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**THE POTENTIAL OF GALLIUM-NITRIDE AS AN ALTERNATE SEMICONDUCTOR MATERIAL IN TRANSISTORS**

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***Abstract –*** *A semiconductor is a compound whose conductance lies between that of an insulator and a conductor. A semiconductor can be treated with non-intrinsic elements of varying electron count to either allow or block the flow of electric current. By applying these principles, transistors manipulate the flow of electricity in circuits to perform desired computations.*

*Since the transistor’s invention in 1947, silicon has been the standard semiconductor in circuits due to its availability and ease of manufacturing. Over the last seventy years, silicon-based transistors have decreased in size from the palm of a hand to the molecular scale. By downsizing, more transistors can fit in a device, drastically increasing computational power. The most recently developed silicon transistors are only seven nanometers wide, close to the size of an individual silicon atom and in the domain of quantum mechanics. Because decreasing transistor size further can yield unpredictable performance, transistor innovation has halted. While an insatiable desire for improved computing power remains in government, business, and academia, research has turned to other semiconductor materials to redefine the nature of the transistor.*

*Gallium-nitride (GaN) has been identified as a prime contender to replace silicon in transistors for large-scale computing devices. The compound possesses a fraction of the resistance of silicon, allowing for a more energy-efficient flow of electricity. Though the conventional manufacturing of GaN is expensive and time-consuming, research groups at institutions such as the Massachusetts Institute of Technology (MIT) have made progress in inventing cheaper methods for mass-producing the material. Despite concerns about the economic sustainability of the material, the widespread interest in GaN will likely persist as organizations seek to maximize computing power in their devices.*

*Key Words – Ammonothermal growth, Doping, Gallium-nitride, Hydride vapor phase epitaxy, Semiconductor, Silicon, Transistor*

**SEMICONDUCTORS, TRANSISTORS, AND THE NEED FOR NEW MATERIALS**

**Conductivity and Transistors**

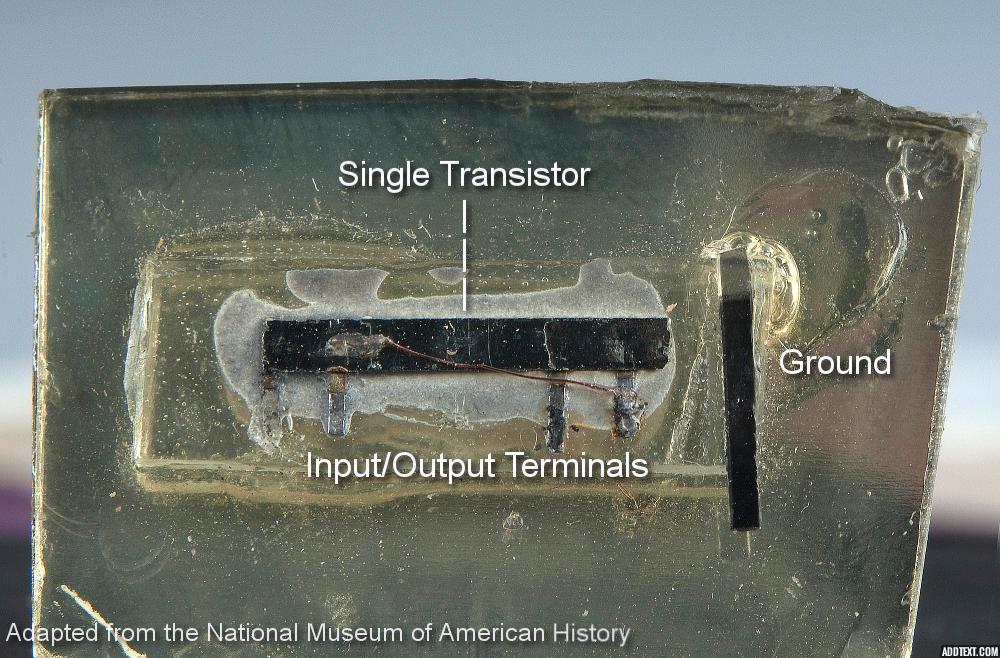
The extent to which a compound can conduct electricity is determined by the number of valence electrons it possesses. Valence electrons are the farthest electrons from the nucleus of an atom, lying in what is known as the valence shell, and therefore “experience the least force of attraction to the nucleus” [1]. Electrons in a nearly-empty valence shell can be easily dislodged from the atoms to which they belong, freeing the particles to move through the material [1]. A relatively uniform flow of electrons through a material allows that material to conduct electricity [1]. Traditional conductors, such as silver and copper, have copious amounts of these free electrons, while insulators, such as rubber and glass, have little to none [1].

Semiconductors are a unique class of elements that can act as both conductors and insulators. At low energy levels, semiconductors bond to prohibit free electrons from flowing out of the valence shell and through the material [2]. However, as energy is increased, semiconductors can release their valence electrons and conduct electricity [2]. The properties of semiconductors form the basis for the transistor, in which the logical values “true” and “false” are represented by the flow of electricity through a circuit. This allows a transistor to perform logical computations and is the lowest level of a computer.

Transistors are traditionally combined onto one surface, known as an integrated circuit, to increase computational power. Since 1958, integrated circuits have been made using silicon-based transistors because, among semiconducting elements, silicon occurs most commonly in nature and is the easiest to manufacture [3]. By decreasing the size of the transistor, more can be placed on a given surface area, meaning integrated circuits can perform exponentially more calculations. This process has facilitated the rapid technological innovation that has occurred since the transistor’s invention [4].

**Moore’s Law: A Plateau**

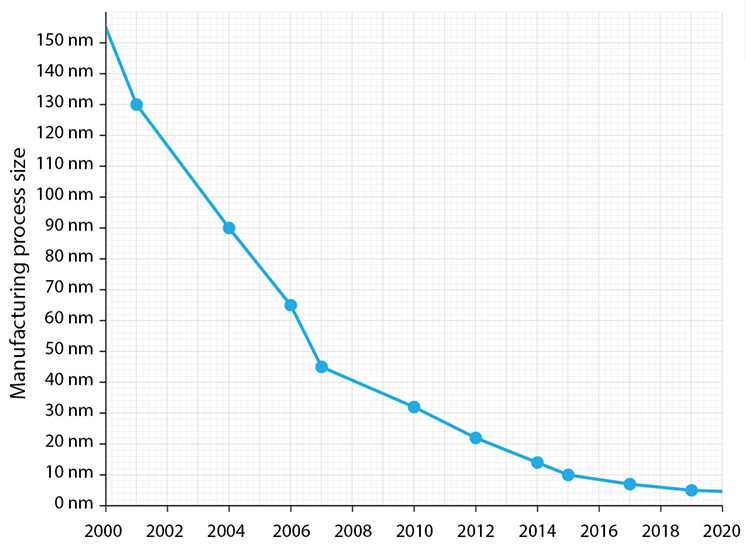
In 1965, Gordon Moore, the head of research at Fairchild Semiconductor and a future co-founder of Intel, was asked for his predictions on the future of integrated circuits [5]. Moore predicted that, every year, integrated circuit manufacturers would “double the number of transistors that could fit on a single chip of silicon so [a customer would] get twice as much computing power for only slightly more money” [5]. Though Moore later changed this doubling frequency to every two years, his prediction has held true, and is now known as Moore’s Law [6]. The first integrated circuit, invented by Jack Kilby of Texas Instruments in 1958 and pictured in Figure 1, held one transistor and was about the size of the end of a finger [7]. Today’s integrated circuits can fit more than 100,000,000 transistors onto the head of a pin [8]. The A11 Bionic, used by Apple in the iPhone 8 and iPhone X, makes use of over 4.3 billion transistors [9].

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**FIGURE 1 [7]**

**The first integrated circuit, currently housed in The National Museum of American History**

However, Moore’s Law is losing its predictive power as silicon transistors approach their physical size limit, as shown in Figure 2. Researchers at the Lawrence Berkeley National Laboratory have recently created the world’s smallest working transistor, at seven nanometers wide [10]. This transistor itself is only fourteen times bigger than an individual atom of silicon [10]. A transistor smaller than this size is subject to a phenomenon of quantum mechanics called quantum tunneling, where the silicon electrons can unexpectedly “leak” from one side of the transistor to the other [11]. Because of quantum tunneling, transistors smaller than seven nanometers lose the ability to control current and are unpredictable. That industry leaders such as Intel and Texas Instruments have been hesitant to consider alternate materials and designs for transistors in the face of this reality is indicative of the extreme economic sustainability silicon transistors have shown over the past half-century.



**FIGURE 2 [12]**

**Graph of transistor size since 2000, with size decreasing at a lesser rate beginning in 2007**

**The Economic Sustainability of Silicon**

The steady decrease in transistor size since 1958 has been accompanied by a corresponding decrease in the price of transistors and integrated circuits. Carver Mead, a former colleague of Gordon Moore at the California Institute of Technology, recalls individual transistors costing about $1 in 1960, equivalent to $8 in 2018 [13]. The high cost of transistors at this time greatly limited the complexity of consumer electronics; the most popular device during this period was the transistor radio, powered by only four transistors and costing the equivalent of $400 today [14]. Devices with more computing power were extremely expensive, and so were only accessible to large organizations such as governments and universities.

As integrated circuit manufacturers invented new fabrication processes that reduced the size of the transistor, more could be produced on a given wafer of silicon, using less materials for the same result and, consequently, leading to a sharp decline in transistor price. Arvin Industries, a leading producer of transistor radios at the time, was able to reduce the prices of its radios by “28 to 37 percent” in the early 1960s [15]. Demand for consumer electronics spiked as more complex electronic devices became accessible to the general population [14].

Because silicon is the second-most abundant element in the Earth’s crust, making up over 25% by mass, there is essentially an infinite supply of the material for use in transistors [16]. With no scarcity issues regarding the supply of silicon, demand has been able to increase freely, thereby motivating companies to create more complicated devices and to reduce existing prices. This virtuous circle between increasing consumer demand and decreasing manufacturing cost has driven the technological revolution of the past fifty years.

**Moving Away from Silicon**

It is estimated that 90% of the world’s data has been generated over the last two years, a phenomenon that has been labeled “Big Data” [17]. To handle this rapidly-increasing amount of data, there must either be an equal increase in computing power or a greater investment in building data centers. However, the electricity used by the three million data centers located in the United States each year is enough to power the entirety of New York City for two years; this is equivalent to “the output and pollution of thirty-four coal-fired power plants” [18]. Building larger data centers to provide necessary computing power would be incredibly wasteful and expensive to the American taxpayer, and so is not a realistic solution to this crisis.

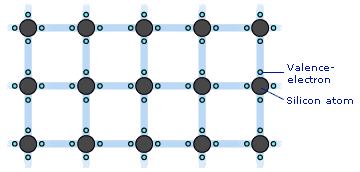
The Semiconductor Industry Association, an organization whose members include Intel, Advanced Microscopic Devices (AMD), and Global Foundries, published a report earlier this year announcing that “by 2021 it will not be economically efficient to reduce the size of silicon transistors any further” [10]. Though Moore’s Law has held true for over fifty years, it can no longer be trusted to predict the future of computing. For computational power to continue to improve, it is evident that transistors must be created using semiconductors other than silicon.

Gallium-nitride (GaN) is one such compound that has drawn interest as a potential replacement for silicon in transistors. Following a $70 million research program funded by the United States Department of Energy in 2013, it has been estimated that GaN could reduce the power consumption of data centers and consumer electronics by 20% over the next ten years [19]. A Los-Angeles based company called the Efficient Power Conversion Corporation (EPC) has currently implemented transistors made from GaN into many applications, from a laser diode to use in Light Detection and Ranging (LiDAR) systems to an extremely small power adapter for laptops [20]. Alex Lidow, chief executive officer of EPC, lists industry leaders Texas Instruments, Panasonic, and ON Semiconductor as companies currently pushing to sell devices powered by GaN transistors [21]. To assess the merits of GaN transistors compared to conventional silicon-based transistors, it is first necessary to examine the molecular processes by which semiconductors generate electrical current on demand.

**ENERGY BAND GAPS AND DOPING**

**Covalent Bonding in Semiconductors**

It is an intrinsic property of an atom to want exactly eight valence electrons in its outermost valence shell, at which point the shell is considered full and stable. There are many different processes by which this can be attained, depending on if the atoms involved are metals or nonmetals [22]. In nonmetals, the category to which semiconductors belong, two or more atoms will share their electrons to fill both valence shells in a process called covalent bonding [22]. A silicon atom has four valence electrons, so it wants to gain four more electrons to complete its valence shell. As shown in Figure 3, the silicon atom will form a covalent bond with each of four neighboring silicon atoms [2]. This array of silicon will form an “infinite crystal, with each silicon atom having four nearest neighbors and eight shared electrons” [23]. These crystals have incredible stability, acting as insulators without the influence of a source of external energy [24].



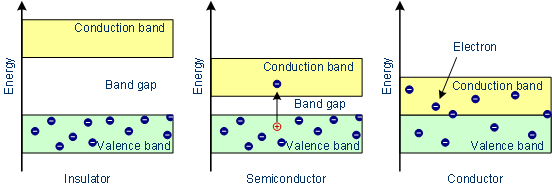
**FIGURE 3 [2]**

**A depiction of many silicon atoms forming covalent bonds to create a crystalline structure of pure silicon**

**Energy Bands**

The ability of an individual atom to conduct electricity at a specific point in time depends on the amount of energy possessed by its electrons. There are two special ranges of energy, called energy bands, with which conductivity is concerned: the valence band and the conduction band. The valence band is a collection of energy levels occupied by electrons when there is no outside energy imparted on the system [23]. These valence band electrons are unable to move throughout the material, locked in place by their covalent bonds, and therefore do not conduct electricity [23]. In the conduction band, electrons are free to move throughout the material; this uninhibited movement is the basis for the conduction of electricity [23]. The two bands are separated by a band gap, which dictates the magnitude of energy that is necessary to move an electron from the valence band to the conduction band, where it can then conduct electricity [25].

As shown in Figure 4, the band gap of insulators is relatively large, requiring an enormous amount of energy to move an electron from the valence band to the conduction band [26]. In conductors, the two bands overlap, so electrons are free to move throughout the material and conduct electricity at all temperatures [26]. Semiconductors have a band gap, but it can be modified to be smaller than that of insulators through the process of doping. It is necessary for semiconductors to possess a band gap as they must act as complete insulators when the flow of electricity is not desired [26]. However, a smaller band gap allows a semiconductor to more easily conduct electricity on demand, as the amount of energy required to move an electron to the conduction band can be supplied by an electrical circuit [23].



**FIGURE 4 [26]**

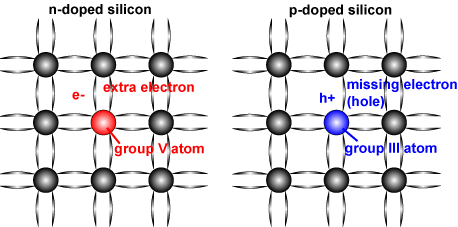
**A visualization of the band gap size in insulators, semiconductors, and conductors**

**N-type and P-type Doping**

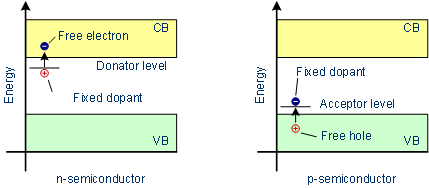
To shorten the band gap in a semiconductor, foreign elements are introduced into the material that either increase or decrease the total amount of electrons; this process is called doping [23]. Most semiconductors have four valence electrons, so silicon will be used in the explanation of doping [27].

In n-type doping, an element with five valence electrons, such as phosphorus, replaces a silicon atom in the crystalline structure [28]. Normally, all five electrons would be tightly bound to the phosphorus atom as it seeks to complete its valence shell. However, when a phosphorus atom takes the place of a silicon atom in a crystal, four of its electrons form covalent bonds with the four surrounding silicon atoms. The fifth electron becomes extraneous and requires much less energy to separate from the phosphorus atom, and therefore jump to the conduction band, than does a typical valence electron in a silicon atom [25]. In effect, the extra energy added by the fifth electron increases the energy level of the valence band, making it easier for an electron to move to the conduction band. When it does so, this extra electron can move through the crystal and generate electrical current [23].

The opposite process occurs in p-type doping, in which an element with three valence electrons, such as boron, is substituted into the silicon crystal. Because the boron atom’s valence shell is unfilled, an electron from elsewhere in the crystal will move to occupy the empty position, leaving its previously-occupied space vacated. As electrons continuously move to fill the empty spaces in the crystal, a small current is generated, decreasing the energy required to move an electron to the conduction band. Visual representations of these doped crystals are provided in Figure 5, while the respective changes to the band gap structure of the material caused by each type of doping are shown in Figure 6.



**FIGURE 5 [29]**

**Visualization of the effects of n-type and p-type doping on the lattice structure in a silicon atom**

**FIGURE 6 [25]**

**Comparison of the changes to the band gap when a semiconductor undergoes n-type or p-type doping**

**The P-N Junction**

When a p-type and an n-type doped semiconductor crystal are joined together, the resulting structure is a transition area called the p-n junction [30]. The extra electrons from the n-type crystal will move to the p-type crystal, inducing an electric field along their path [23]. Eventually, enough electrons will have moved from one crystal to the other that they are unable to overcome this electric field and move in the opposite direction [23]. Macroscopically, this means that, given a sufficient external voltage, the material will allow current to flow in one direction and block it in the opposite direction [30]. The combination of oppositely-doped semiconductor crystals in this manner forms a transistor that selectively allows the flow of electricity through part of a circuit and, in doing so, can perform calculations.

**COMPARISON OF GALLIUM-NITRIDE AND SILICON IN TRANSISTORS**

**Band Gap Size**

Gallium-nitride is classified as a wide band gap (WBG) semiconductor because its energy band gap is wider than that of silicon [31]. While silicon has an energy band gap of 1.1 electronvolts (eV), gallium-nitride possesses a band gap of 3.4 eV [31]. For context, an electronvolt is the amount of energy gained by an electron when an electric potential of one volt is applied to it [32]. While the energy band gaps of both materials are on the nanoscale, the difference between the band gap size of gallium-nitride and silicon is significant.

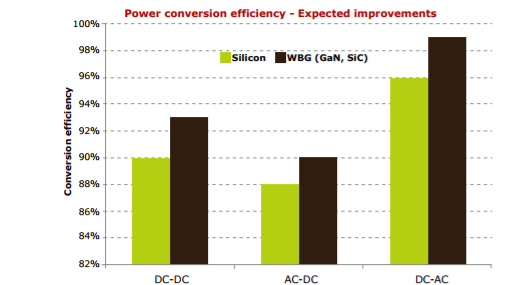
The difference in band gap size between these two semiconductors is due to the interatomic spacing of a gallium-nitride crystal being much less than a silicon crystal [33]. While a silicon atom occupies 5.43 Å (one hundred-millionth of a centimeter), a single gallium-nitride molecule occupies only 3.19 Å [34]. Even though an individual molecule of GaN has more protons, neutrons, and electrons than a silicon atom, the larger attractive forces within the GaN molecule mean it is packed together more densely than silicon. As such, more energy is required for an electron to be freed from its covalent bond in the GaN crystal than in the silicon crystal [32].

**Differences in Transistors**

Because electrons need to jump across the band gap to conduct electricity, it seems counterintuitive that a WBG semiconductor could outperform silicon in transistors. However, Landa Culbertson of Mouser Electronics states that the wider band gap means that a transistor made of this material can “tolerate much higher operating temperatures in a smaller size than the equivalent silicon-based device, enabling previously impossible applications” [31]. This means that more transistors could be placed on a given surface without fear of overheating, therefore enabling faster computations.

Additionally, WBG semiconductors that have undergone the traditional doping process are preferred for use in transistors because their switching speed is superior to silicon [31]. Essentially, switching is the speed at which a transistor can change from allowing current to blocking it, or vice versa, and is related to the internal resistance of the material. GaN transistors have one-tenth the resistance of silicon-based transistors, meaning electrons can flow through the material with much less impedance [35]. A GaN transistor can switch once every five nanoseconds, ten to twenty times faster than conventional silicon systems [36]. This significant increase in switch speed means that GaN transistors can perform the same amount of calculations as silicon in a fraction of the time, drastically increasing a device’s overall computing power.

WBG semiconductors also possess a higher efficiency in power conversion than silicon, again due to their tendency to possess a relatively low internal resistance. By switching to a WBG semiconductor such as GaN, a device’s power conversion efficiency can be increased by about 3%, as shown in Figure 7 [37]. A 3% increase in the efficiency of a transistor represents a 10-20% reduction in energy consumption in a large-scale device, such as a data center [19]. This potential for environmental sustainability has led to the creation of many prototype devices that utilize WBG semiconductors.



**FIGURE 7 [36]**

**Improvements in power conversion efficiency through the use of WBG semiconductors, such as gallium-nitride**

**Current Device Applications**

Gallium-nitride transistors have recently been implemented in a wide range of technologies with a significant degree of success. MIT offshoot company Cambridge Electronics has created a 1.5 cubic inch laptop power adapter prototype, the smallest ever made, through the use of GaN transistors [35]. Mouser, an electronics distributor based in Texas, has begun offering GaN transistors for “infrastructure, defense and aerospace applications such as radar, electronic warfare (EW), communications, navigation, and similar applications” [38]. A market research report from Transparency Market Research (TMR) estimates that the market for GaN devices will grow 17% per year, from $871 million in 2015 to over $3.4 billion by 2024 [39]. Though considerable research must still be conducted to fully optimize GaN for transistors, its increased use in power electronics systems for military and infrastructure programs clearly shows its value as a semiconductor for the near future.

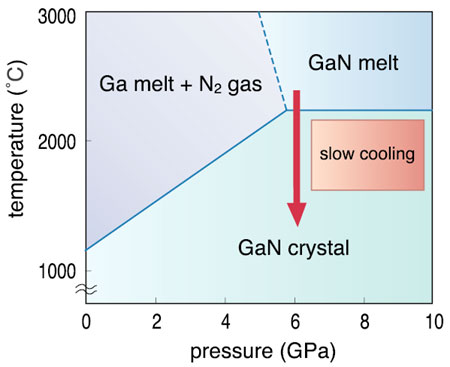
**GALLIUM-NITRIDE CRYSTAL FABRICATION**

**The Conventional Method**

While gallium-nitride shows extreme promise as an alternate semiconductor to silicon, there remain challenges in integrating it into the commercial market. One such challenge stems from issues with the growth of the GaN crystals, which are doped to create transistors. Conventionally, semiconductor crystals, or substrates, are manufactured by a method known as the Czochralski process, in which a small, high-quality seed crystal is rotated inside the liquid of that same material [10]. The seed crystal is then extracted, and the molten liquid is allowed to cool [10]. This forms a small cylinder of the solid material, known as the boule, which is then sliced into wafers for use in transistors [10].

However, this method cannot be used with GaN. Liquid GaN is very difficult to obtain naturally, so the compound must be created in a laboratory. As shown in Figure 8, the creation of GaN crystals by this conventional process requires extremely high temperature and pressure conditions [40]. Only after the pressure reaches 4.5 gigapascals (GPa) and the temperature reaches 2500°C can GaN crystals be produced [41]. For perspective, 4.5 GPa is around 40,000 times the normal atmospheric pressure. These conditions are extremely expensive to create and maintain and so cannot be depended on for consistent crystal production [10].

Additionally, the size of the crystals produced by the Czochralski process only have a size of around 100 micrometers, slightly larger than the width of a human hair [41]. The revenue generated by the sale of these crystals is not sufficient compared to the cost of creating them, so they are not suitable for production [41]. Therefore, it is not surprising that alternate methods have been developed to successfully grow GaN crystals. The two most popular methods are the hydride vapor phase epitaxy (HVPE) process and the ammonothermal growth method [42]. The distinct benefits and drawbacks associated with each method mean that it is necessary to explore each in a separate section.

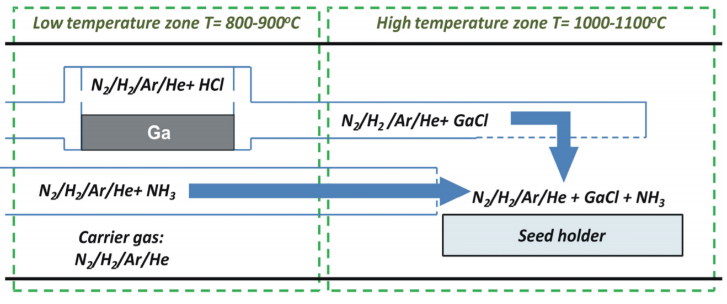


**FIGURE 8 [40]**

**Phase diagram of GaN, showing the temperature and pressure necessary to create GaN crystals**

**HVPE Growth Process**

Currently, HVPE is the most commonly-used process to grow GaN crystals [41]. The basis of the HVPE method is creating solid GaN crystals from the gaseous phase [42]. As shown in Figure 9, solid gallium is reacted with hydrochloride in a low-temperature reactor, typically 800°C – 900°C, to form gallium chloride (GaCl) [42]. The GaCl is then transported by a carrier gas, such as nitrogen, hydrogen, argon, or helium, to a high temperature reaction zone, heated to 1000°C [42]. The GaN is then crystallized on a “native or foreign substrate,” another crystal that is typically a mixture of gallium and sapphire [42]. The HVPE process can grow GaN crystals at a rate upwards of 1800 micrometers per hour, a rate unmatched by alternate growth methods since its invention in 2007 [42].

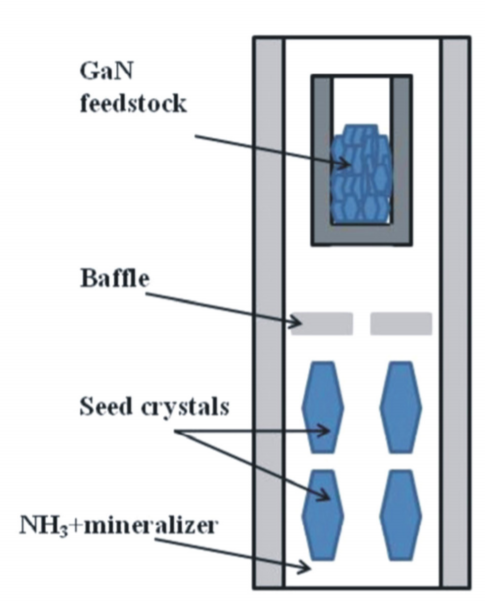
**FIGURE 9 [42]**

**Diagram of the HVPE reactor layout, showing the creation of crystals from a gas**

However, the task of growing GaN on a foreign substrate poses an issue for the quality of the resulting crystals. Because GaN and sapphire are different compounds, and therefore have a different crystalline structure, their crystals do not match when brought together [10]. Specifically, this leads to a “bowing of crystallographic planes,” resulting in the presence of many foreign molecules within the crystal [42]. There can be up to 15,000 foreign molecules per square centimeter in the HVPE-fabricated crystals, severely limiting the quality at which they can be produced [10]. In an effort to solve this issue, research is currently being conducted into growing GaN crystals on a native GaN substrate, which would drastically reduce the amount of imperfections the final material possesses [43]. According to University of California, Santa Barbara professor Steven DenBaars, “GaN grown on GaN can have as few as 100 to 1000 defects per centimeter squared in the crystal” [43]. Thus, there exists a significant incentive to produce high-quality GaN crystals to use as substrates in the HVPE method.

**Ammonothermal Growth Process**

The recently developed ammonothermal growth process has the potential to fabricate GaN crystals at the quality necessary to supersede silicon in terms of performance. While the HVPE method is centered around the crystallization of GaN from the gaseous phase, the ammonothermal method focuses on growing GaN crystals from the solution phase. The apparatus which houses the reaction is called the autoclave, shown below in Figure 10 along with the reactions that model this process [42]. In Reaction 1, the GaN is dissolved in an ammonia solution with the use of a basic mineralizer, such as potassium amide [42]. The mineralizer is necessary as GaN is highly insoluble in pure ammonia [42]. The temperature and pressure of this reaction can vary but are usually in the range of 475-525°C and 150 megapascals (MPa) respectively [42]. The two regions of the autoclave are separated by the baffle, which maintains a temperature difference and a constant circulation of the ammonia [42]. The temperature and pressure of the second region usually range between 400-600°C and 0.1-0.3 GPa [41]. GaN is known as a retrograde soluble material, which means that its solubility decreases as temperature increases. An article in the journal *Semiconductor Science and Technology* shows that under these more extreme conditions in the second region, the GaN “recrystallizes… …onto GaN seeds in the crystallization zone” in Reaction 2 [42].



KNH2 + GaN + 2NH3 🡪 KGa(NH2)4  (1)

GaN + 2NaNH2 + 2NH3 🡪 Na2Ga(NH2)5  (2)

**FIGURE 10 [42]**

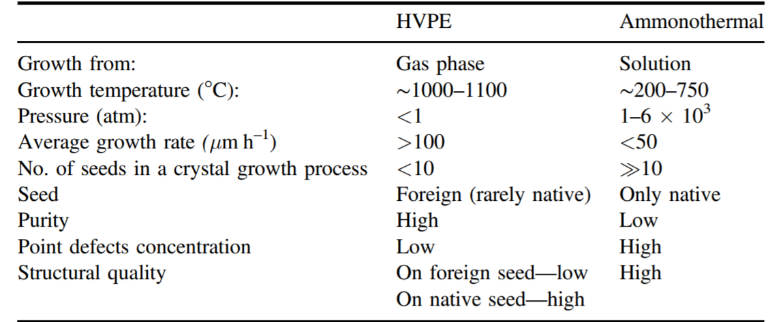
**Diagram of the autoclave used for the ammonothermal growth process as well as the reactions that guide this process**

Because the key reactions of ammonothermal growth take place at lower temperatures than in the HVPE process, the ammonothermal growth process sometimes takes weeks to fabricate full-size crystals, paling in comparison to the speed of HVPE [42]. However, ammonothermal growth has the capability to mass-produce crystals, as “many (even a few hundred) seeds can be placed in one autoclave for one crystallization run,” according to researchers at the Institute of High Pressure Physics Polish Academy of Sciences [42]. The Polish company Ammono is a pioneer in the ammonothermal growth process, its lead scientists being among the first developers of the method. Ammono’s process can produce upwards of 70 two-inch crystals of GaN in one iteration, far greater than the overall production of HVPE [10].

Despite this advantage in overall production, Ammono’s crystals, priced at around $5000, are rendered impractical in comparison to the price of silicon crystals, around $370 [44]. It is necessary to increase the supply of GaN transistors through more efficient crystal production methods if GaN is to experience the same virtuous circle of economic sustainability as silicon. Ammono expects its prices to fall eventually, but it remains to be seen if it will produce a crystal that can realistically compete with silicon in the open market.

**Combining HVPE and Ammonothermal Processes**

Research is currently being done to combine HVPE and ammonothermic growth to compensate for their respective disadvantages, which can be seen in Figure 11 [42]. The United States-based WBG materials supplier Kyma Technologies recently won a $3.2 million contract from the Department of Energy to develop high-quality gallium-nitride substrates [45]. Kyma’s researchers want to use the ammonothermically grown crystal as a seed crystal for the HVPE method [42]. The incorporation of Ammono’s crystals as the HVPE seed crystal would solve the issue of lattice mismatch between GaN crystals and a foreign substrate. Pairing these two methods together offers a solution to the need for mass-produced GaN, combining the quality of ammonothermic growth with the speed of the HVPE process. Though the issue of crystal affordability still remains, the amount of research being conducted on the different growth methods is indicative of its overall potential as a replacement semiconductor in transistors.

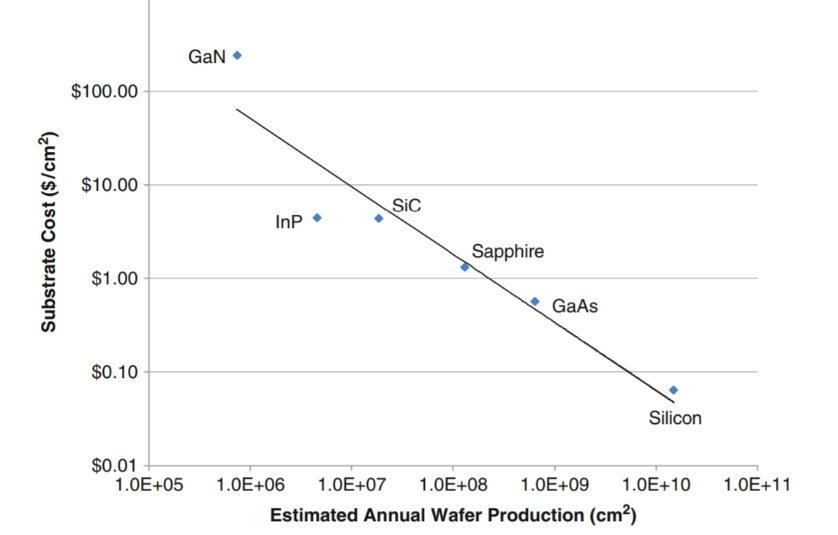


**FIGURE 11 [42]**

**Comparison of the faster HVPE process with the higher-quality ammonothermal growth method**

**THE OUTLOOK OF GALLIUM NITRIDE**

As silicon-based transistors reach their theoretical size limit, it is imperative to find an alternate way of increasing computing power. New semiconductors are currently being developed to address this issue, with gallium-nitride being one of the most likely successors to silicon. GaN’s physical properties as a wide band gap semiconductor mean that its performance in electrical circuits is far superior to that of silicon. However, the cost to produce GaN crystals of suitable quality hinders its viability in the marketplace. Silicon transistors continue to be the industry standard due to their cost even despite a growing inability to keep pace with the predictions of Moore’s Law. As shown in Figure 12, GaN is clearly the most expensive crystal currently produced, and so cannot significantly impact the semiconductor industry at this time [41]. However, research at companies such as Ammono and Kyma indicates that the production of GaN crystals will soon become more competitive. If significant developments are made in the growth process of GaN so the crystals can be produced in a sustainable manner, it would be reasonable to predict that GaN transistors could see significant integration into consumer devices in the coming decades.



**FIGURE 12 [41]**

**Cost comparison of commonly-used semiconductor substrates, with GaN being the most expensive**

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