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Transistors based on gallium nitride (GaN), growth techniques, and nanostructures

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Abstract
Gallium nitride(GaN) is a material with a wide and straight band gap of 3.39eV. This semiconductor has the crystal structure of Wurtzite as one of the most stable phases of matter in environmental conditions. This material and its alloys have a low intrinsic charge carrier density due to their wide band gap, but on the other hand, they have significant charge transfer properties. These include high electron mobility of about 1300cm^2/Vs and usability in high-temperature applications due to its very high thermal conductivity. They also have a saturation velocity of about 2.5$\times 10^7$cm/S and a high breakdown electric field of about 3.5MV/cm compared to 0.3MV/cm for silicon. This paper discussed the most important GaN crystal growth methods, such as Ammonothermal, Hydride Vapor Phase Epitaxy(HVPE), Sodium flux(Na-flux), Metal-Organic Chemical Vapor Deposition(MOCVD), and Molecular Beam Epitaxy(MBE). Each of these methods has its advantages and drawbacks and is used in research and industrial fields. MOCVD and MBE techniques are more widely used than other techniques, and due to larger throughput and larger wafer size, MOCVD is widely used in industrial applications. According to the articles, which were discussed in this paper, countries such as the United States, Japan, and Germany, among other countries, have focused more on these two methods. The most common nanostructures obtained from the studied methods are nanowires, quantum wells, quantum wires, quantum dots, and GaN nanoparticles. This paper mentioned that nanowires and quantum wells are the most widely used morphologies in the structure of GaN-based transistors. Over the past few years, countries such as the United States, South Korea, India, China, and Germany have focused more on the growth of widely used GaN nanostructures.

Keywords
Gallium Nitride(GaN), MOCVD, MBE, Nanowire, Quantum well.

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1. Introduction

There are several types of semiconductor materials that are used in numerous electronic devices, including transistors. Each has its unique advantages, disadvantages, and scope of work that can be used to deliver its optimal performance. Some of them are important for high-frequency amplifiers and others for high-power applications. Germanium, silicon, gallium arsenide, silicon carbide, gallium nitride, and gallium phosphide are some examples of very common semiconductors. This research has focused on Gallium Nitride(GaN) and its extraordinary properties. GaN was first synthesized in 1969 by Maruska and Tietjen using the Hydride Vapor Phase Epitaxy (HVPE) method [1,2]. In 1991, with the development of equipment, Nakamura synthesized it using the Metal-Organic Chemical Vapor Deposition(MOCVD) method [2,3]. GaN has a Wurtzite crystal structure which is the most thermodynamically stable phase in environmental conditions. The first blue light-emitting diode was made using GaN, and researchers Akasaki, Amano, and Nakamura received the 2014 Nobel Prize in Physics for their invention of blue light-emitting diodes [4]. A major market for GaN equipment is high-power and high-frequency transistors. GaN has high bandgap and high-temperature performance advantages over silicon and silicon carbide, which have been the most common semiconductors, earlier. GaN and its alloys have a low intrinsic charge carrier density due to their wide bandgaps, but on the other hand, have significant charge transfer properties that can be attributed to high electron mobility ($\sim$ 1300cm^2/Vs) and Use in high-temperature applications (very high thermal conductivity). They also have a saturation velocity of ($\sim 2.5 \times 10^7$cm/s) and a high breakdown electric field of ($\sim$ 3.5MV/cm as compared to the breakdown electric field of $\sim$0.3MV/cm for silicon). These characteristics allow the production of equipment with smaller dimensions that consume less energy and can operate at higher frequencies [5]. The first high electron mobility transistor (HEMT) based on GaN was fabricated in 2004 in the silicon carbide substrate by Eudyna in Japan [6]. In 2005, Nitronex developed the first high electron mobility radiofrequency transistor in depletion mode with the growth of GaN on a silicon wafer [7]. Emerging demands in energy and power conversion applications require high frequency and

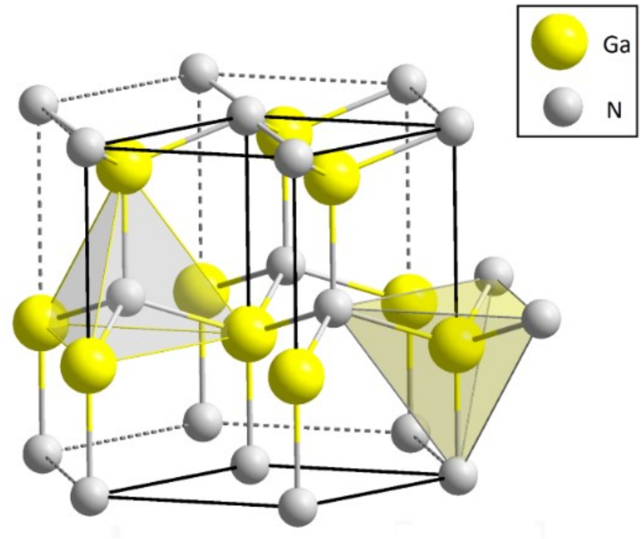


Figure 1. wurtzite structure in GaN.

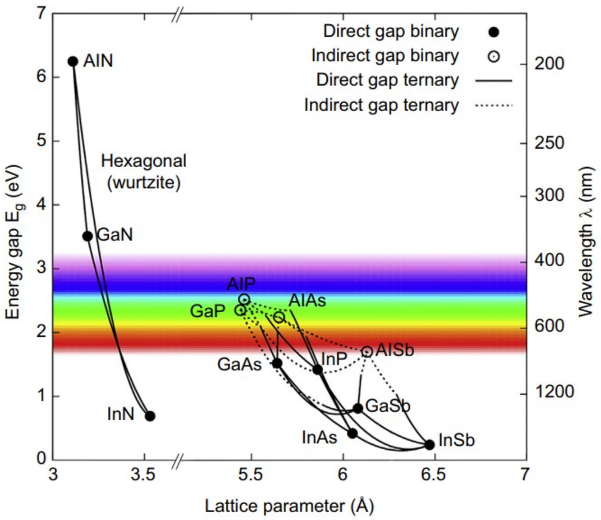


Figure 2. Bandgap diagram related to binary and ternary semiconductors of elements of groups III, V, and IV[16].

high-efficiency switching equipment. GaN as a wide bandgap material has shown its potential in some important applications of high frequency and high efficiency. The utilization of GaN in radiofrequency(RF) amplifiers with a frequency range from 100MHz to 100GHz and other applications that require high bandwidth and high power density can be seen. Recent advances in the development of GaN-based switching equipment in DC to DC, AC to DC, and DC to AC conversion applications are also of interest. Other applications of radiofrequency in the field of power electronics for use in applications such as power converters and inverters can be mentioned. Undoubtedly, GaN will be a good alternative to silicon in the semiconductor industry, and research on this promising material and its high potential will greatly contribute to semiconductor-based technologies in the not too distant future. In this study, first, important parameters of GaN crystal structures will be discussed and then the GaN-based transistor fabrication stages will be briefly marked out.

2. Structures used in high-frequency transistors

The Wurtzite crystal structure is known as a three-dimensional crystal lattice and hexagonal-based structure. This structure, which is based on Wurtzite mineral, is a kind of crystal structure for some biphasic materials. This structure is an example of a hexagonal crystal lattice that can be considered a narrow hexagonal structure (hcp) with a basis of two atoms [8,9]. The crystal structure of Wurtzite is known by the Strukturbericht designation B4 and the Pearson symbol hP4 according to the classification provided by the International Union of Crystallography, its space group is 186 and its Hermann-Mugen symbol is P63mc [10, 11]. The semiconductor bandgap is related to the amount of force of the chemical bonds between the atoms of the lattice. This force between bonds means that electrons are likely to move from one place to another, which means that if there is a stronger bond, a lot of force is needed to separate the electron from the atomic nucleus and reach a higher energy level. Given the above results and the fact that GaN with an energy gap of 3.39eV is known as a material with a wide bandgap and poor electrical current, better high-temperature performance can be achieved for these semiconductors considered [11].

According to Figure2, all ternary alloys also have a wurtzite structure, which is the most thermodynamically stable phase in environmental conditions. Due to the polar nature of wurtzite in GaN and its alloys, it is possible to produce emitters with 100% polar light using non-polar crystalline directions [12, 13].

The structure of wurtzite is chemically very stable and can withstand high temperatures without decomposition. The wurtzite crystal structure produces the piezoelectric properties of GaN, which leads to its ability to achieve very high electrical conductivity as compared to silicon and silicon carbide [12]. The piezoelectric property of GaN is often due to its charged elements in the crystal lattice. If the grid is pressurized, the deformation causes a small displacement in the position of the lattice atoms, which produces an electric field so that the higher the pressure, the larger the electric field. As a layer of aluminum gallium nitride (AlGaN) grows on top of the GaN crystal, a pressure is created on their interface that creates a neutral two-dimensional electron gas (2DEG). 2DEG is used to conduct electrons when an electric field is applied across it. This 2DEG creates a highly conductive region due to the confinement of electrons in a small area at the interface. Electron mobility increases from 1000cm^2/Vs to the range between 1500cm^2/Vs to 2000cm^2/Vs in the 2D electron gas region. High electron density along with high electron mobility is the basis of HEMT transistor performance [12]. GaN transistors can generally be divided into two categories

Table 1. Key parameters of sapphire, silicon carbide, and silicon [16].

Substrate	Crystal Plane	Lattice Spacing $\AA$	Lattice Mismatch %	Relative Thermal Expansion $10^{-5}K^{-1}$	Thermal Conductivity W/cm.K	Relative Cost
Al_2O_3	(0001)	4.758	16.1	-1.9	0.42	Middle
6H-SiC	(0001)	3.08	3.5	1.4	3.8	Highest
Si	(111)	3.84	-17	3	1.5	Lowest

based on operating modes. Depletion mode (D-Mode) and advanced or enhancement mode (E-Mode) are shown in Figure3. Figure3 shows both off and on modes. The source and drain electrodes make ohmic contact with the two-dimensional electron gas (2DEG) through the AlGaN layer. This connection creates a short circuit between the two electrodes, which discharges the electrons in the gas electron. Given the critical GaN and AlGaN failure fields combined with good charge transfer characteristics in the 2DEG region, the researchers soon realized that such transistors operate at much higher bias voltages than gallium arsenide or silicon transistors, resulting in a tenfold increase in power density.

The construction of a GaN transistor begins with the heterogeneous growth of the GaN/AlGaN structure. A heterogeneous structure is a type of semiconductor structure that has at least two adjacent layers with different chemical compositions but the crystal structure will be the same. There are four different substrates used in the manufacture of HEMT GaN transistors. GaN crystals are grown in the bulk form of sapphire (Al_2O_3), silicon carbide, and silicon. The best choice for the raw material of this transistor is high-quality GaN crystal. The first attempts to grow GaN crystals were made in the 1960s. Inherent defects due to high concentrations of nitrogen made these efforts to build semiconductor-based devices unusable. Because GaN crystals are not readily available, much activity in the growth of GaN crystals has focused on sapphire, silicon carbide, and more recently silicon substrates. The starting point for trying to grow on a layer of crystal is dissimilar to finding a layer with suitable physical properties. Table1 compares some of these characteristics for the three items listed. Sapphire, for example, has a 16.1% lattice mismatch with the GaN crystal lattice and also has poor thermal conductivity. Heat conduction in transistors is a very important parameter because a significant amount of heat is generated during operation due to the loss of internal power.

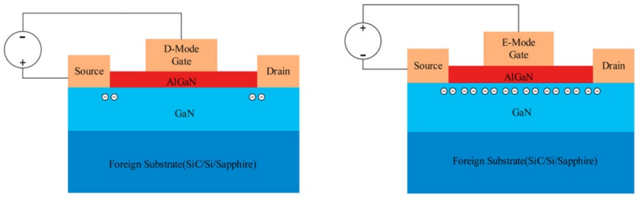


Figure 3. GaN transistors in D-Mode and E-Mode[8].

The next option is a silicon carbide substrate, which has a structure close to GaN and has excellent thermal conductivity. But one of the most important disadvantages is the high cost of making this crystal, which is almost 100 times more expensive than making the same device of the same size but made of silicon [12]. Silicon is not an ideal option for the heteroepitaxial structure of GaN due to the incompatibility of the crystal lattice with GaN and its higher thermal expansion coefficient than other options. But silicon is the least expensive material for this purpose and has a very good infrastructure for use in equipment with silicon substrate [12]. Heteroepitaxial is the process by which a type of crystal structure grows on top of different crystals. For the reasons mentioned above, silicon carbide is commonly used for equipment that requires high power density, such as linear radiofrequency applications. Silicon is used for cost-sensitive commercial equipment such as DC to DC, AC to DC converters, acoustic amplifiers, and motion controllers [14]. Silicon carbide is the substrate of choice for radiofrequency applications of GaN, which was rapidly used for space and defense applications. Although silicon carbide is not a cost-effective solution, its crystal structure and parameters are relatively close to those of GaN, which makes high-quality heteroepitaxial possible. High thermal conductivity is the most important parameter for high-power electronics. Silicon carbide has excellent thermal conductivity. So that equipment made with the silicon carbide substrate can easily control high power densities [15]. In general, GaN transistors can be structurally divided into lateral and vertical types.

2.1 Lateral and vertical structure in GaN-based transistor

In the last decade, GaN power transistors that rely on heterogeneous structures of AlGaN/GaN have achieved significant efficiencies. The lateral transistors shown in Figure4(a) are currently available in silicon substrates with a maximum operating voltage of more than 650V to achieve breakdown voltages above 1kV. Although lateral structures perform well, there are certain limitations to them, Which can be seen in Table2.

In comparison, these limitations can be solved by the vertical configuration of GaN. It is important to increase the safe operating range so that we can create higher output power, which

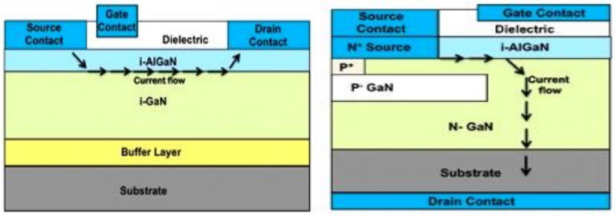
Table 2. Limitations of lateral configuration and advantages of vertical configuration of GaN-based transistors[18].

limitations of a lateral configuration of GaN	benefits of a vertical configuration of GaN
The size of transistors with lateral structure increases dramatically with increasing power.	Ability to achieve a high safe operating range with the same chip size.
They need large sizes in proportion to the voltage and current rate.	Easier heat management.
In high voltage applications, the management of electric field profiles and their relationship to each other is required. The distance between the gate and drain electrodes must be within a suitable range to create a high , thereby reducing the breakdown voltage effective current density.	Transistors with a vertical structure of GaN reach currents above 100A with a voltage greater than 600V.
Heat transfer is difficult because the total electrical current is limited to the upper surface and a thin part of the system.	Special connection design methods are used to control and form an electric field at the edge of the device to achieve high breakdown voltage.

is difficult in designing systems with lateral structures [16].

Contrary to the lateral design, the vertical GaN transistor architecture is shown in Figure4(b) overcomes the limitations of the lateral structure because the electric fields are established in the upper part from the bottom to the top of the structure in the vertical dimension [17]. The development of vertical GaN transistors is a technological challenge for the widespread use of GaN because high currents and high voltages can be easily achieved in vertical systems. A new vertical GaN transistor structure is proposed in which a p-type gate electrode is made on the groove of the GaN thrust layers. Devices with vertical structure offer resistance of about $1m\Omega/cm^2$ and a high breakdown voltage of about 1.7kV [6]. This compound is preferred to peripheral systems, a compound in which a near-surface current is generated in a two-dimensional electron gas at the surface layer of the AlGaN/GaN interface [18].

Researchers at Stanford University have reported that a phenomenon called a functional gap occurs when the electrode gate length of a transistor falls below 50nm. This functional gap prevents work at or near terahertz, thus limiting the frequency of work. This functional gap allows for wireless communication with ultra-broadband and advanced imaging [19]. At Harvard University, scientists designed and implemented the structure of a DC to DC converter in transistors with high electron mobility. In this work, mathematical analysis has been investigated for when voltage is applied in the transistor to the DC to DC converter [20]. At the University of Electronics Science and Technology in China, using a barrier made of AlGaN in the layer where the GaN channel is located, by modulating the distribution of electric field along the channel, the breakdown voltage is significantly improved [21]. Japanese researchers have reported the development of vertical direction GaN-based transistors with voltages greater than 1kV. These findings are important for the application of GaN-based equipment in electric vehicles. Low resistance, which leads to reduced power consumption and heating, has



(a) (b)

Figure 4. Structure of GaN: (a) lateral design and (b) vertical design[20].

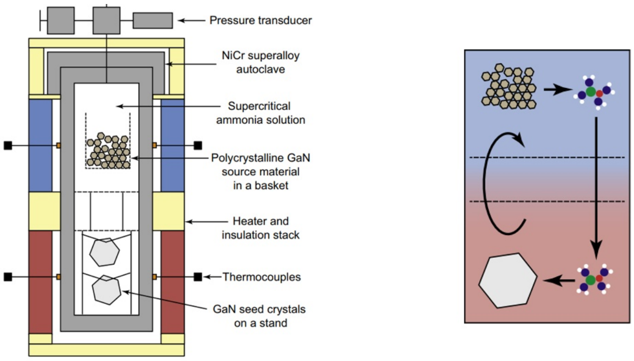


Figure 5. Schematic of autoclave used in the ammonothermal growth method with external heating system and the process performed in the ammonothermal growth method.

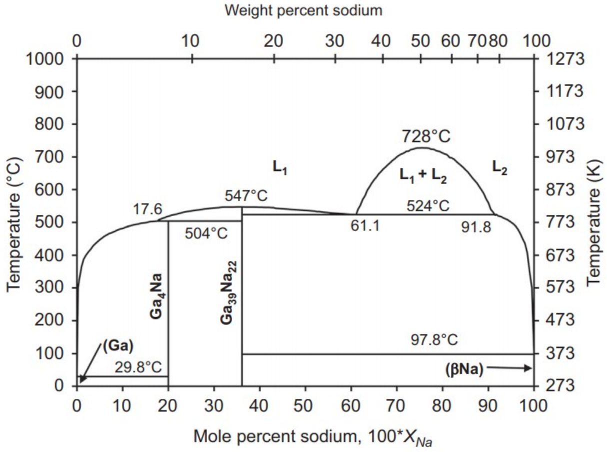


Figure 6. Phase diagram of sodium and gallium containing system.

attracted the attention of researchers to study GaN systems for Nano electronics. Structures that are limited in terms of breakdown voltage and threshold voltage are not very suitable for applications such as those used in electric vehicles. At Cornell University's Institute of Physics, a team of semiconductor engineers has developed a structure of GaN that contains the building blocks of an electric current switch. Silicon-based semiconductors are rapidly approaching the limits of their electronics performance, so materials such as GaN are being considered a viable alternative. Researchers at Cornell University aim to develop low-cost, high-efficiency switches to replace outdated, bulky, and inefficient technologies. Researchers at the University of Oxford and Cornell University have recently conducted a study that examines the inherent mobility of electrons and holes in the Wurtzite crystal. Their observations show that the mobility of GaN holes can be increased by inverting the applied field sign to the crystal and separating light and heavy holes. Engineers at Tohoku University in Japan have developed omnidirectional photoluminescence (ODPL) spectroscopy equipment, a method for examining crystalline semiconductors, to detect defects and impurities. And in another work, they were able to discover a way that could quickly detect carbon impurities using light.

3. Crystalline growth techniques of GaN

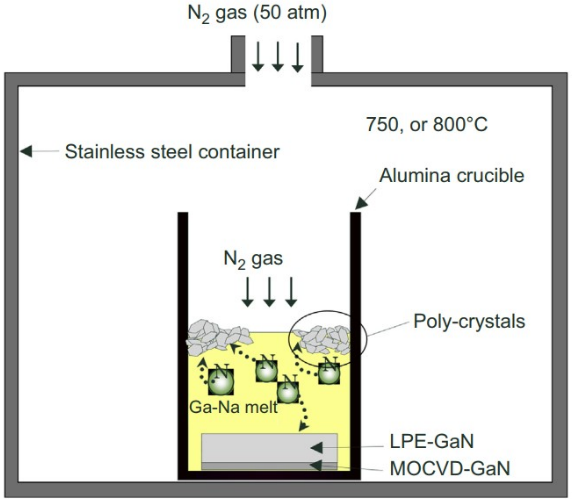


Figure 7. Schematic of GaN crystal growth system by sodium flux method with external heating system.

Due to the limitations of GaN, standard crystal growth techniques such as Czochralski, Bridgman, and Verneuil cannot be easily applied to this material. Despite the challenges of direct synthesis of solid GaN from molten GaN, several methods have been developed that can grow monocrystalline GaN in bulk under normal conditions. One of these techniques is solution growth, which is an Ammonothermal method based on the solution growth technique. Another technique is the growth of GaN flux, which consists of a melt bath resulting from the flux of the material. This technique involves the Na-Flux method. The next growth technique is the vapor phase, which includes the Hydride Vapor Phase Epitaxy (HVPE) method. Another technique is Metal-Organic Chemical Vapor Deposition(MOCVD) and finally, the latest technique is Molecular Beam Epitaxy(MBE) which is proposed as a method of Physical Vapor Deposition (PVD) and we will briefly review.

3.1 Ammonothermal method:

The ammonothermal crystal growth method is a mass through the solvothermal process which is similar to the hydrothermal method which is used for the growth of single-crystal quartz (silicon dioxide) on an industrial scale (approximately 3000 tons per year) [22]. This method is very useful for the growth of nitrides. The growth of GaN involves the process of dissolving gallium (typically polycrystalline GaN or metallic gallium) into a supercritical ammonia solution and then depositing it on a high-quality GaN single crystal grain. The solubility of gallium is increased by adding substances to the supercritical ammonia solution. By adding NH_2^- or amides the solution is named basic and by adding NH_4^+ or ammoniums the solution is named acidic. The basic ammonothermal solution is usually composed of alkaline metals such as sodium and potassium, and the acidic ammonothermal solution is composed of halogens such as fluorine and chlorine [13].

The supercritical fluid has a temperature and pressure higher than the critical point. These fluids act like gases in terms of transfer properties, have high permeability and low viscosity, and are similar to liquid solvents in terms of solubility. The region above the critical point, called the supercritical fluid, is the stage where there is no distinction between gas and liquid, and the density of the liquid equals that of the gas. Supercritical ammonia is used as a solvent for gallium species and may in some cases act as a source of nitrogen. It should be noted that excess minerals increase the solubility of gallium

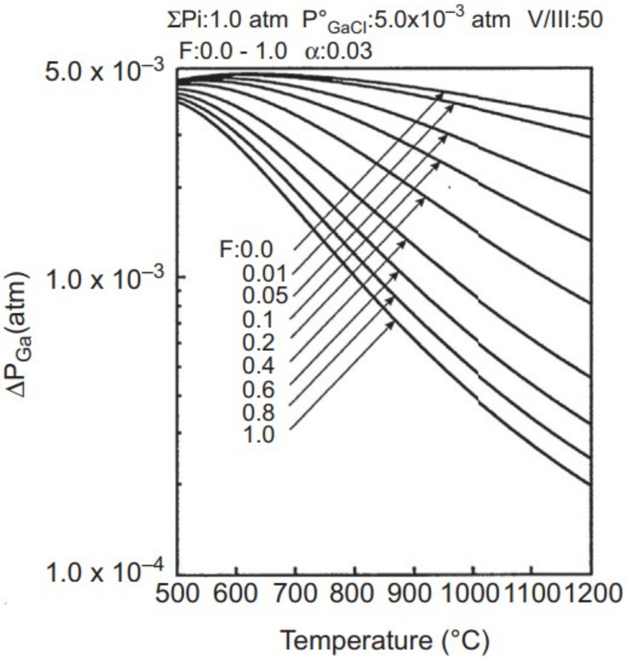


Figure 8. Driving force for the growth of GaN as a function of growth temperature and a molar ratio of hydrogen to inert gas atoms (F).

in the solution. Sodium or potassium is used as a mineral. Ammonia decomposes easily at high temperatures according to the following equation

$$NH_3 \longrightarrow \frac{1}{2}N_2 + \frac{3}{2}H_2$$

At temperatures above 700K, we achieve good solubility, and pressures above 100MPa are required to prevent decomposition. The temperature and pressure required under normal conditions for the ammonothermal method will be T = 800-1000K, P = 100-300MPa [13]. Crystal growth can be accomplished by a supersaturated solution containing gallium around one or more single-crystalline GaN grains. The amount and extent of this saturation must also be controlled. Super saturation greatly causes the growth of GaN crystals on the inner surfaces of the autoclave. Figure5 shows the configuration of crystal growth by the ammonothermal method. In this case, the gallium source is at a lower temperature and the crystalline GaN grains are at a higher temperature. The GaN source material in the solution moves through the baffle plates and to the higher temperature region and crystallizes on the GaN grain crystal. Floating forces cause the hotter fluid to rise, which results in a continuous transfer of mass from the source to the growth zone, creating a true temperature gradient. The ammonothermal method is considered to be the most promising route for the production of high-quality and large surface GaN crystals at a low cost [13]. Finally, the product of the ammonothermal method will be GaN nanoparticles [23].

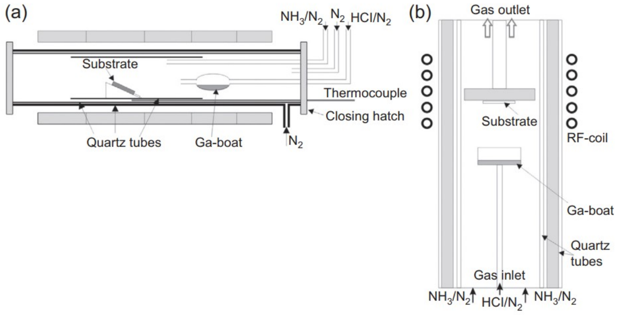
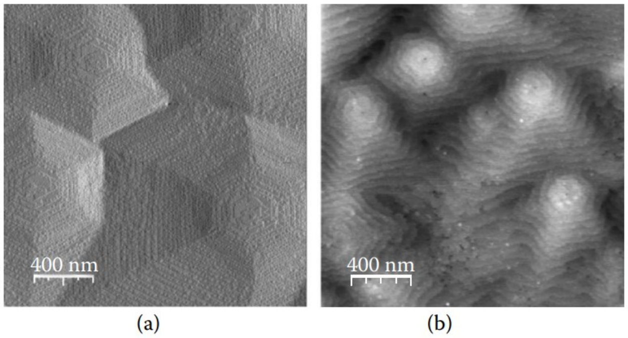


Figure 9. Schematic of structure (a) with the horizontal flow and (b) with the vertical flow in HVPE reactors.

3.2 Sodium flux(Na-flux) method

The sodium flux method is a high-temperature solution-based growth method that precipitates GaN from molten sodium gallium solution in a supersaturated nitrogen solution. This sediment is due to the high-pressure environment of nitrogen gas. This process was first performed in 1997 by two scientists, Yamane and DiSalvo, and although it is shorter in life than other methods, it has been very promising [24]. The method is implemented by placing a crystalline seed in a sodium gallium solution. The dose of this solution is still or in another case, the base solution is spinning around the crystal. In all cases, the temperature is kept constant. The temperature range is about 800°C to 900°C and growth is controlled by nitrogen pressure in the range of 3MPa to 5MPa. Nitrogen becomes supersaturated in solution due to its high pressure. Key challenges in this method include diffusion of nitrogen through the melt, spontaneous nucleation of GaN crystals in the melt container and surface, change in the sodium gallium ratio in the melt, and proper inhibition of sodium vapor. Another problem with this method is the lack of experimental data for temperatures below 650°C, so there is uncertainty about the accuracy of the phase diagram of this system, which has not been measured experimentally in some areas. Note that the ratio of molten components, i.e. the ratio of sodium to gallium, should be 73mol to 27mol, which is kept at 850°C. The latest phase diagram is shown in Figure6 [13].

The high solubility of nitrogen in the molten solution significantly increases the growth rate, but it is important to note that the solubility of nitrogen in the melt of pure metals such as gallium and sodium is not high. Certain compounds of sodium gallium melt increase the solubility by up to 5 times, and in general, this solubility increases with increasing temperature and pressure of nitrogen gas. After solving the problem of low nitrogen solubility, considering that sodium ionization leads to electrochemical reduction of nitrogen (N^{-3}), it can be studied based on calculations of density functional theory and simulation of molecular dynamics. These calculations show that sodium and gallium tend to separate and thus create holes in the liquid, nitrogen can easily fill these holes and bond with gallium. A schematic of the sodium flux crystal growth system is shown in Figure7 [13].



(a) (b)

Figure 10. Atomic force microscopy(AFM) image of the surface of GaN layers grown with (a) ammonia and (b) plasma nitrogen[51].

3.3 Hydride Vapor Phase Epitaxy(HVPE) method

The growth of GaN by the HVPE method was first performed in 1968 by Maruska and Tietjen [25]. This technique can produce GaN bulbs in large dimensions, some of which are up to about 1cm thick. They are currently available industrially with a diameter of 6inches to 7inches in the direction of the c plate. The HVPE method is a vapor phase growth method in which gallium species (in the form of gallium chlorides) react with ammonia gas to form GaN. The formation of gallium chlorides is easily achieved by giving a stream of hydrogen chloride gas (HCl) to a container containing gallium melt at an optimum temperature of 800°C to 900°C. At a base temperature of 600°C, gallium monochloride (GaCl) is found to be stable and present in significant concentrations in the gas phase. Upon entering the growth zone, which is usually kept at a temperature of 1000°C to 1100°C, the driving force of growth is obtained by over-saturation of the gas phase in GaCl. It is found that the growth rate of GaN increases linearly with the HCl flow rate and leads to a growth of 2.4mm/day [26]. Continuous advances in the design of equipment and chemicals have led to the growth of crystals in the c direction at speeds of more than 1870μm/h or 44.9mm/day [27]. The heteroepitaxial growth of GaN on the sapphire substrate poses challenges related to lattice mismatch and thermal expansion coefficient mismatch and ultimately leads to an increase in the concentration of misalignments, and network curvature, and in other cases cracks in the boules. Nevertheless, this is still the preferred choice of the substrate to date. Due to the growth conditions (pressure of 1 atmosphere and temperature of about 1000°C) and the availability of extensive databases of thermodynamic properties of various compounds in the gas phase, accurate thermodynamic analysis of the system can be achieved. This has led to a comprehensive understanding of the thermodynamics of the process and the effect of multiple parameters on the thermodynamic driving forces. For example, the effect of using an inert gas such as helium instead of hydrogen to increase the growth driving force and thus increase the growth rate is shown in Figure8 [13]. In this method, GaN is produced in the form of nanowires like molecular beam epitaxy [28]. GaN-based nanowires and GaN nanoparticles are one of the most widely used nanostructures used in GaN transistors, which in addition to HVPE and MBE methods are also produced and used by the thermal evaporation method [29–35].

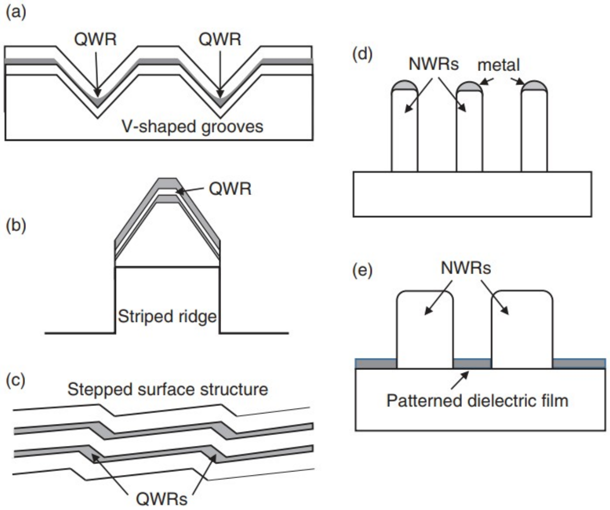


Figure 11. Schematic of MBE grown quantum wires and nanowires: Quantum wires grown with (a) V-shaped grooves, (b) quantum wire grown on the striped ridge, (c) the stepped surface structure, and nanowires grown with (d) formed by catalysis (e) formed by selective-area growth[51].

While most commercial growth of GaN is by HVPE with GaCl, research is investigating the use of $GaCl_3$, which consists of the reaction of Cl_2 with Ga and GaCl. This has the potential to solve the problem of ammonium chloride formation in the steam outlet due to HCl deficiency. In addition, the thermodynamic driving force for the growth of GaN with $GaCl_3$ is higher than GaCl, and not only will it increase the growth rate but also the growth process will take place at higher temperatures (about 1350°C). In this way, GaN will grow with better quality. Figure9 provides an overview of the structure in question.

In the use of $GaCl_3$, growth in the [0001] direction is preferential, unlike most GaN crystals that grow in the HVPE method in the [0001] direction. In general, the use of trichlorides offers new opportunities for the growth of ternary alloys such as thick layers of indium gallium nitride (InGaN) in a direction other than the polar direction.

3.4 Metal-Organic Chemical Vapor Deposition(MOCVD) method

Metal-organic chemical vapor phase deposition is introduced as one of the most suitable techniques for epilayer deposition from the III-nitride group [17]. In electronic physics, the layer that grows on the substrate is called the epilayer. Crystal growth from semiconductor materials can be accomplished by a variety of techniques, including Molecular Beam

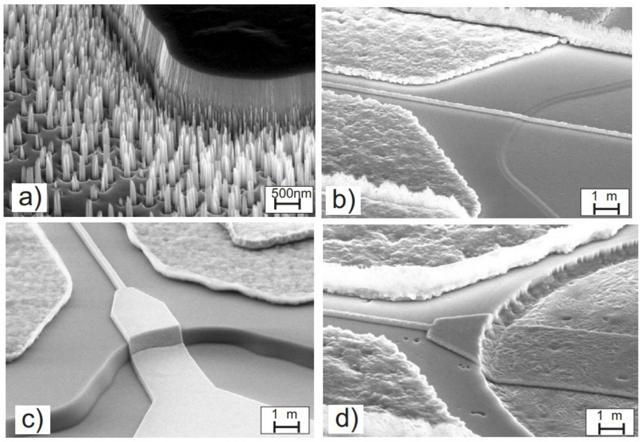


Figure 12. Etching process with (a) Reactive Ion Etching(RIE) methods using titanium mask (b) Resist mask (c) Ion Beam Etching(IBE) with Ar$^+$ ions and (d) PhotoChemical Etching(PCE) etching process [69].

Epitaxy (MBE). In practice, the method of choice for the deposition of epitaxial layers on an industrial scale is the Metal-Organic Chemical Vapor Deposition (MOCVD), also known as the Metal-Organic Vapor Phase Epitaxy (MOVPE) [36]. The nanostructure obtained by the MOCVD method is GaN nanowires [37]. In this technique, the atoms that make up the growing crystal in the reactor chamber are gasified under controlled thermodynamic conditions. The lamination process is performed by a gas-carrying molecule. This carrier gas can be nitrogen (N_2) or hydrogen (H_2) or a mixture of both. By supplying the required thermal energy, these molecules are separated from each other, and in the gas phase, they react with the surface molecules of the substrate and the growth process begins. The precursor forming molecules for the III-nitride group elements are a combination of group III of metals with organic groups such as ethyl or methyl groups. This is why this technique is called MOVPE. The source of gallium gas is usually tri-methylgallium $(CH_3)_3Ga$(TMGa) or tri-ethylgallium $(C_2H_5)3Ga$(TEGa). The sources of aluminum and indium are tri-methylaluminium $(CH_3)_3Al$(TMAl) and trimethylindium $(CH_3)_3Al$(TMIn), respectively. The epitaxial growth process is controlled by controlling thermodynamic conditions such as temperature, pressure, etc. both through the gas phase in the reactor medium and through the substrate. Under these conditions, the Gibbs free energy of the substrate material and the gas phase is determined, which is determined by the difference between the two energies, whether a dynamic equilibrium is provided for the growth of the semiconductor solid phase, which includes the substrate and the epilayer. Another important point is surface kinetics, which explains how the growth process is affected by adsorption and excretion from the surface [17]. It is important to note that there is always an equilibrium between the composition of the gas phase and the vapor pressure of the components of the solid phase, which means that any contamination of the gas phase also contaminates the semiconductor material. Metal-organic precursors are themselves a source of contamination due to impurities present in the material. Carbon and hydrogen atoms are inherent in the gas phase and require fine tuning of growth conditions, including control of the corresponding vapor pressures, to minimize the atoms in the solid phase. Control of pollution in the gas phase is very important for oxygen sources such as CO, H_2O, O_2, and CO_2.

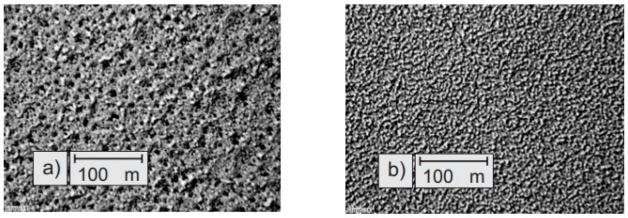


Figure 13. Different surface roughness in increasing temperature (a) fast and (b) slow annealing temperature [69].

The MOCVD process for GaN usually occurs at temperatures above 1000°C. Occurs for Indium gallium nitride less than 700°C and aluminum nitride above 1200°C. The reactor pressure for GaN is between 10mbar and 200mbar [17]. This process operates at limited pressures, which means that in addition to thermodynamic considerations, the MOCVD process must also be optimized in terms of fluid dynamics and thermophoresis effects [38]. Although HEMT, as one of the most efficient electronic devices, does not require doping or contamination in the active structure, doping is required in bipolar equipment. The doping method commonly used for n-type conduction in GaN introduces group atoms. One of the most widely used is silicon, which is used as a silane gas (SiH_4).

The most well-known element for p-type conductivity is magnesium doping, which is widely used in GaN LED and laser technology, and more recently in GaN JFETs. Magnesium has the disadvantage of forming a compound with hydrogen (used as a carrier gas in MOCVD) that electrically inactivates magnesium. The MOCVD method allows the growth process to be monitored by monitoring the in situ conditions. MOCVD is limited to techniques, one of which is laser interferometry. The semiconductor growth rate is represented by the semiconductor epitaxial growth interference measurement model. By slightly modifying the performance of such tools, the wafer can be expanded to measure mechanical deformation. By measuring the reflection of the white light spectrum, data on the composition of materials are obtained [17].

Using a new manufacturing technique, MIT researchers built a three-dimensional transistor less than half the width of today's thinnest commercial models that could fit more transistors into a single computer chip. A team of researchers at the University of Illinois has improved a transistor with GaN technology with a silicon substrate to optimize the composition used in the semiconductor layers of the device. The team, in collaboration with their industrial partners Veeco and IBM, built the

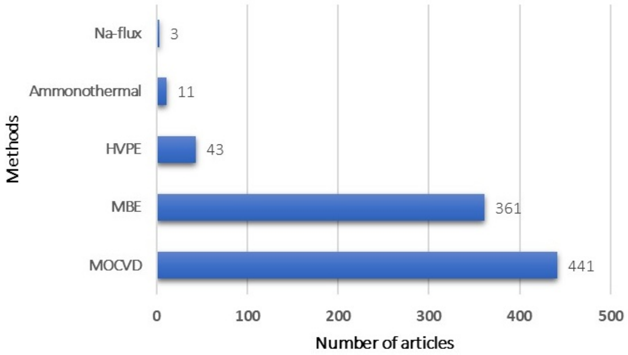


Figure 14. Comparison of published articles based on conventional GaN crystal growth methods.

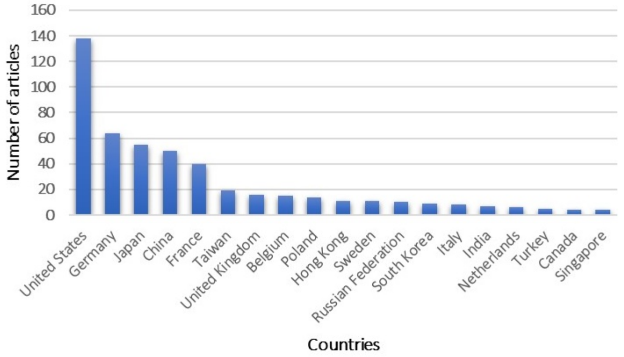


Figure 15. Number of research articles published on MOCVD growth method in different countries.

structure of a high electron mobility transistor (HEMT) on a 200mm silicon wafer, which is larger than standard industrial wafer wafers [39]. A new method for growing layers of thin semiconductors several nanometers thick is not only a scientific discovery but also a new type of transistor for high-power electronic devices. This achievement is the result of a close collaboration between scientists at Linköping University and SweGaN, a research company in materials science. The company manufactures electronic components based on GaN. High-temperature stability is a feature that distinguishes GaN for use in the manufacture of industrial transistors. Especially in transistors used in electric vehicles. In this method, GaN vapor is allowed to condense on the silicon carbide wafer to form a thin coating. Scientists at the University of Georgia in the United States have developed a room-temperature bonding technique to combine materials with a wide bandgap such as GaN with thermally conductive materials such as diamonds that can enhance the cooling effect on GaN-based equipment. Better performance, longer machine life, and reduced production costs are the strengths of this technique. This technique can be used in wireless transmitters, radars, satellite equipment, and other high power, high frequency electronic devices. GaN, a semiconductor that revolutionized low-power LEDs, can also change wireless communications thanks to a discovery by Cornell University researchers. Pure materials are often doped or contaminated with impurities such as phosphorus or boron to increase the current by providing negative charges (electrons) or positive charges (holes, no electrons) if needed. In recent years, the latest and more effective family of laboratory composite semiconductors has emerged: the III-nitrides group. GaN and aluminum nitride and their alloys have a wide bandgap and allow them to transmit higher voltages and higher frequencies. Now the research team can create hole channel transistors (called p-type), they plan to pair these transistors with n-type transistors in the next work, creating more complex circuits and new features in technology. Provide 5G cell and electronic devices including phone and laptop chargers.

3.5 Molecular Beam Epitaxy(MBE) method

Molecular Beam Epitaxy (MBE) is a versatile growth technique for the production of semiconductors, insulation, and metal films [40]. MBE as an epitaxial growth method has many advantages in the growth of various semiconductor compounds. This method was not a promising alternative to the MOCVD method until the first pulsed laser(LD) diodes with an emission wavelength of 400 nm were fabricated by the MBE method [41]. Since then, significant progress has been made in the nitride material grown by the MBE method, nanostructures, and related equipment [42]. The use of this method is known in both production and research [40]. This growth technique is used to create light sources that operate over a wide range and has produced new advanced devices. Two growth techniques based on the MBE method have been developed for epitaxy nitride structures: 1. Ammonia Molecular Beam Epitaxy and 2. Plasma-Assisted Molecular Beam Epitaxy [42].

In the MBE growth method, ammonia was initially used as a nitrogen-containing precursor, while later plasma was used to atomize nitrogen gas. The ammonia molecular beam epitaxy method can be used to grow GaN at a relatively high growth rate (average 1 μm/h) with a relatively wide width. Normal growth of ammonia molecular beam epitaxy requires an ammonia stream of about 200 sccm with a high flux ratio (above 10^3) rich in NH_3. The growth temperature is also high and is kept in the range between 800-900°C, which is close to the MOCVD method. The first InGaN-based pulsed laser diode was fabricated by Hooper et al. Using the ammonia molecular beam epitaxy method with an emission wavelength of 400nm and a threshold current of 30kA/cm^2 [41]. Since then, the group has continued to develop these lasers, and the best lasers are made using the ammonia molecular beam epitaxy method. The main features of the ammonia molecular beam epitaxy method can be summarized as follows. Ammonia decomposes thermally on the surface of the layers at temperatures above 450°C [43]. The typical temperature for GaN growth is 800°C, and AlGaN films can usually be grown in the 800-875°C temperature range. The optimum temperature depends on the amount of aluminum in the structure and the

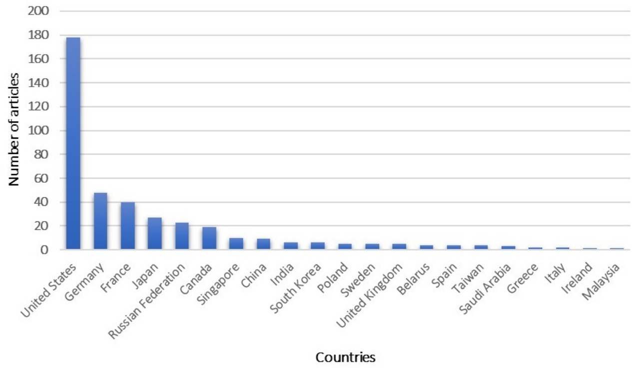


Figure 16. Number of research articles published on MBE growth method in different countries.

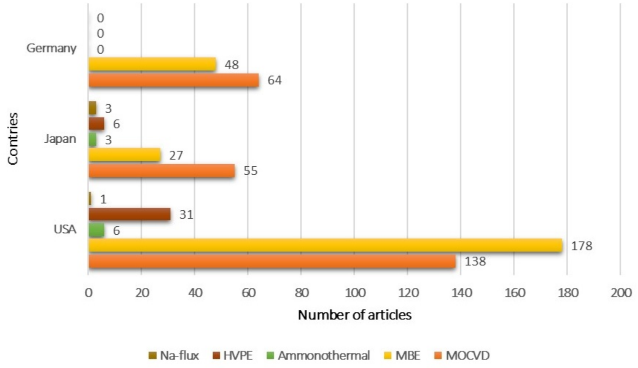


Figure 17. The rate of use of GaN growth methods by the United States, Japan, and Germany as leading countries in the field of GaN crystal growth.

thickness of the layer to be grown. In this method, the growth rate in the range of 0.5 to 1.5 μm/h is easily achievable.

In this section, the effect of nitrogen source flow rate on the growth of GaN is investigated. Optimal growth conditions are N-rich, meaning that a large flux rate of ammonia is required (about 200 sccm) [44]. For optimal growth temperature at 800°C and constant gallium flux rate, growth rate and surface morphology change slightly. This is while the ammonia flux rate decreases. Further reduction of ammonia flow rate leads to slower growth rate as well as further development of surface roughness due to insufficient amount of active nitrogen species compared to input gallium species [43], [45]. Although improvements have been made with this method, due to the high consumption of ammonia, most manufacturers of nitride-based equipment with the MBE method are less welcome. High growth temperature, corrosive nature of ammonia, and high hydrogen background during the epitaxial process are the reasons that limit its widespread use for the growth of the nitride family.

MBE growth charts, also known as surface phase diagrams, are very effective in producing high-quality thin films. GaN coatings are generally grown in 1-2mm thick molds by MOCVD on sapphires, with a dislocation density estimated at between $5\times10^8-5\times10^9$cm^{-2}. The growth of GaN epilayers has been studied by plasma-assisted molecular beam epitaxy with different growth conditions using different technologies, such as Reflective High-Energy Electron Diffraction(RHEED). RHEED patterns are generated from hexagonal GaN surfaces in the (0001) direction under different gallium fluxes.

High gallium flux is considered one of the Ga-rich growth conditions and low gallium flux is considered one of the N-rich conditions. Ga-rich conditions are more commonly used for two-dimensional growth, while N-rich conditions are often used for three-dimensional growth [53]. Two plasma sources are used for plasma-assisted molecular beam epitaxy: Electron-Cyclotron Resonance (ECR) and Radio-Frequency (RF) plasma [46]. Nitrogen is molecularly ineffective in the MBE method but can be effectively broken down into active nitrogen species such as neutral and charged nitrogen atoms (N, N$^+$) and free electrons. Radio-frequency plasma sources are generally preferred to electron-cyclotron resonance plasma sources because they produce more neutral nitrogen, which is desirable for nitrogen fusion during the epitaxial process. In addition, have been shown that high-quality nitride-containing compounds are obtained at much lower temperatures than the molecular beam epitaxy method. Understanding growth behavior extensively and experimentally and theoretically is essential for the development of growth mechanisms [53]. Modern nitride-based equipment requires Al-rich AlGaN alloys or In-rich InGaN and doping at a controlled level. However, there are several challenges, including material degradation with increasing indium content in InGaN alloys and the difficulty of obtaining n-type doping in Al-rich AlGaN alloys. Growth conditions have been optimized and new structures have been created, leading to the production of various high-performance devices [53]. Plasma-assisted molecular beam epitaxy will be more difficult than other methods. The most common growth conditions reported for GaN smooth films are growth at 720-730°C with fine-tuning of the nitrogen flow rate. The gallium flow rate to keep the thin metal gallium film (two to three monolayers) afloat on the growth surface results in surface roughness of about 1nm (Figure10(b)). Out of this equilibrium, either an uneven film is obtained or too much gallium causes droplets to form on the surface [47]. To reduce these effects, growth at higher temperatures (780-790°C) under high nitrogen flux rates has been suggested [48]. Compared with ammonia and MOCVD molecular beam epitaxy methods, the low growth rate of the plasma-assisted molecular beam epitaxy method (0.3-0.5μm/h) is considered a major drawback. The first point to solve this problem is the simultaneous use of several nitrogen plasma cells that increase the growth rate to more than 0.8μm/h [49]. Recent advances in plasma cells allow the growth rate to reach more than 2μm/h without changing the surface morphology and optical properties [50, 51]. Significant achievements in the fabrication of transistors based on GaN have been achieved by both methods [52–56].

In the MBE method, quantum well structures usually grow on substrates. Due to the two-dimensionality of this quan-

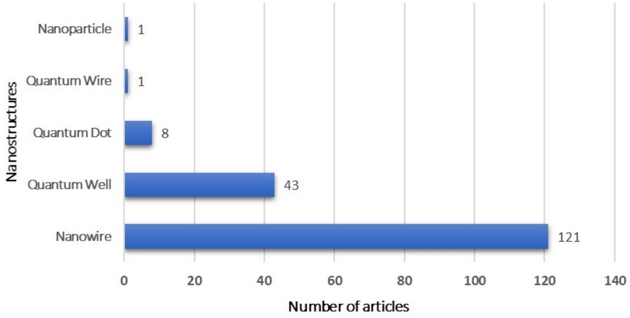


Figure 18. Comparing the conventional GaN nanostructures used in transistor structure.

tum structure, in the growth process, controlling the thickness of the heterostructure layers at the atomic surface and the flatness of the intersections will be important points. In the MBE method, Reflective High-Energy Electron Diffraction(RHEED) is a carefully developed tool for controlling the thickness of the epitaxial layer. Because the intensity of the beam in the RHEED instrument depends on the degree of roughness at the atomic surface, the intensity changes provide information about the surface of the layer during the growth of MBE [57]. Other structures produced in the MBE method are quantum wires and nanowires. The difference between these two structures is in their dimensions. The size of the nanowires is not small enough to show the effect of quantum confinement. Figure11 shows three types of quantum wires and two types of nanowires. It should be noted that quantum nanowires grow in both lateral and vertical positions. Figure11, (a) shows the quantum wires with V-shaped grooves and (b) shows quantum wires grown on the striped ridge that grew by the MBE method. (c) show the stepped surface structure, (d) show nanowires formed by catalysis, and (e) show nanowires formed by selective-area growth. Another product of the MBE method is quantum dots. Quantum wells and nanowires will be widely used in the Nano electronics and Nano photonics industries due to their good and new functions [51].

4. Fabrication process of a transistor

4.1 Sample preparation

Control of metal/semiconductor shared surface is crucial for proper machine operation. The GaN and AlGaN levels are unique and very different from other common semiconductors in groups three to five of the Periodic Table. Although the wetting process performed by ordinary acid and alkaline does not produce a clean atomic surface on GaN, it is effective in removing a significant portion of surface oxides and other contaminants, resulting in surface contact. Metal/semiconductor is obtained relatively well [58]. The coating on GaN is composed of transparent organic and mineral-based materials and an oxide layer. Organic parts can be removed with methanol,

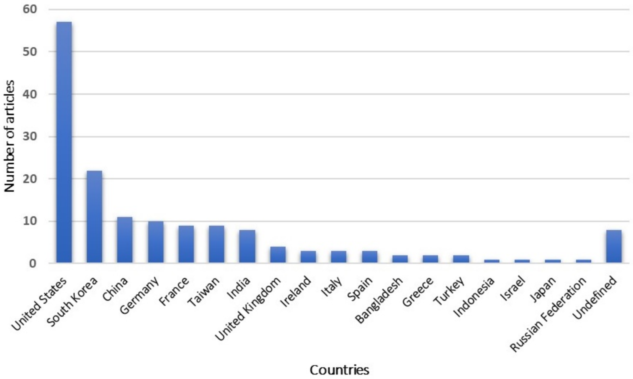


Figure 19. Number of articles of GaN nanowires in transistors in different countries.

acetone, propanol, and plasma oxygen. The use of NH_4OH, $(NH_4)_2S$, and NaOH is recommended to remove the oxide layer and inorganic parts. Acids such as HCl and HF are also effective in the complete removal of surface oxides in GaN [59]. HCl-based solutions are effective in removing residual oxygen oxides and HF is effective in removing carbon or hydrocarbon contamination. In general, both acids are equally effective in eliminating total pollution [60].

4.2 Etching process

Creating an insulation layer called mesa is an important step in making HEMT transistors. Mesa is a raised surface that remains after removing the semiconductor material to access the substrate. Creating parts like an island of active materials on the sample, parts of 2DEG are separated by electrical insulation. This insulation is done according to the position of 2DEG. Due to the strong bond energy in the III-nitride group compared to other composite semiconductors, it is a bit difficult to find the most suitable etching technique. The wet etching process is not very suitable for execution due to the low etch rate [61, 62]. Given these results, considerable effort has been devoted to the development of the dry etching process. Dry etching techniques are achieved with high etching rates and smooth sidewalls which are important for the structure of the mesa [69]. The dry etching technique has become a dominant method for nitrides, but the main problem that must be solved first is choosing the best mask for etching. In this regard, a simple mask and an advanced mask with a titanium metal layer have been tested. A thin layer of titanium (100nm) has been tested in an attempt to achieve smooth edges. These experiments have shown that the use of thin titanium masks results in uniform and homogeneous etching profiles (Figure12(a)).

The first technique used to etch mesa structures was based on RIE ECR with Cl_2 plasma. The plasma obtained in RIE ECR systems is two to four times higher than that of RIE, which leads to a higher etching rate. A plasma based on $Ar/CH_4/H_2/cl_2$ has been investigated. By changing the ratio between gases, different results of etching rate are obtained.

Satisfactory quality is obtained with the relation of gases (5sccm)Ar/(5sccm)CH_4/(15sccm) H_2/(2sccm) Cl_2. The etching rate, in this case, is 70nm/min to 100nm/min. Figure12(b) patterns of islands on the surface are defined by optical lithography [69]. The second technique used is Ion Beam Etching (IBE) based on Ar^+ ion spraying. The surface of the sample is bombarded by Ar^+ ions at a certain velocity and angle of impact. The speed (adjusted by voltage) and the angle of impact are well defined to achieve smooth etching on the surface and sidewalls. The small angle of impact leads to sloping walls and a very large angle (about 90 degrees) causes the etched material to move on the walls. Good results are obtained with an angle of 30 degrees. A voltage of 500V is also optimal for this. The etching rate is proportional to the density of Ar^+ ions, which can be adjusted by the corresponding currents. The optimum etching rate is 30nm/min. The mesa structure created by this type of etching has good side walls and sharp edges (Figure12(c)). The third technique used is PhotoChemical Etching (PCE). In this case, with the help of ultraviolet light, GaN is etched in a KOH-based solution. The important point of this method is to create an ohmic contact between the mask and the GaN surface. For this reason, a resist mask cannot be used. A 100nm thin layer of titanium is used as the mask, which disappears after etching. The etching rate in this process is about 10nm/min. The etched surface has high roughness, heterogeneous depth, and rough sidewalls with a negative slope. Surfaces with such characteristics are not very suitable (Figure12(d)) [69].

4.3 Ohmic contact

The ohmic connections of HEMT devices are an important factor in their performance. The high resistance of these contacts negatively affects the features of the device. Since HEMTs are high current, low voltage devices, the saturation voltages and conductivity are very sensitive to the resistance of these connections, and very little resistance is necessary to take full advantage of the HEMT potential. AlGaN/GaN HEMT transistors require ohmic contact with 2DEG located approximately 30nm from the surface. Due to the large bandgap caused by the AlGaN or GaN layer, it is difficult to establish a proper ohmic contact. The two layers of titanium and aluminum are very important in the ohmic semiconductor/metal connection, and the gold layer at the top makes contact with the outside world possible. The ohmic contacts are located on top of the created islands and are patterned by optical lithography. Metals such as Ti, Al, Ni, and Au are used to make ohmic contacts with the AlGaN/GaN structure [69]. The Ti/Al ratio is approximately 15nm/200nm in one sample and 35nm/200nm in the other. The resistance of $7 \times 10^{-7} \Omega cm^2$ is obtained in the Ti/Al ratio selected in the second case. Annealing is an important step in making an ohmic contact. The precipitated metal begins to react with the surface immediately after deposition. For this reason, the time of deposition until the sample is annealed will play an important role. The annealing temperature must be optimized to create a stable ohmic contact with the smooth surface. This level of surface roughness and smoothness in the later stages of construction is very important due to the connection of the gate electrode with the structure. Changes in the annealing temperature lead to surface roughness in ohmic contacts. The contact surface is smoother for changes with a slower slope [69]. Changes in roughness with annealing temperature are shown in Figure13.

4.4 Schottky contact

The controlled formation of stable Schottky connections at low current losses is an important factor for the realization of high electron mobility transistors based on AlGaN/GaN. The electrode length of HEMT gates is in the range of 200nm to 700nm. Gate electrodes longer than 300nm should be made using lithography and lengths below 300nm should be made using electron beam lithography, which allows for greater reproducibility. Using this lithography method, an electron beam with a voltage of 10kV is placed on the sample and absorbed in the resistance of the part. PMMA lithography is used as a resistor for this method. The total thickness of the resistor must be greater than the thickness of the deposited metal. A multilayer structure for resistance must be used to obtain the resistance profile. In the case of non-insulating substrates, such as silicon substrates, a thin layer of gold should be layered on top of the resistive layer to prevent surface loading and electron scattering. In data published by various researchers, a large variation in barrier height is found for standard metals deposited on GaN [69].

4.5 Contact pads

In electronics, the pad is a layer that reduces the intensity of radiofrequency signals to a desired constant value without causing significant distortion. It is also called a constant attenuator. Contact pads must be present to connect the HEMT to the outside world. These pads must be compatible with the measuring devices. For HEMTs, pads with specific areas are used. Contamination from these contact pads can affect the performance of the device. These pads are also resistant to high temperatures and must be mechanically strong [69].

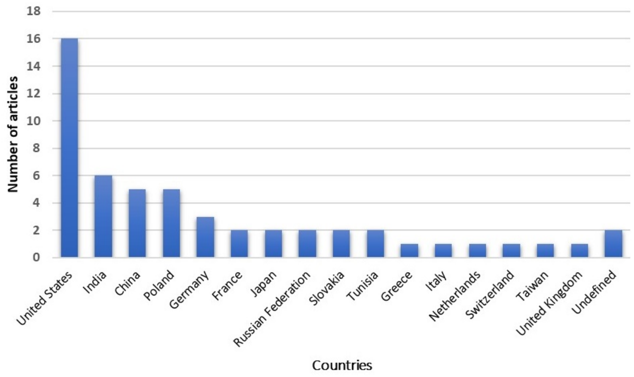


Figure 20. Number of articles of GaN quantum wells in transistors in different countries.

Table 3. Investigation of basic features of widely used methods in crystalline GaN growth[16], [17], [51], [53], [65], [81-83]

Method	Ammono thermal	HVPE	Na-Flux	MOCVD	Ammonia-MBE	PA-MBE
Growth method	Solution growth	Gas-phase growth	Flux Flux	Gas-phase growth	Gas-phase growth	Gas-phase growth
Precursor	Dissolution of polycrystalline GaN or metallic Ga into supercritical ammonia solution	Volatilized gallium chlorides and ammonia gas	Molten Na-Ga solution and and nitrogen gas	Trimethylgallium or Triethylgallium and nitrogen gas	Knudsen cell of solid gallium and ammonia gas	Knudsen cell of solid gallium and nitrogen plasma
Temperature	520-720°C	1050°C Almost	800-900°C	1000°C	800-900°C	720-730°C
pressure	1000-3000 bar	1 bar	30-50 bar	10-200mbar	-	-
Growth rate	Basic Almost 350 μm/day along c-plane m-plane $<$ 30 μm along Acidic Generally 1000 μm/day	Between 200 to 1800 μm/day	On average 1700 μm/day	Between 48 to 72 μm/day	Between 12 to 36 μm/day	Between 7.2 to to 12 μm/day
Background impurities	O, Na, Transition metals	O, Si, C, H	O, Ca, Ge	Fe, Tri-methyl-gallium, Tri-ethyl-gallium	C, O , ,	
Impurity density	$10^{16}-10^{19}$ cm^{-3}	5×10^{13} cm^{-3}	$10^{16}-10^{18}$ cm^{-3}	5×10^{15} cm^{-3}	5×10^{16}- 1×10^{17} cm^{-3}	
Structure quality	High	Good	High	High	High	High
Dislocation density	10^4 cm^{-2}	10^{15} cm^{-2}	10^3-10^6 cm^{-2}		5-7$\times10^9$ cm^{-2}	
Cost	Low	Low	Low	Medium		
Product	Nanoparticle	Nanowire		Nanowire	Quantum well-Quantum wire-Nanowire-Quantum dot	Quantum well-Quantum wire-Nanowire-Quantum dot

4.6 Passivation

In electronics, a layer of insulating material such as silicon dioxide or silicon nitride is applied to the semiconductor or part of it to stabilize and protect its surface from moisture, pollution, and mechanical damage. This layer reduces current losses in semiconductors and improves breakdown voltage. To prevent the loss of the properties of the manufactured parts as well as to increase the performance, a passive layer was placed in the structure. It is grown by Plasma Enhanced Chemical Vapor Deposition (PECVD) at 150°C to 300°C. The SiO_2 or Si_3N_4 layer will grow to a thickness of about 100nm. This layer may affect the electrical properties. This deposition process must be done very carefully and the deposited layer must be as small as possible to achieve high uniformity of the layer. After the deposition process, different parts of the sample are covered by the passive layer [69].

The electronics industry expects a new high-performance transistor made of GaN to offer significant advantages over modern high-frequency transistors. Now, for the first time, researchers at the Paul Scherrer Institute (PSI) have observed electrons flowing through the transistor. Their findings show when entering the high power domain in GaN transistors. Two NASA research teams are investigating the use of GaN in space applications. Among the many properties of GaN, its low electrical resistance and the loss of only a small portion of its power in the form of heat have received much attention. It has 10 times more electron conductivity than silicon, which ensures smaller, faster, and more efficient equipment. In addition, stability in a wide range of temperatures and radiation resistance are their main characteristics. Fujitsu in Japan has announced the development of a power amplifier in high electron mobility GaN transistors for use in W-band (75-110 GHz) transmitter systems. To achieve high-capacity wireless communication, a promising approach is to use the W-band and other high-frequency bands, which include a wide range of usable frequencies. A team of researchers has developed a low-cost, portable medical sensor package that can alert users to medical issues ranging from severe heart disease to cancer. A portable biosensor capable of warning of heart attack and stroke will be made using transistors based on GaN. The researchers announced the design, development, and construction of a prototype of a device that could measure C-reactive protein. C-reactive protein (CRP) in the bloodstream, if increased, indicates inflammation that can be associated with heart attack, stroke, vascular disease, and many other medical diagnoses. A team of researchers in Fraunhofer, Germany, has significantly increased the performance of GaN-based power ICs for voltage converters. The integrated current and temperature sensors on a GaN-based semiconductor chip, along with power transistors, diodes, and gate electrodes. This development paves the way for smaller and more efficient chargers in electric vehicles. When it comes to sending equipment into space, size and mass are considered two important parameters. High electron mobility transistors based on GaN are a good alternative to large and low-efficiency transistors and also have more resistance to the intense radiation of the space environment. Compared to similarly high electron mobility transistors such as aluminum gallium arsenide or gallium arsenide-based transistors, GaN-based transistors are ten times more tolerant of radiation damage. Yuji Zhao, an electrical and computer engineering expert at Arizona State University, plans to develop the first GaN processor, which could revolutionize future space exploration missions. GaN is a semiconductor compound that can conduct electrons more than 1,000 times more than silicon. It has surpassed silicon in speed, temperature, and power control, and is expected to replace silicon-based devices when they reach the end of their life.

5. Conclusion

This paper provides a brief overview of the GaN transistor and its structure. GaN was introduced as a promising material for use in transistor structure and conventional crystal growth methods were investigated. Finally, a brief overview of transistor fabrication was made, and some recent advances in GaN-based transistors were reviewed. Ammonothermal, HVPE, Na-flux, MOCVD, and MBE are the most commonly used methods for the growth of GaN crystals, which were discussed in this research. The conditions of each method are reviewed in Table3. The ammonothermal method requires the lowest temperature and the MOCVD method requires the lowest pressure for GaN growth. The highest growth temperature belongs to HVPE and MOCVD methods with temperatures above 1000°C. The highest crystal growth rate for GaN is observed in HVPE and Na-flux methods.

According to Figure14, among the conventional methods of growing GaN crystals, MOCVD and MBE methods are more frequent than other methods.

Figures 15 and 16, illustrate the research and development of MBE and MOCVD methods as the most widely used methods of GaN growth in different countries

According to research results, the United States, Japan, and Germany can be introduced as leading countries in the development and manufacture of GaN transistors. Figure17 compares the conventional methods of GaN crystal growth and the rate of use of each method in these three countries. The results indicate that the MOCVD and MBE methods have received more attention in these three countries.

As discussed, the most common growth techniques in heterogeneous GaN structures are MOCVD and MBE, each of which has its advantages and drawbacks. While the MOCVD method is widely used due to its larger throughput and larger wafer size, MBE operates at low temperatures under high vacuum with much less resource consumption and is equipped with monitoring tools, such as Reflective High-Energy Electron Diffraction (RHEED). Lower growth temperatures enable epitaxy of In-containing layers such as AlInN [46], [63], GaInN [64,65] and AlGaInN [66,67], which are suitable for high power and high frequency equipment. The tools for producing GaN crystals in the MBE method are very few, but it is still used in many research reactors around the world [55]. Another advantage of the MBE method over MOCVD is the possibility of developing structures that are compatible with operating temperatures such as MOSFETs [68,69]. According to these studies, MBE method is one of the useful and effective methods in the construction of equipment such as HEMT [55]. Ammonothermal method is also one of the most promising methods in producing high quality, large area and low cost GaN substrates. Therefore, efforts have always been made to understand the process and improve its efficiency. Equipment for simultaneous temperature measurement during growth, a more accurate understanding of growth thermodynamics, and a better understanding of the ammonia decomposition process will help advance this method. Due to the long growth time for ammonothermal grown crystals, grains prepared by HVPE and Na-flux methods are used, which will increase the growth rate of GaN crystals [16].

The Na-flux method is commonly used to produce GaN crystals of high purity and high quality. Despite the significant progress that has been made, many issues need to be addressed. Issues such as the thermodynamics of molten sodium-gallium and the behavior of nitrogen from the gas phase to fusion in GaN crystals. One of the main limitations of this method is the inability to produce crystals on a large scale. By eliminating this limitation, the Na-flux method will be among the best inexpensive methods for mass production of GaN. This method will be effective in producing GaN-based grains for other inexpensive, high-purity, large-scale polycrystalline growth methods. According to the studies conducted in this research, the HVPE method provides high-quality and controllable crystals for electronic equipment in the vertical direction. This method has a higher control capability than other methods to grow nanocrystal structures and also provides the ability to produce very good quality substrates at a very low cost. Due to the conditions of use on a laboratory scale, this method still needs to be developed for use on an industrial scale. Finally, considering the widespread use of the MBE, HVPE, and Na-flux methods, as the methods that are mostly used in the laboratory, MOCVD is the most commercially successful method for this material. The most common nanostructures obtained from the above methods are nanowires, quantum wells, quantum wires, quantum dots, and nanoparticles. According to Figure18, GaN nanowires and quantum wells are introduced as the most widely used morphologies in GaN-based transistors.

In Figures 19 and 20, the research and development of nanowires and quantum wells as two widely used nanostructures in GaN transistors in different countries are investigated.

Conflict of interest statement:

The authors declare that they have no conflict of interest.

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