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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. However, 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. The widespread interest in GaN is likely to be sustained by organizations seeking to maximize computing power in their devices.*

*Key Words – Ammonothermal growth, doping, gallium-nitride, semiconductor, silicon, transistor*

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

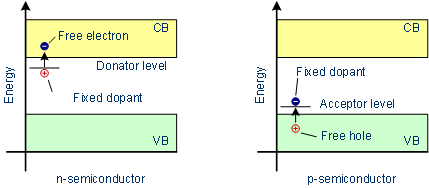
In this introduction, we will outline the electrical properties of semiconductors, with an emphasis on their role in the transistor, to give readers a glossary of the concepts we will reference throughout the paper. An explanation will be given about the relationship between the number of transistors on a given device and the device’s computing power. We will use this information to show how decreasing the size of the transistor throughout its existence has correlated with a widespread increase in the capabilities of technology [1]. To contextualize the need for new semiconductor materials, we will briefly discuss the consequences of creating transistors on a nanoscale, where the uncertain mathematics of quantum mechanics dictates their behavior.

We will then introduce gallium-nitride (GaN) as a semiconductor possessing the potential to replace silicon in transistors. Using recent news articles, we will give examples of companies involved in developing GaN to show that it is a popular topic of interest, as opposed to a fringe technology. We will include excerpts of articles from the Efficient Power Conversion Corporation (EPC), a Los Angeles-based company that is currently “investigating the capacity of gallium-nitride to disrupt the $400 billion silicon industry” [1]. EPC has currently identified many applications for GaN, ranging from a laser diode to use in Light Detection and Ranging (LiDAR) systems to an extremely small power adaptor for laptops [2].

**ENERGY BAND GAPS AND DOPING**

In this section, we will explain the characteristics of semiconductors on a molecular level using introductory information on the topic. We will first discuss how elements or molecules such as silicon take advantage of covalent bonding to form crystalline structures of considerable stability [3]. We will give a detailed explanation of the valence and conduction energy bands, and the band gap between them. The band gap 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 [4].

We will also explain the concept of doping, where foreign elements are introduced to increase or decrease the amount of electrons present in the material [3]. Semiconductors can be doped to become either negative (n-type) or positive (p-type), depending on the amount of valence electrons possessed by the element introduced [5]. The distinction between the two types of doped semiconductors will be explained with a discussion regarding charge carriers, as is previewed in Figure 1.



**FIGURE 1 [4]**

**Comparison of the energy band gaps of n-type and p-type semiconductors**

We will conclude this section by outlining how multiple p-type and n-type semiconductors can be combined to form a p-n junction, which can “allow an electric current in one direction (called the forward biased condition) and to block the current in the opposite direction (the reverse biased condition)” [6]. We will show how the combination of these layers forms a transistor that, given a sufficient external voltage, will allow the flow of current through a circuit [6]. Information from this section will give context to the technical comparison between GaN and silicon in the following section.

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

In this section we will strengthen the argument for gallium-nitride as a superior semiconductor material compared to silicon. We will discuss how the electric field of GaN is stronger than in silicon, meaning that its electrons can move with less resistance [7]. We will then show how this translates to GaN transistors having “much higher energy-efficiency, and orders-of-magnitude faster switching frequency [than silicon] – meaning power-electronics systems with these components can be made much smaller” [8]. We will give examples of devices that can be made smaller, and therefore consume less energy, using GaN transistors. One such example is a 1.5 cubic inch laptop power adapter made by the MIT-offshoot company Cambridge Electronics, Inc [8]. These examples will allow us to establish GaN as a superior semiconductor material to silicon, shifting our focus in subsequent sections to the creation and implementation of GaN.

**RECENT DEVELOPMENTS IN GALLIUM-NITRIDE FABRICATION**

**Crystal Growth: A Limitation**

Of course, it will be necessary to explain why, despite its merits, GaN is not currently mass-produced for use in transistors. Most notable is the difficulty of creating raw GaN substrates of high quality. We will explain the “incumbent” process for creating GaN substrates, hydride vapor phase epitaxy (HVPE), and show why it is unfit to mass-produce GaN [9]. We will detail the Polish company Ammono, which has been able to grow high-quality GaN crystals using a process based on extreme heat and pressure known as ammonothermal gallium nitride growth [9]. Describing Ammono’s growth process will anchor a discussion on the future of GaN in the final section.



**FIGURE 2 [9]**

**A comparison of Ammono’s first GaN crystals, small and tinted brown with impurities, with the company’ newest 2-inch crystals grown under the ammonothermal technique**

**Transistor Fabrication**

GaN transistors were previously fabricated by heteroepitaxial growth on substrates such as silicon, silicon carbide (SiC), and sapphire [10]. It should only be necessary to briefly detail this process, as the differing substrates led to billions of defects throughout the material, “impeding performance of the semiconductor and electronic devices based on it” [11]. We will highlight an article from the Japanese Journal of Applied Physics in which a Tokyo research team fabricated GaN using a GaN substrate, resulting in a material with less defects [10]. In citing these examples, we hope to highlight the amount of research dedicated to GaN as an indicator of its potential as a semiconductor material for the future.

**THE OUTLOOK OF GALLIUM-NITRIDE**

While GaN is certainly promising for the future of transistors, there remain valid concerns among companies currently hesitant to switch to using GaN for their transistors. Alex Lidow writes of three such concerns: supply chain risk, cost risk, and reliability risk [12]. We will take an objective perspective in explaining the merits of each of these issues. Finally, we will weigh the progress in GaN development against current reservations throughout the semiconductor industry in order to provide a realistic assessment of the potential of GaN to become widely implemented in the coming decades.

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