), laser diodes (LDs), and high-electron-mobility transistors (HEMTs) are just a few examples of III-nitride technologies that are finding their way into everyday electronics and appliances (HEMTs). The epitaxial development of crystalline materials on substrates like sapphire, silicon (Si), and silicon carbide (SiC) through metalorganic vapour phase epitaxy (MOVPE) or molecular beam epitaxy is crucial to the success of III-nitride devices (MBE). Hydrogen vapour phase epitaxy (HVPE) produced bulk GaN substrate is also widely used because of its low dislocation density. In contrast, heteroepitaxial GaN based on silicon or sapphire substrates costs merely a fraction for a 6-in. substrate, often less than 5% that of the bulk GaN substrate pricing, with a 2-in. c-plane bulk GaN substrate costing over $1000 at present. It is generally accepted that larger layer thicknesses in the epitaxial structure are necessary to reduce the effects of dislocations and produce a viable III-nitride film.

Keywords - Optoelectronic Device, III-Nitride, Semiconductors, epitaxial lift-off, Light-emitting diodes

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INTRODUCTION

Many of us are now big users of technology, and large-scale enterprises have been set up to suit our ever-increasing demands for technical advancements. The fields of secure communication, optoelectronics, and the medical sciences are just a few where it has become increasingly commonplace. Technological progress has benefited humankind in countless ways. Transistors, integrated circuits, microprocessors, the computer, and the information age are only a few examples of the many ways in which silicon semiconductor materials have changed modern life. The semiconductor materials known as III-Nitride share this same esteem, and they promise to drastically alter our daily lives. The spectral range covered by IIInitride semiconductors, such as aluminium nitride (AlN), gallium nitride (GaN), and indium nitride (InN), and their ternary (AlGaN and InGaN) and quaternary (AlGaInN) alloys, is from 0.7 eV (InN) to 6.2 eV (AlN) (UV). The speed with which these materials are being developed enables the quick commercialization of semiconductor devices with novel capabilities and prompts the reinvention of established technology.

III-NITRIDE TECHNOLOGY

Several long-held beliefs about what kinds of materials are necessary to successfully fabricate devices have been called into question by the development of nitride-based electronics. Table 1 lists some elementary physical features shared by semiconducting materials in the group III nitride family. Both cubic zinc blende and hexagonal wurtzite can be found among the crystal formations of group-III nitrides. Both can coexist when crystals are grown using different conditions[1]. In terms of thermodynamic stability, the cubic structure is metastable, while the wurtzite structure is stable. Lattice points in hexagonal wurtzite structures are indexed by four indices, h, k, I l, where i= -h - k, and the wurtzite structure as a whole belongs to the P63mc space group with ABAB stacking sequences along the c-direction. In the horizontal plane, the first three indices represent the vector in the direction, while the fourth represents the vector in the c direction. The basic lattice vectors of the basal plane of the hexagonal wurtzite structure are seen in Fig. 1. Over the index, a bar is used to indicate a negative vector.

Table 1: Basic properties of group III – Nitride semiconductors

Physical Property	AlN	GaN	InN
E_g (eV)	6.2	3.44	0.7
Thermal Expansion coefficient (300 K)			
a (x 10^{-6} K^{-1})	4.2	5.59	5.59
c (x 10^{-6} K^{-1})	5.3	3.17	3.7
Lattice constant (300 K)			
a (Å)	3.112	3.189	3.545
c (Å)	4.982	5.185	5.703
Bond Length (Å)	1.89	1.94	2.15
Cohesive Energy per Bond (eV)	2.88	2.24	1.93
Melting point (°C)	>3000	>2500	>1100
Density (g/cm^3)	3.26	6.10	6.99

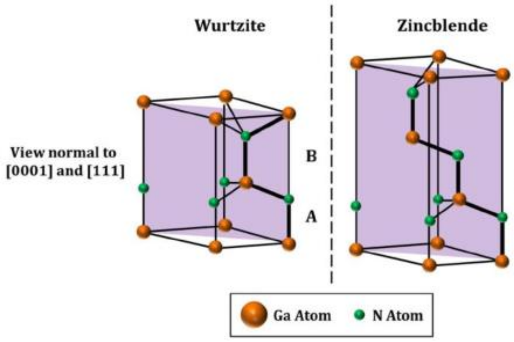

Figure 1: The three-dimensional view of a stick-and-ball stacking model of crystals with 2H wurtzite and 3C zinc blende polytypes.

Indices enclosed in square brackets "[]" or angled brackets ">" are commonly used to specify a direction or a family of directions. A plane or a family of planes can be described by an index enclosed in parentheses (()) or curly brackets ( ). It is important to note that in real space, the direction [h k I l] is not normal to the plane (h k I l) unless either l = 0 or h = k = 0. Moreover, Fig. 2 displays the many GaN planes that exist.

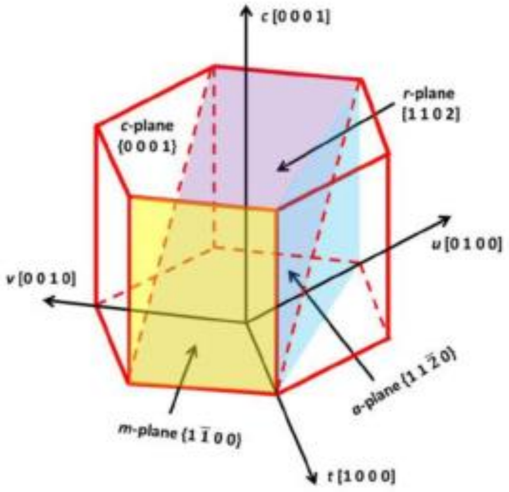

Figure 2: Schematic representation of different planes (c-, a-, r- and m-planes) of GaN

The c-plane is located at the apex of the hexagonal unit in GaN wurtzite. The terminal of this plane, known as a polar oriented plane, can be composed of Ga or N ions, and as a result, the plane itself will always have a positive net charge. The m- and a-planes (yellow and blue colour planes in Fig. 2) are non-polar oriented planes and are located along the side wall of the hexagonal system. Ga and N ions are both involved in the termination process here, which means that the overall charge is cancelled out. In contrast, the r-plane (shown in violet in Fig. 2) is a surface with a polar orientation where the termination is dominated by Ga or N ions. Furthermore, it is critical to note that the wurtzite structure's Ga-polar (0001) and N-polar (0001) surfaces are not identical and display different chemical characteristics. As shown in Fig. 3, the (0001) and (0001) polarity are determined by whether Ga or N atoms terminate at the top of the (0002) bilayer. Surfaces made of Ga-polar GaN are often more chemically stable and smooth than those made of Npolar GaN.

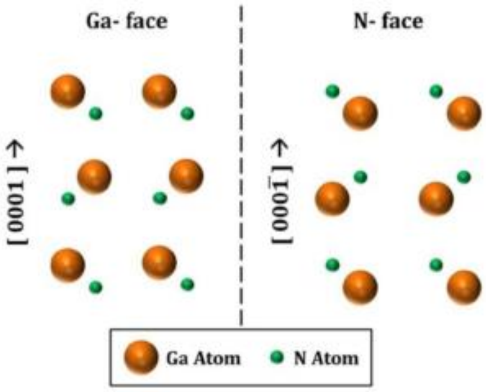

Figure 3: The wurtzite GaN in Ga- and N- Polarity

In addition, GaN and similar III-Nitride semiconductors have garnered considerable interest due to their potential application in high-power, high-temperature electronic devices that require short-wavelength light [3, 4]. InN's bandgap was found to be smaller than expected in 2002. As can be shown in Fig. 4, the optical emission of direct bandgap nitride-based devices is broadened from the ultraviolet (UV) to the near infrared (NIR) by the lower bandgap value of InN (0.7- 6.2 eV).

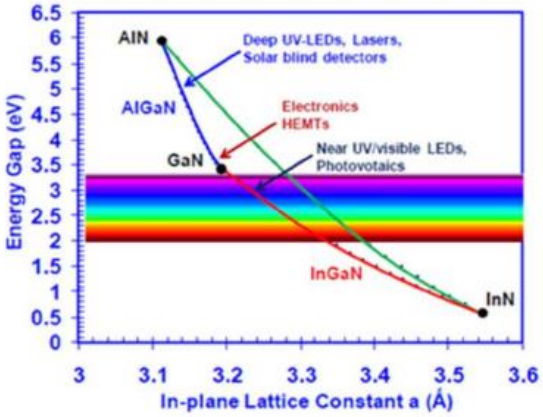

Figure 4: Bandgap vs lattice constants for III-Nitride materials representing various areas of interest for device applicability[5].

Small effective mass, excellent electrical mobility, and high peak and saturation velocities[6] are just a few of the impressive material features that make InN-based devices so exciting. While GaN is relatively easy to cultivate, InN presents greater challenges because to its low dissociation temperature (630 °C) and high equilibrium vapour pressure of nitrogen. Even so, high-quality wurtzite InN film growth has made significant strides in recent years [7, 8]. In addition, optoelectronic applications make extensive use of ternary alloys of III-nitrides. Since its bandgap energy ranges from 0.7 eV (InN) to 3.4 eV (GaN), spanning most of the solar spectrum [12-14], the InxGa1-xN alloy (0X1) system has received substantial attention for solar cell applications [9-11]. As a result, InGaN has strong optical characteristics and can be put to use in photo sensing devices. To operate under the VIS to NIR range and absorb lower energy photons, the indium composition of all future InGaN-based devices must be increased.

GROWTH KINETICS OF III-NITRIDES

In spite of the fact that the history of III-nitrides dates back more than fifty years, there have been a few significant breakthroughs that have established the technological foundation and opened the door to the enormous economic and scientific interest in nitrides. There are many variables that influence the growth kinetics, including as the substrate material, the impinging flow of adatoms, the growth parameters, and the surface contact with the adatoms. Adatoms, which live on the surface of a substrate, provide an explanation for the growth mechanism by requiring the presence of a number of surface phenomena. Adatom adsorption, desorption, surface diffusion, and nucleation leading to cluster formation are all examples of these processes (Fig. 5). The following explains the fundamentals of growth kinetics, which are based on surface diffusion. When an adatom reaches its destination surface (substrate), it typically loses momentum in a direction perpendicular to the surface while gaining energy for in-plane diffusive motions from the substrate; this energy is proportional to the substrate's temperature. This spreading can be modelled as a "random walk" in two dimensions, where particles "jump" from one location to another.

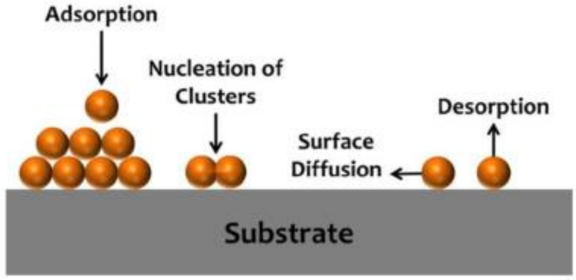

Figure 5: A schematic representing various microscopic kinetic processes of growth

Adatoms' free random-walk will be halted by other kinetic events on the surface, such as nucleation, adatom attachment, desorption from the substrate, etc., as shown in Fig. 5. In an effort to create high-quality group III-Nitride thin films, several different crystal-growth techniques, substrate types, and orientations have been tested during the past few years. Researchers are increasingly capitalising on plasma-assisted molecular beam epitaxy (PAMBE), molecular beam epitaxy (MBE), and metal-organic vapour phase epitaxy (MOVPE) to achieve significantly higher quality films. Specifically for In-containing nitride semiconductors, all of these epitaxial techniques must overcome challenges related to a scarcity of native GaN substrates and the complexity of nitrogen incorporation at the high ammonia flow rates required for this process.

1. Nitride epitaxy on different substrates

The absence of a suitable substrate material that is lattice matched to and thermally compatible with III-nitrides is one of the key issues that have hampered III-nitride research. Since commercially available bulk GaN crystals are currently unavailable, III-nitride materials are typically produced via the heteroepitaxial method on a foreign substrate. Attempts to solve the issues caused by a deficiency of GaN substrates have taken a lot of time and energy. Substrate materials for nitride epitaxy are traditionally evaluated based on their lattice constant mismatch. Crystals with various lattice planes have a lattice mismatch if their lattice constants are not identical. Typically, a defect-free epitaxial film cannot be grown due to lattice mismatch. As a result of lattice mismatch, a uniform tension will develop if a film grows coherently on a thick substrate. Whether the epitaxial film's in-plane lattice space is greater or smaller than the substrate's determines the stress state of the underlying heteroepitaxial layers.

2. Growth techniques for nitride epitaxy

In order to create highly effective III-nitride based devices, high grade III-nitride films must be grown. In 1969, Maruska and Tietjen used HVPE to create the first single-crystalline GaN layer. In this case, gallium chloride and ammonia are used as the gallium and nitrogen sources, respectively. The rapid growth rate of this method is its primary benefit since it allows the fabrication of single crystal GaN for subsequent nitrides epitaxy. However, this kind of film development results in a rough surface. MOVPE, which uses metal organic (e.g., trimethylgallium) gases and ammonia as reactants, has become a popular III-nitride growth process in recent years. GaN's crystalline quality was found to be enhanced by a thin layer of low temperature AlN buffer, as discovered by Akasaki and Amano in 1986. A "two-step" approach is used for this procedure. In recent years, MOVPE growth has found widespread commercial application in IIInitrides. It expands by about 2 micrometres every hour, which is quite fast. The epitaxial layer is of very high quality and features sharp atomic-scale boundaries. The MBE growth method is currently the most popular for III-nitrides in the lab.

NITRIDE BASED OPTOELECTRONIC

Devices Some researchers believe that the III nitrides (AlN, GaN, InN, and their ternary and quaternary compounds) were a foreseen technology for the creation of high-performance UV photo detectors (PDs), particularly in the latter part of the twentieth century. They have a wide straight band gap from the deep UV to the infrared area, a strong breakdown field, a high thermal stability, radiation hardness, and a predicted high responsivity. One of the best things about III-nitride materials for use in optoelectronic devices is their straight band gap. Also, the low intrinsic carrier density that emerges from III-nitrides' wide band gap is crucial for PDs and high-temperature electronics since it results in minimal leakage and low dark current. We also know that III-nitrides have high melting temperatures and impressive mechanical strength. When radiation resistance is factored in, we have a material system that can withstand high frequencies, high powers, and high temperatures. Important uses of solar blind PDs include early missile threat warning, detection of chemical/biological agents, detection of flames, monitoring of power lines, and non-line-of-sight communication (when combined with UV light emitters). Due to GaN's higher saturation velocity and around three-fold-higher optical photon energies, it is more conducive to transient transport since the initiation of optical photon emission is delayed. Full UV region photo detection is provided by III-Nitride semiconductors such as GaN (360 nm with the bandgap of 3.42 eV), InxGa1-xN (bandgap of InN is 0.7eV), and AlxGa1-xN (bandgap of AlN is 6.2 eV with 210 nm) [8, 13]. The In0.1Ga0.9N alloys can be used to attain the visible-blind at wavelengths below 400 nm. Some of the most promising materials for solar-blind detection are AlxGa1-xN alloys with x greater than 40%. Furthermore, GaN-based detectors have drawn significant interest in basic research for high-temperature and high-photon-energy detection, as well as for high-energy particle detection. Since there is a simple guideline for optimising device performance: superior devices result from superior epitaxial device layers. The epitaxial layer structure should be very consistent with the blueprint, and there should be no major structural flaws. These are just two of the many characteristics indicative of a product's high quality. In turn, the substrate you choose with and the meticulous and optimised epitaxial growth strategy you take together will determine the quality of the device epitaxy you get. As was previously said, a high quality device epi-wafer is characterised by low defect densities and precise layer thicknesses and compositions across all device layers. As a result, there are major obstacles to be addressed before these materials may be used to create practical devices. The lack of lattice-matched substrates and the consequently low doping effectiveness were the primary obstacles that scientists had to overcome in this field. Dislocation density of the order of 108-1010 cm-2 makes it seem unlikely that this material will form the basis of many practical next-generation technologies. Today, blue/violet light emitting diodes (LEDs) and laser diodes (LDs) based on (Al, In, Ga) - N have been successfully marketed thanks to the diligent efforts of researchers in this sector. While blue and green LEDs have already found a home in full-color LCD panels and traffic lights, blue LDs are projected to soon replace red lasers in conventional CD and DVD read/write systems. As a result of their exceptional features, III-nitrides find use in everything from optoelectronics to high-power electronics. GaN's large bandgap makes it useful in a variety of high-temperature contexts in addition to its more traditional use as a light-emitting source. GaN and its alloys can be used to create high-power electronic components like transistors and thyristors. Pankove and Berkeyheiser began researching GaN's photoconductive capabilities in 1974. In the early 1990s, scientists first began working on a method to create UV PDs using a material called illuminoboron nitride. GaN was the primary focus of the first studies, and these results stemmed largely from the technological improvements made in the pursuit of producing high-quality GaN material for use in blue light generating diodes and lasers. The few PDs that had been proven up to that point were rudimentary devices like GaN photoconductors and Schottky photodiodes. AlxGa1-xN was studied for the creation of detectors functioning across the full 200-400 nm range after wide band gap GaN proved itself as a promising material for UV detectors in the second half of the 1990s. Back-illuminated PDs were studied for possible solar and visible-blind UV imaging applications in the late 1990s and early 2000s, when AlxGa1-xN had reached a certain level of maturity. Since then, many groups have investigated and developed unique PD structures, including photoconductors, metal-semiconductormetals (MSMs), Schottky barriers, MISs, p-n junctions, and p-i-n junctions. GaN PDs, which are closely related to film epitaxy processes, were the primary emphasis during the first stage due to their potential for high responsivity, fast speed, and genuine visible-blind. Real applications, like as focal-plane PD arrays, required a second phase of development.

CONCLUSION

This study presents a comprehensive analysis of the challenges involved in designing and fabricating effective photo detectors based on nitride. Epitaxial III-Nitride semiconductor growth on a variety of substrates has been successfully applied to the development of high-performance photo sensing devices. To this end, we performed epitaxial growth of GaN and GaN/AlN heterostructures on a c-plane sapphire substrate and correlated the structural and optical features of the produced films. Temperature-induced stress relaxation in epitaxially produced GaN films is shown to be the governing factor in defect minimization. By carefully adjusting the growth temperature, a GaN film with little compressive stress was formed; this was achieved for a film grown at 730 °C. Additionally, the relationship between surface defects and stress relaxation in the produced GaN films and their thermal stability and electrical structure were studied. The results show that the lattice expands at higher temperatures, and that the stress-relaxed GaN film exhibits a highly intense, narrow NBE emission with diminished yellow band-related defects and a low TD density. Stress relaxation also improves topographical features, like pit density and surface roughness. An in-depth structural characterization of a GaN/AlN/GaN/AlN/GaN heterostructures produced on a sapphire c-plane substrate is also provided. As a result, the PAMBE produced heterostructures was able to achieve both a crisp hetero-interface and low TDs. This research makes a significant contribution toward clarifying how to minimize defects in GaN films, which is essential for the development of high-performance nitride-based devices. The highly crystalline quality of epitaxially grown GaN layer on an a-plane sapphire substrate was established, and the effect of substrate orientation on structural and optical properties was examined systematically.

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