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Research of Gallium Nitride as Next-Generation Semiconductor

Ziwen Ye

Wuhan Cogdel Cranleigh High School, Wuhan, China
*Corresponding author: qiweiyu@ldy.edu.rs

Abstract:

In today's society, semiconductors have become an indispensable material in people's lives, as they are closely related to daily needs such as internet access, power supply, and computing. The most widely used semiconductor material currently is silicon. Its cost advantage in the early stage made other semiconductor materials lag far behind. As semiconductor manufacturing has progressed to nanoscale and even 3-nanometer technology, problems with silicon semiconductors have become increasingly apparent. As the size of silicon transistors continues to shrink, quantum tunneling effects such as leakage current and gate leakage current have caused power consumption to increase continuously. Moreover, the silicon manufacturing process requires harsh conditions such as high vacuum, high temperature, and multiple steps, which increases the production cost and process complexity. Therefore, people have pinned their hopes on the next-generation semiconductor material, gallium nitride (GaN), as an alternative to silicon. Given its superior properties such as wider bandgap, higher electron mobility, and better thermal conductivity, gallium nitride (GaN) offers promising solutions to overcome the limitations of silicon-based semiconductors.

Keywords: Semiconductor, transistor, gallium nitride

1. Introduction

Nowadays, the problems of silicon transistors have gradually been exposed as the manufacturing process scales down. For example, excessive heat generation can lead to chip soldering and desoldering issues, and the high transistor switching frequency can result in degradation of transistor performance. Among these issues, electromigration has been a major source of problems in modern silicon semiconductors. The main reason for this situation is that the size of the solder joints is relatively large, while the current density is relatively low [1]. Silicon semiconductors also face limitations in power performance. These limitations stem from challenges in both power supply and heat dissipation, which collectively constrain technological performance. These limitations stem from challenges in both power supply and heat dissipation, which collectively constrain technological performance [2]. The cost of producing silicon semiconductors was quite low around the 20th century. However, as semiconductor manufacturing evolved to the nanoscale, the cost of silicon transistors rose rapidly. The manufacturing of silicon semiconductors requires precise and high-cost equipment such as clean rooms, ion implantation machines, and epitaxial deposition systems. The complex multi-step manufacturing process, including lithography, etching, and ion implantation, significantly increases the manufacturing cost. In highly sophisticated semiconductor manufacturing processes, silicon does not have a significantly greater cost advantage compared to gallium nitride (GaN) of the same performance [3].

2. The advantages of gallium nitride (GaN) in physical properties

2.1 Wide bandgap

"GaN has a wider bandgap compared to silicon, which allows it to operate at higher voltages, temperatures, and frequencies. This advantage stems from GaN's unique properties: as mentioned earlier, it is a direct wide bandgap semiconductor, typically crystallizing in the wurtzite structure. The value of the energy bandgap and its gradient with respect to the temperature are determined from measurements of absorption edge position and its temperature evolution. Also, the wide bandgap means that the probability of thermal excitation of electrons to the conduction band is reduced, allowing the device to have more stable performance at high temperatures.

2.2 Higher thermal conductivity

GaN has better thermal conductivity, which helps in efficient heat dissipation and allows for higher power density. Based on some modeling and experimentation of electrical characteristics of GaN/AlGaN HFET's these authors concluded that, due specially to a large conduction band discontinuity at the GaN/AlGaN hetero-inter face, GaN/AlGaN HFET's should exhibit high-temperature performance, higher power, and a large dynamic range, necessary for specific applications for linear amplifiers. Consequently, a simpler passive cooling structure can be employed to maintain normal operation, benefiting small electrical devices in terms of cost and power control. What's more, it can proceed the efficiency of electric power supply.

2.3 Higher breakdown field

GaN can withstand higher electric fields before breakdown, making it suitable for high-power and high-voltage applications. This is in contrast to highly doped semiconductors, where high doping concentrations in the base and collector can lead to negligible Early voltage and very small breakdown voltage [4]. The strength of the electric breakdown field in GaN is illustrated in Fig. 1 [5]. This demonstrates that GaN can withstand higher voltages without breaking down. The GaN transistor can work under a high voltage that broad the use of transistor.

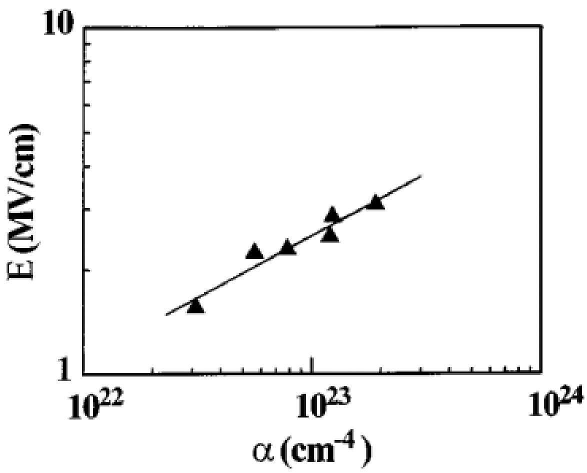

Fig. 1 Strength of the electric breakdown field in GaN p-n junction [5].

2.4 Higher electron mobility

GaN has a wider bandgap compared to silicon, which allows it to operate at higher voltages, higher temperatures, and higher frequencies.

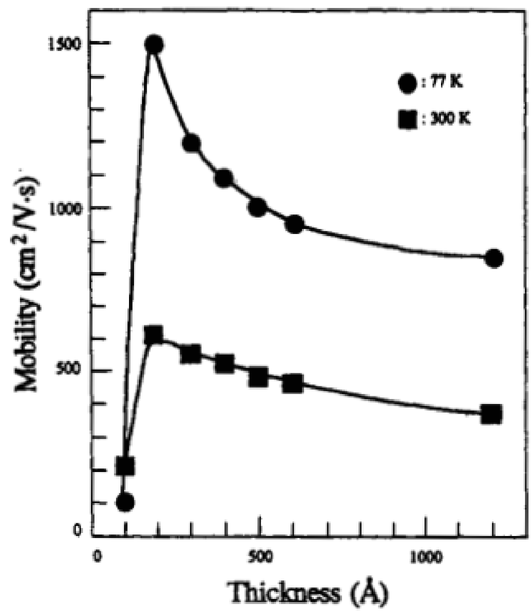

Fig. 2 Variation of Hall mobility of GaN as a function of GaN buffer layer thickness at two different temperatures [4].

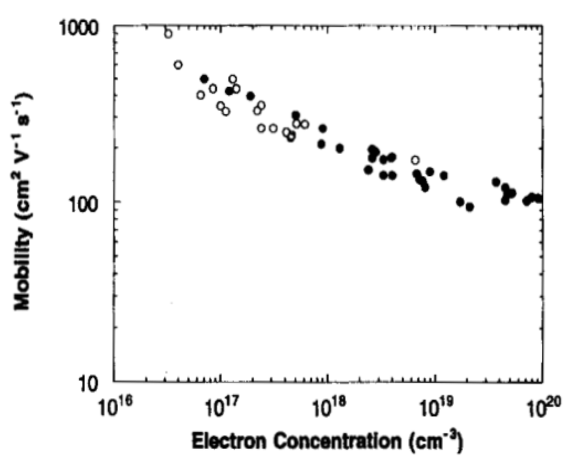

Fig. 3 The 300 K Hall mobility versus free electron concentration for GaN from various groups using both OMVPE and MBE.The open circles are from unintentionally doped samples and the solid circles are from samples doped with either Si or Ge [4].

The electron mobility of GaN and Si and Ge is shown in the Fig. 2 and Fig. 3. So, the faster the electrons move in semiconductor materials, the faster the switching speed of the transistor. And the transistor made with GaN can work in a higher frequencies. Also, the higher electron mobility means that at the same voltage, the electrons in GaN requires less energy to get velocity than that of silicon made transistor. So the power required for GaN is much less than Si.

3. The advantages of gallium nitride (GaN) in manufacturing costs

3.1 Simpler manufacturing process

Compared to the complex multi-step manufacturing process of silicon semiconductors, GaN devices can be fabricated using fewer and simpler steps. The process of producing silicon transistor contains 1) Purifying natural silicon using the Siemens process or other methods. 2) Cutting silicon ingots into thin slices to form silicon wafers, and performing chemical-mechanical polishing on the surface of the silicon wafers to ensure a flat and smooth surface. 3) Growing a layer of silicon dioxide (SiO_2) film on the surface of the silicon wafer as an insulating layer, and doping with impurities through diffusion or ion implantation to create n-type or p-type regions. 4) Photolithography. 5) Dry etching or wet etching: Removing unwanted material according to the photolithography pattern to form the desired structure. 6) Thin film deposition and structure formation. 7) Cutting and packaging. 8) Testing and sorting. As chip manufacturing processes become more refined, both the production costs and the number of steps for silicon semiconductors tend to increase. However, the process of producing GaN transistor can be easier: 1) Substrate selection and pretreatment. 2) GaN epitaxial growth: Using techniques such as Metal-Organic Chemical Vapor Deposition (MOCVD) or Molecular Beam Epitaxy (MBE) to epitaxially grow GaN layers on the substrate. During the epitaxial growth process, parameters such as temperature, pressure, and gas flow must be strictly controlled. 3) Growth of buffer layers and charge trapping layers: Growing heterojunction buffer layers such as AlGaN or InGaN on the GaN epitaxial layer to improve the epitaxial quality. A high-resistance AlGaN charge trapping layer is inserted between the GaN layer and the buffer layer to enhance device performance. 4) Using photolithography and etching techniques to define the active regions of the device. Depositing thin films such as insulating layers and metal electrodes to form the gate, source, and drain structures. 5) Etching. 6) Testing and sorting. The process of producing GaN transistor is much less than that of Si transistor. Therefore, GaN transistors have a greater cost advantage compared to Si transistors.

3.2 Lower thermal budget

GaN devices can be grown at lower temperatures, reducing the energy consumption and costs associated with high-temperature processing. GaN devices can be grown at lower temperatures. Although GaN can be grown by epitaxial deposition at high temperatures (above 1000°C), which is much higher than the growth temperature for silicon, recent advancements have enabled lower temperature growth processes for GaN devices. This enables the formation of higher quality crystal structures and reduces the density of defects. In multilayer structures, a lower thermal budget can protect the underlying materials from damage due to high temperatures, preserving their performance. Although GaN can be grown by epitaxial deposition at high temperatures (above 1000°C), which is much higher than the growth temperature for silicon, recent advancements have enabled lower temperature growth processes for GaN devices. Reducing the thermal budget can simplify certain process steps, decrease reliance on complex thermal treatments, and thereby lower manufacturing costs.

3.3 Compatibility with existing infrastructure

GaN can be integrated with the existing silicon manufacturing infrastructure, leveraging the existing investment and expertise. New GaN technologies can utilize existing equipment and processes, reducing upgrade or replacement costs. New technologies that are compatible with existing systems can be more easily integrated into current processes, shortening the implementation time. Utilizing familiar tools and processes reduces the need for extensive employee training or retraining. Due to the ability to leverage existing infrastructure, the return on investment for new technologies may be higher, as there is no need for additional infrastructure investment. Technologies that are compatible with existing infrastructure can be more easily adopted, thereby accelerating the market adoption of new technologies. Companies can gradually introduce new technologies instead of replacing everything at once, thereby reducing risk.

3.4 Potential for monolithic integration

GaN devices can be integrated monolithically, potentially reducing the overall system cost and complexity. Monolithic integration can reduce the connection distance between components, lowering signal delay and improving overall performance. By implementing multiple functions on the same chip, material and manufacturing costs can be reduced, along with a decrease in production complexity. Integrating all functions onto a single chip reduces the number of connection points, thereby lowering the failure rate and improving system reliability. Monolithic integration can simplify circuit design and manufacturing processes, making the design more efficient. Monolithic integration makes devices more compact, making them suitable for miniaturization applications, especially in mobile devices and Internet of Things (IoT) devices. Due to the increased level of integration, new functions and applications can be realized, such as integrating sensors, processors, and communication modules. By implementing various functions on a single chip, system interoperability is enhanced while the need for external components is reduce.

3.5 Scalability

GaN device manufacturing offers easier scalability compared to silicon devices. GaN's high breakdown voltage and high electron mobility make it excellent for high-power and high-frequency applications, suitable for larger-scale power electronic devices in the future. The high efficiency and power density of GaN devices contribute to more compact designs, particularly meeting the miniaturization needs of mobile devices and Internet of Things (IoT) applications. As GaN production processes mature and scale up, manufacturing costs may decrease, making GaN technology more economically competitive. GaN materials can be compatible with existing silicon-based technologies, facilitating upgrades and expansions on current infrastructure. The potential for monolithic integration of GaN allows multiple functions to be combined on a single chip, further enhancing system performance and integration. GaN's high efficiency and thermal stability make it suitable for emerging fields such as electric vehicles, renewable energy, and 5G communications, driving development in these areas.

4. Conclusion

The advantages of GaN semiconductors significantly outweigh those of silicon semiconductors. The physical properties of GaN made it be used in many cases. For example, electric vehicles, renewable energy, 5G communications, consumer electronics, aerospace and defense, power management, Lasers and Optoelectronics and so on. GaN's high efficiency and power density make it ideal for use in chargers and power converters for electric vehicles, enhancing range and charging speed. In solar and wind energy conversion systems, GaN can be used in high-efficiency inverters, optimizing energy conversion and management. GaN's superior performance in high-frequency communication makes it an ideal choice for 5G base stations and RF amplifiers, supporting faster data transmission and more stable connections. In consumer electronics such as smartphones, tablets, and laptops, GaN can be used in efficient chargers and power management systems, enabling smaller and more powerful devices. GaN's high thermal stability and radiation resistance make it suitable for high-power systems in aerospace and defense applications. In data centers and servers, GaN can be used in efficient power modules, reducing energy consumption and heat generation, and improving overall system efficiency. GaN materials can also be used to manufacture blue lasers and efficient photodetectors, driving advancements in optical communication and display technologies. Therefore, gallium nitride, which is cheaper, has lower manufacturing costs, greater stability, and higher performance, has become the top choice for the next generation of semiconductors.

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