

Research and Analysis of Gallium Nitride (GaN) Materials in the Diode Application

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Abstract: Gallium Nitride (GaN) material is an important third-generation semiconductor material, with many excellent physical and chemical characteristics, such as high forbidden band width, high electron mobility, high saturation drift speed, high temperature resistance, high pressure resistance, good thermal conductivity, etc. These features make GaN show a wide range of applications in many fields. This paper details the physical and chemical properties of semiconductor material gallium nitride (GaN), synthetic methods, and application in diode, which can make it have lower conduction resistance and higher voltage resistance, and puts forward the prospect for its future development trend and application prospect.

Keywords: Third-generation semiconductor, Gallium nitride(GaN), Thermal conductivity

1. Introduction

Gallium nitride (GaN), as the third generation of semiconductor materials, occupies an important position in the semiconductor material family, and its emergence has far-reaching significance. Gallium nitride is a typical representative of the third generation of semiconductor materials, compared with the first generation of silicon (Si) and the second generation of gallium arsenide (GaAs), has significant advantages [1]These advantages include features such as high band width, high thermal conductivity, high electron mobility and high breakdown electric field. These characteristics make gallium nitride perform well in high temperature, high power, and high frequency applications, such as radio frequency devices, power electronics, and optoelectronic devices. The development of gallium nitride materials has driven the progress of related technologies. For example, the application of gallium nitride-based materials in optoelectronic devices such as blue light LED, UV LED and lasers has greatly improved the performance of these devices.

2. Basic Properties of Gallium Nitride

2.1. Physical Properties

Gallium nitride (GaN) is a group III-V direct band gap semiconductor material, with many excellent physical properties, making it has a wide range of applications in the fields of electronics, optoelectronics and energy conversion. Here are some of the key physical properties of gallium nitride: Gallium nitride (GaN), a semiconductor material with multiple excellent physical properties, is

showing extraordinary potential in multiple high-tech fields due to its unique advantages. Its broadband gap of about 3.4 eV allows gallium nitride to maintain high carrier concentration at room temperature and be susceptible to thermal excitation, which makes it ideal for high frequency and high power electronic devices. At the same time, the high melting point of gallium nitride (over 2000°C) ensures excellent thermal stability in harsh environments, and is especially suitable for manufacturing devices that can operate at high temperatures. In high electron mobility transistors (HEMTs), the electron mobility of gallium nitride can be up to $2000 \text{ cm}^2 / \text{V} \cdot \text{s}$, which is far higher than silicon materials, thus greatly improving the operation speed and efficiency of the device.

In addition, gallium hardness and wear resistance of nitride is also extremely excellent, its Vickers hardness is close to diamond level, with excellent mechanical stability, not easy to wear, which provides a significant advantage in the application scenarios that require high hardness and wear resistance. In terms of chemical stability, the nitridesGallium can remain stable in most environments and is not easy to react with acid and base. This stability ensures the long life and reliability of the device. The optical properties of gallium nitride are also remarkable, with light coverage from ultraviolet to visible spectrum, especially in blue and green LED, which greatly drives the development of full color display and solid state lighting technology. At the same time, the high sound speed of gallium nitride also makes it have a wide application prospect in acoustic wave devices, such as piezoelectric transducer and acoustic surface wave (SAW) filter. More importantly, gallium nitride also shows a strong nonlinear optical effect, which is of great significance for optical communication and optical signal processing. In addition, gallium nitride has excellent radiation resistance and can withstand high doses of radiation without significant degradation, giving it great potential in aerospace and other applications requiring radiation-resistant environments.

To sum up, gallium nitride with its unique physical properties, in radio frequency electronics, solar inverter, automotive electronics, radar system, deep ultraviolet light source and high brightness LED lighting, and other high-tech fields have shown extraordinary application potential and broad market prospects, become a high power, high frequency, high temperature and strong radiation environment work ideal material.[2]

2.2. Chemical Properties

Gallium nitride (GaN), as an important semiconductor material, has a range of stable chemical properties in addition to its striking physical properties, which allows it to maintain performance in a variety of environmental conditions. Here are some of the key chemical properties of gallium nitride: Gallium nitride (GaN), as a high-performance semiconductor material, With its high stability in the atmosphere — does not react with other substances even at high temperatures, Thanks to its strong covalent bond structure; Excellent oxidation resistance, Can resist oxidation at high temperatures, Ensure the reliability and durability of the devices; Good corrosion resistance, Stay inert in most acid-base solutions, It is eroded only under special conditions such as concentrated nitric acid and hydrofluoric acid; at the same time, Selective etching is achieved with carefully designed chemical reagents and processes, Provide the possibility of microstructure processing and patterning; [3]besides, GaN Excellent doping ability, Can adjust its conductive type and characteristics by introducing impurity elements, It is the basis of realizing various functional devices; Photochemical activity enables it to play a role in photocatalysis and photochemical applications; Pressure sensitivity has made some achievements in areas such as pressure sensors; and, The synthetic pathway of GaN is diverse, Including molecular beam epitaxy (MBE), metal-organic chemical vapor deposition (MOCVD), pulsed laser deposition (PLD) And other methods, each method has its own advantages, these unique physical and chemical properties together make gallium nitride in a wide variety of high-tech fields to show a wide range of application potential and important technical value.[4]

2.3. Preparation Method of Gallium Nitride

Gallium nitride (GaN) is usually prepared using several advanced crystal growth techniques, each with its own unique advantages and limitations. Here are several common methods for preparing gallium nitride: Gallium nitride (GaN) has various preparation techniques, each of which has its own unique advantages and applicable scenarios. Molecular beam epitaxy (MBE) is a pure atomic source beam that is directly sprayed onto the substrate under ultra-high vacuum conditions to obtain extremely high purity and crystallization quality GaN film, which is very suitable for experimental research and small batch preparation of high-performance devices. Metal-organic chemical vapor deposition (MOCVD) is the most commonly used commercial GaN film preparation method. GaN is generated through the reaction of gas precursors at high temperature, which supports large area growth and can adjust layer thickness and doping level, which is very suitable for large-scale production. [5] Pulsed laser deposition (PLD) uses laser pulse to evaporate the target material and deposit the evaporation on the substrate in vacuum to form a film. This method is particularly suitable for the preparation of multilayer structure and complex compound film, and can provide better composition control. Halide volatilization method (HVPE) uses gallium chloride or gallium bromide and ammonia reaction to prepare GaN, which is suitable for the growth of thick crystal layer, the cost is relatively low, but the growth rate is fast, and the requirements for equipment are also high. Template-guided growth technique utilizing the template or The mask guides the GaN to grow in specific directions, such as self-assembled nanowires, nanosheets, etc., which are used to prepare one- or two-dimensional structures to increase the specific surface area and functionality of the material. [6]

The gas phase transport (VPE) is similar to MOCVD, but uses solid rather than liquid organometallic compounds, suitable for growth at lower pressures and temperatures, to help reduce energy consumption. Direct nitride produces GaN by heating directly gallium and reacts with nitrogen, which is commonly used for scientific exploration. The sol-gel rule is applicable to the preparation of GaN in the powdered or coated form, with the advantage of low cost and large-scale production. The hydrothermal rule is to dissolve metal salts in high pressure and high temperature water and then cool the crystallization to obtain GaN, which is often used to study and prepare small amounts of samples. When choosing the appropriate preparation method, the end use of the material, the required quality standard, cost effectiveness and easy to scale production. In recent years, with the continuous progress of technology, researchers are also actively exploring more efficient synthesis paths to improve the yield and performance of gallium nitride, reduce energy consumption, and further broaden its application scope in electronics, optoelectronics, energy and other industries.[7]

3. Application Status and Challenges of Gallium Nitride in the Diode Field

3.1. Current Status of Gallium Nitride in Diodes

3.1.1. Consumer Electronics Sector

Fast charging: Gallium nitride diodes are widely used in fast charging adapters for consumer electronics such as smartphones and tablets. Traditional silicon-based diode has large conduction loss and switching loss in high frequency and high power applications, while gallium nitride diode can effectively reduce energy loss with its low conduction resistance and fast switching characteristics, improve charging efficiency, and achieve faster charging speed. For example, gallium nitride diodes are used in many famous brands 65W or even 100W fast charging adapters, which greatly reduces the charging time of the device and improves the user experience.

Power management: In the power management module of the laptop computer, TV and other equipment, the gallium nitride diode helps to optimize the power conversion efficiency and reduce

the volume and weight of the power module. This is crucial to the pursuit of lightweight, portable, modern consumer electronics. By adopting gallium nitride diodes, a higher power density can be achieved in a limited space, making the power supply more stable and reliable.[8]

3.1.2. The Field of Automotive Electronics

On-board chargers: With the popularity of electric vehicles, the performance requirements of on-board chargers are getting higher and higher. Gallium nitride diodes can meet the needs of on-board chargers for high power, high efficiency and high reliability. Compared with traditional silicon-based diodes, gallium nitride diodes can withstand higher voltage and current, reduce the energy loss in the charging process, improve the charging speed, and also adapt to the complex electrical environment and temperature changes of the car.

Automotive lighting: Gallium nitride diodes also start to emerge in lighting systems such as headlights and taillights. Due to its fast switching characteristics and high brightness output ability, it can achieve more precise lighting control and more energy efficient lighting effect. Especially in the adaptive far-light control, dynamic turn signal and other functions, gallium nitride diode can quickly respond to signal changes, providing better visual effects and driving safety.

3.1.3. Industrial Applications

Switching power supply: In the fields of industrial automation equipment, server power supply and other fields, the efficiency and power density of switching power supply are extremely high. The application of gallium nitride diode can significantly improve the performance of switching power supply and reduce energy consumption. For example, in the server power supply in the data center, the use of gallium nitride diodes can effectively improve the power conversion efficiency, reduce heat dissipation requirements, and reduce operating costs.

Renewable energy generation: In solar and wind power generation systems, gallium nitride diodes are used for power conversion and power management. Its characteristics of high voltage resistance and low loss can help to improve the overall efficiency of the power generation system, convert more renewable energy into usable electricity, and achieve stable power output. In photovoltaic inverters, gallium nitride diode can optimize the electric energy conversion process, reduce energy loss, and improve the economic benefits of photovoltaic power generation system.

3.2. Challenges for GNN Diodes

3.2.1. Material Growth and Manufacturing Process

Difficulty to grow high quality materials: Although some progress has been made in the growth technology of gallium nitride materials, it is still challenging to obtain high quality, large area gallium nitride epitaxial layer with good uniformity. Lattice mismatch and thermal stress can easily lead to material dislocation and defects, which can affect the electrical performance and reliability of the diode. At present, the growth cost of gallium nitride materials is relatively high, which limits its large-scale commercial application.

Complex manufacturing process: The manufacturing of gallium nitride diodes involves a variety of complex process steps, such as lithography, etching, doping, etc. The compatibility and stability of gallium nitride process need to be further improved. Precise control of process parameters to achieve high performance and consistent diode manufacturing is still an urgent problem.

3.2.2. Device Performance and Reliability

Reverse current and leakage problem: Gallium nitride diode in reverse bias conditions may appear large reverse current and leakage phenomenon, which will not only reduce the efficiency of the device, but also may affect its reliability and stability. Especially in the harsh environmental conditions such as high temperature and high humidity, the problem of reverse current and leakage may be more prominent, which needs further optimize the device structure and material performance to solve.

Electrostatic discharge (ESD) sensitivity: Gallium nitride diode is relatively sensitive to electrostatic discharge, and it is easy to be damaged by ESD in the process of production, transportation and use, leading to the performance decline or even failure of the device. Therefore, effective ESD protection measures need to be developed to improve the anti-ESD capability of GNN diodes in practical applications.

3.2.3. Cost and Market Acceptance

High cost: At present, the cost of gallium nitride materials and manufacturing process is relatively high, resulting in the price of gallium nitride diodes is much higher than traditional silicon-based diodes. This partly limits the popularization and application of GaN diodes in some cost-sensitive applications. To achieve the large-scale popularization of gallium nitride diodes, we need to further reduce the cost and improve the cost performance.

Lack of market awareness and application experience: Although GA diodes have obvious performance advantages, some users have doubts about their reliability and long-term stability due to their relative novelty. In addition, with the lack of sufficient application cases and design experience in the market, engineers may face some technical difficulties when integrating gallium nitride diodes into existing systems. Therefore, more marketing and technical training are needed to improve users cognition and application ability of gallium nitride diodes[9]

4. Conclusion

Gallium nitride has made remarkable achievements in the field of diodes, especially in consumer electronics, automotive electronics and industrial applications. However, to achieve a wider range of applications and the further development of the industry, the challenges in material growth and manufacturing processes, device performance and reliability, and cost and market acceptance need to be overcome. With the continuous progress of technology and the increase of R & D investment, it is believed that gallium nitride diodes will occupy an increasingly important position in the future semiconductor market, providing strong support for technological innovation and development in various fields.

References

- [1] SiC power components market trends and strategic planning of Rm products [J]. *World Electronic components*, 2019 (07): 46-51.
- [2] China Silicon wafer Market Industry Research Report 2021 [C]. Shanghai iResearch Market Consulting Co., LTD. *IResearch series* (No.4,2021), 2021:28.
- [3] The GaN [J] of the third-generation semiconductor. *Superhard Material Engineering*, 2021,33 (03): 15.
- [4] Yang Fan, Wang Meiqi, Guan Wei Province. Progress in the preparation and application of group nitride semiconductor materials [J]. *LICAL*, 2019,48 (07): 1203-1207.
- [5] Li Chengming, Suning, Li Lin, et al. A vertical variable flow field analysis of gas phase epitaxial (HVPE) reaction cavity and growth of large size material [J]. *Vacuum*, 2021,58 (02): 1-5.
- [6] Liu Cuicui, Guo Gang, Li Zhiming, etc. SiC MOSFET Current status of single-particle effect research [J]. *Nuclear Technology*, 2022,45 (01): 3-16.

- [7] Sami Suihkonen, Siddha Pimputkar, Sakari Sintonen, Filip Tuomisto, Defects in single-crystal gallium nitride (GaN) prepared by thermal nitridation. 10.1002/aelm.201600496.
- [8] Elbara Ziade, Jia Yang, Gordie Brummer, Denis Nothern, Theodore Moustakas, Aaron J. Schmidt, Thickness-dependent thermal conductivity of gallium nitride (GaN). 10.1063/1.4974321
- [9] A.M. Jeffries, L. Ding, J.J. Williams, T.L. Williamson, M.A. Hoffbauer, C.B. Honsberg, M.I. Bertoni. Gallium nitride (GaN) grown by low-temperature molecular beam epitaxy (MBE). 10.1016/j.tsf.2017.07.066.