Applications and Research Progress of GaN

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Abstract. As a typical wide bandgap semiconductor material, GaN has the advantages of high temperature resistance, high breakdown resistance voltage and high electron migration rate, and GaN growth technology is very critical to give full play to the above advantages of GaN and ensure material reliability. This paper first introduces the development process of semiconductor materials, and introduces the advantage intervals of GaN compared with other semiconductor materials, and then introduces several different growth methods commonly used by GaN, and discusses the possible shortcomings of the current research. Based on the review analysis, this paper proposes the problems that need to be solved urgently in the future GaN growth method and the research prospects.

Keywords: semiconductor material, growth technology, defect behavior.

1. Introduction

Semiconductor materials are important basic materials for making transistors, integrated circuits, power electronic devices, new semiconductor light-emitting and power devices and other optoelectronic devices. In the development of the semiconductor industry, Si and Ge are called the first-generation semiconductor materials, which promote the creation of semiconductor components and the industrial application of semiconductor materials; GaAs, InP, GaP, InAs, etc. are called the second-generation semiconductor materials, driving the The rapid development of electronic materials. It can be seen that the fields of communication, software, electronics and other fields make full use of the Internet, artificial intelligence and other technologies to develop rapidly, but the benefits of these above fields from the development of basic materials and new architectures cannot be ignored. Nowadays, the third-generation semiconductor materials with wide band gap characteristics show better performance than the previous two generations [1]. There have been some commercial applications in LED, field-effect transistors and other fields, and there are also huge market prospects.

This article starts from the development history of semiconductor materials, and analyzes the properties of GaN, one of the third-generation semiconductor materials, and the advantages of this material compared with previous generations of semiconductor materials. The preparation methods of GaN semiconductor material are emphatically introduced and some application scenarios of this material are also introduced.

The research and development of semiconductor materials has always been one of the representatives of cutting-edge technology. The development of such materials can bring more portable or durable electronic devices and bring more possibilities for human civilization to explore the unknown.

2. GaN Material

2.1. Development of semiconductor

At the beginning of the 20th century, scientific research discovered that silicon had many special physicochemical properties, such as decreasing resistivity with increasing temperature, the magnetoelectric effect and the rectification effect of contact with metals. Thanks to the excellent properties of silicon, Alcatel-Lucent Bell Labs invented the silicon transistor in the early years, marking the beginning of the semiconductor era. Not only silicon but also germanium had similar

properties, and single-element semiconductor materials made from either of these two elements were the first generation of semiconductor materials. Thanks to the reserves of the element silicon, a great deal of research into silicon semiconductors was born, and most of today's integrated circuit chips are made on silicon wafers [2].

By the 1990s, Group II-VI compound semiconductor materials, represented by GaAs and InSb, were gradually developed and put into use. Compared to elemental semiconductors, the new generation of semiconductors has a higher electron mobility, which facilitates high frequency transmission. At the same time, the second generation semiconductor has a direct band gap, which means that the electron wave vector is constant when the electron leaps, meaning that the momentum can remain constant, without the need for phonons to provide momentum, electrons and holes can be directly compounded when they meet, and this compound can release most of the energy in the form of light, bringing light-emitting components and optical communication technology innovation. The advent of second-generation semiconductors brought about rapid growth in the performance of electronic chips and in the communications industry, allowing the Internet to soar in the ensuing 21st century.

Over the years, as human civilization explored harsher realms such as deep sea, space and volcanoes, the disadvantages of silicon-based semiconductors gradually became apparent. Limited by the low electron-hole leap rate and the material's inherent lack of heat resistance, scientists needed transistors that could cope with high temperatures, high pressures and other harsh environments. As a result, the focus of research has gradually shifted to broadband semiconductors, the third generation of semiconductors represented by materials such as GaN, SiC and diamond. With the advantages of high saturation electron drift rate, high thermal conductivity and high breakdown electric field strength, third-generation semiconductors are able to meet the need to cope with severe weather as research progresses.

2.2. Structure of GaN

As can be seen in Figure 1, nitrides are usually either fibrillated zincite or sphalerite structures [3], while the latter two are sub-stable phases of nitride, which are more difficult to prepare and less thermodynamically stable compared with fibrillated zincite structures, and most of the GaN materials are currently fibrillated zincite structures. The structure of the nitride has a polarized charge, which is capable of forming a polarized electric field, which means spontaneous polarization. Due to the existence of spontaneous polarization phenomenon, GaN grown along the c-axis direction exists in two states, gallium polarized and nitrogen polarized. If the GaN film is epitaxially grown along the c-axis [0001] direction, its surface is (0001) surface, which is called gallium-polar GaN. In gallium-polar GaN material, the direction of Ga-N chemical bond is Ga atoms pointing to N atoms, and the polarization direction points to the substrate. In contrast, GaN epitaxially grown along the c-axis [0001] is called nitrogen-polar GaN, and in nitrogen-polar GaN materials, the Ga-N bond is oriented with the N atoms pointing toward the Ga atoms and the polarization is directed away from the substrate, which causes strain on the material [4]. Under the combined effect of both polarization effects, the semiconductor element can undergo polarization covariance. Thanks to the properties of this material, GaN-based Schottky diodes prepared from GaN have a higher reverse breakdown performance compared to conventional Schottky diodes and have good prospects for application in the field of high-power devices.

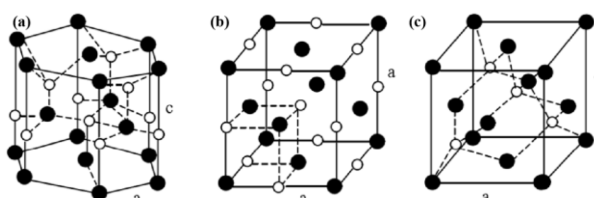

Figure 1. Crystal structure of GaN

(a) Fibrillated zincite structure (b) Sphalerite structure (c)Rock salt ore structure.

2.3. Physical and Chemical Properties of GaN

As shown in Table 1, according to the experimental results, the third generation semiconductor materials represented by GaN have a higher forbidden band width compared to the previous two generations of semiconductor materials [5].The Johnson quality factor (JM) characterizes the power-frequency characteristics of the material, while the Baliga quality factor (BFOM) measures the ability of the device to reduce power losses, again confirming that third generation semiconductors have a high power applications.

Table 1. Comparison of the properties of different semiconductor materials [1].

material properties	Si	GaAs	4H-SiC	GaN
band gap	indirect	direct	direct	indirect
Eg (eV)	1.12	1.42	3.62	3.44
Ec (MV/cm)	0.3	0.4	22.0	3.8
μn (cm2/V-s)	1400	8500	950a/1190c	1000a/20002
vs (×107cm/s)	1.0	1.2	2.0	2.5
εr	11.8	13.1	10	9.5
λ (W/cm-k)	1.5	0.46	4.9	1.3
JM (=Ecvs/2π)	1.0	1.33	20	27.5
BFOM (=ε0μEc2)	1.0	1102	51.9	179.3

As can be seen in Figure 2, GaN has certain advantages over SiC, which is also a third generation semiconductor, in the fields of electric breakdown field, energy gap, saturated electron velocity and electron mobility, but only in thermal conductivity. Thanks to the development of epitaxial technology, GaN can be grown on substrates with high thermal conductivity, which makes up for the lack of thermal conductivity.

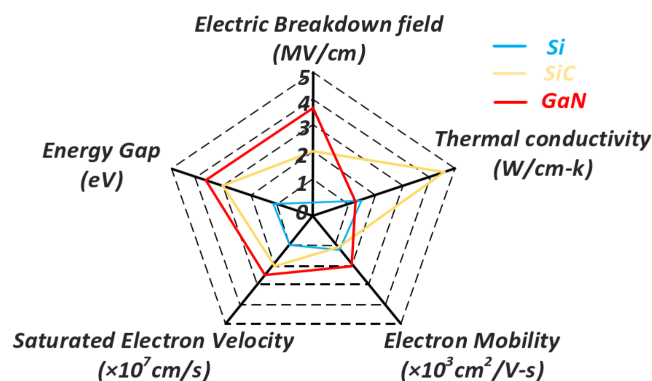

Figure 2. Comparison of the properties of GaN, SiC and Si semiconductor materials.

3. Preparation Methods

Heterogeneous epitaxy is currently the mainstream GaN growth technology, the technology is the main method for the preparation of optoelectronic devices, the technology has matured and is gradually achieving industrialization and commercialization. The substrate for this technology is usually sapphire material, on which GaN is epitaxially grown, and the epitaxial layer is mainly used metal organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), hydride vapor phase epitaxy (HVPE) and other technologies.

3.1. MOCVD

Among the various production techniques, metal organic chemical vapor deposition technique is now the most mature technology, and the method is also easy to mass production and has higher commercial value. The epitaxial layer product obtained by this method has many advantages such as good flatness, high purity and thin epitaxial layer, therefore, this method is widely used in the field of optoelectronic devices, especially LEDs. The metal-organic source for this method is TMGa, and the nitrogen is derived from ammonia gas. The feedstock is placed in a reaction furnace filled with hydrogen, nitrogen, or a mixture of both, and the reaction occurs at the appropriate temperature. Molecular clusters of the corresponding thin film material are generated, which undergo a series of processes such as adsorption, nucleation and growth on the surface of the substrate, and finally form the epitaxial layer of GaN. The reaction equation is shown below.

$$Ga(CH)_3 + NH_3 \rightarrow 3CH_4 + GaN \downarrow \quad (1)$$

In the process of growing GaN by MOCVD, there are a series of side reactions including decomposition reaction, side reaction, atomic migration process and transport process, etc. The above chemical reaction formula cannot accurately describe the whole process of GaN.As shown in Figure 3, the whole reaction process can be roughly considered as four steps. In the first step, the carrier gas carries the MO source and hydrides into the reaction chamber, where the MO source is TMGa and the hydrides are NH3; the second step is the molecules of the reactants move to the surface of the high-temperature substrate and undergo a cleavage reaction, resulting in the cleavage of Ga and N atoms and a series of by-products; then those Ga atoms on the substrate surface react with N atoms to form GaN; finally, unreacted reactants exist during the GaN growth process, and these reactants, along with the resulting by-products, leave the reaction chamber and enter the exhaust gas.

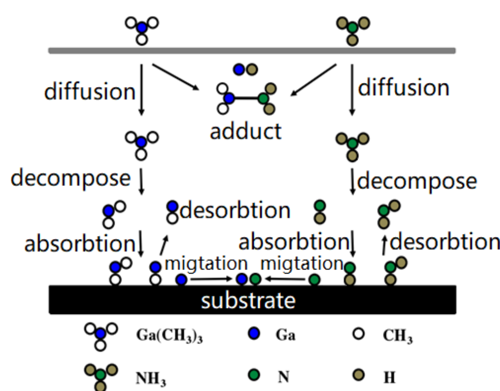

Figure 3. Diagram of GAN growth process in MOCVD reaction

When GaN is prepared by the MOCVD method, the growth rate can be adjusted in a wide range, so the MOCVD method can be used to prepare both GaN thick films in devices and quantum well structures with precise thickness requirements [6], so the MOCVD technique is currently the most widely used method for the growth of group III nitride materials. Since the MOCVD technique has certain advantages over the other two techniques, the GaN thin films and quantum well structures described in this thesis were grown using the MOCVD method for epitaxy.

3.2. MBE

The MOCVD reaction sometimes requires hydrogen as the carrier gas for the transport of the reaction gas, and the H atoms in p-type doping will form Mg-H bonds with the doped Mg atoms, which affects the doping efficiency. In addition, ammonia cracking requires high growth temperature which affects the growth of high In component InGaN, and there is also the problem of parasitic reaction in the growth of high Al component AlGaN. In contrast, MBE can achieve the technology of growth under non-thermal equilibrium conditions, and the reaction process has the characteristics

of ultra-high vacuum, low growth temperature, and low growth rate, and thanks to these characteristics, its epitaxial layer therefore has the advantages of low impurity concentration and steep heterogeneous interface. At the same time, the low growth temperature of MBE is also favorable for the growth of InGaN with high In fraction.

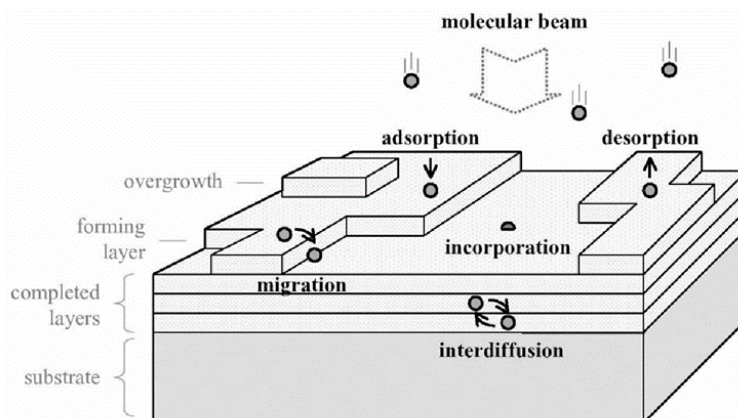

Figure 4. Diagram of GAN growth process in MBE reaction

The essence of the epitaxial growth of MBE is the reaction process of adsorption, decomposition, migration, binding, and desorption of several thermal molecules or thermal atomic beam streams on the surface of a substrate with a certain temperature, as shown in Figure 4. The growth process is mainly a kinetic process controlled by surface chemistry and surface reactions, rather than a thermal equilibrium process.

MBE equipment is distinguished from other epitaxy technologies by its ultra-high vacuum growth environment, and the vacuum system is the most important part of the MBE system, which is a prerequisite for MBE experiments. The MBE system used in this paper has three vacuum chambers, Growth Chamber, Buffer Chamber and Load-Lock Chamber, which are connected and closed by vacuum valves, and each chamber is equipped with a corresponding vacuum pump to maintain high vacuum level. Figure 5 shows the schematic diagram of the vacuum components of the MBE system.

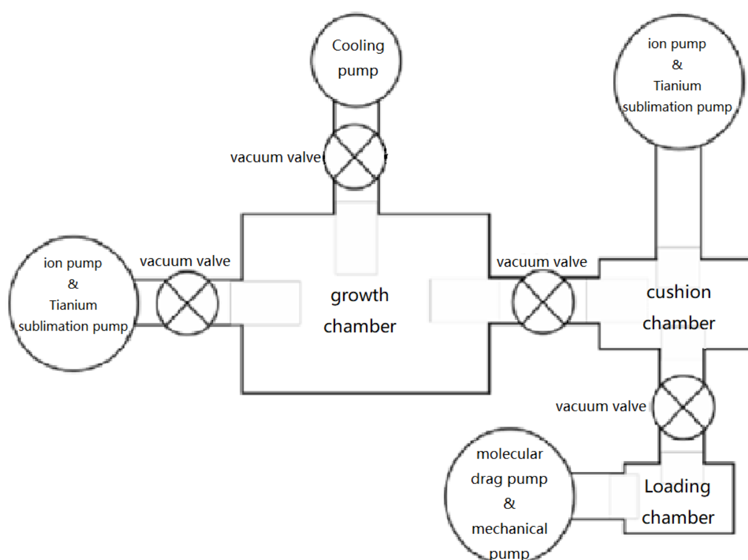

Figure 5. Diagram of MBE vacuum system

3.3. HVPE

Figure 6 shows the reaction process of this preparation method. In the process of growing GaN by HVPE method, HCl enters into the gallium boat with N_2 and reacts with liquid Ga to form GaCl.

Subsequently, NH3 is passed into the reactor to react with GaCl to form GaN and deposit onto the surface of sapphire substrate, and the reaction mechanism is as follows.

$$2HCl+2Ga \rightarrow 2GaCl+H_2 \quad (2)$$

$$GaCl+NH_3 \rightarrow HCl+H_2+GaN\downarrow \quad (3)$$

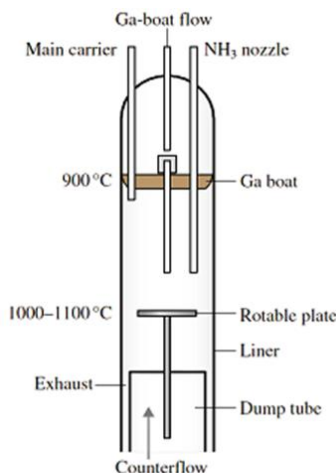

Figure 6. Diagram of GAN growth process in HVPE reaction

When the technique was first proposed, Marusk et al used a horizontal HVPE device to prepare GaN crystals. Recent studies by Dam et al found that changing the angle of the inlet gas can make the reaction gas react more fully on the substrate, while the old equipment leads to parallel gas flow with a small reaction contact area and a very inadequate reaction. At the same time, in order to achieve the uniformity of substrate contact, so that the reactants can be more fully mixed and contact, and increase the growth rate of GaN, the position of the substrate gradually evolved from horizontal placement to a certain angle with the gas path, and then developed into a vertical HVPE equipment.

Even so, HVPE still has the disadvantage of high defect density and poor crystal quality of the epitaxially grown GaN films. Moreover, the product growth rate is too fast to achieve high precision growth when preparing GaN by vertical HVPE.

4. Applications of GaN

4.1. LEDs (light emitting diodes)

Group III nitrides as LED materials have the advantages of large forbidden band width, high electron saturation rate, and high breakdown electric field.

Due to the low cost and large size of Si substrates, LEDs based on heterogeneous epitaxial GaN on Si substrates have become a research hotspot. Ra et al [7] fabricated InGaN/GaN multiple quanta well nanowires based on both axial and radial structures LED devices, and it was found that the electroluminescence emission intensity of the m-plane LED was about 28.6% higher than that of the c-plane LED.

4.2. Field Effect Transistors

The wide band gap semiconductor GaN is very suitable material for high frequency, high voltage and high output power field effect transistors (FETs) because of its high saturation electron velocity, high dielectric breakdown voltage and the possibility of constructing heterostructures of AlGaN/GaN to achieve high electron concentration. yu et al [8] fabricated FETs based on GaN nanowire arrays, which have a threshold voltage of 1.5 V and the output current was greater than 10 mA, and Li et al [9] constructed metal-oxide-semiconductor FETs using GaN nanowires grown by molecular beam epitaxy, which had an on/off ratio of up to 108. The above studies demonstrate potential application

scenarios for GaN in areas such as next-generation power switches and high-temperature digital circuits.

4.3. Electrochemical Energy Storage Devices

Research work on electrochemical energy storage devices is devoted to the development of electroactive novel nanostructures to improve their energy storage capacity. Based on the large specific surface area of nanostructures, when used in electrochemical energy storage devices, nanostructured materials will have a larger contact surface area and will be able to store more charges. The current high carrier concentration, thermal conductivity and chemical stability about GaN nanomaterials make them suitable for electrochemical energy storage devices. Wang et al [10] prepared GaN nanomaterials by chemical vapor deposition on graphite paper and fabricated them into symmetric supercapacitors, obtaining energy densities up to 0.30 mW·h·cm-3 and power densities of 1000 mW·cm-3. The material also shows good energy storage performance in lithium batteries. Supercapacitors based on GaN/MnO2/MnON sandwich structure composites have achieved significant improvements in the cycling stability and specific capacity of the capacitors [11].

5. Conclusion

Although GaN materials break through the limitations of the physical properties of the traditional semiconductor materials themselves, but there are still many problems in the realization of applications, such as less preparation methods, efficiency is not high enough, the reaction process is difficult to control, the reaction results are difficult to predict, etc. are urgent problems that need to be solved, the need for GaN material growth methods, growth mechanism, defect behavior and its performance for in-depth research.

The present era requires deep integration of all industries, the integration of solutions and application scenarios, the integration of networks and devices, the integration of communication equipment and supporting, etc. GaN materials and devices are developing rapidly, and wide-band semiconductor devices have higher operating frequencies, higher blocking voltages, stronger operating temperature tolerance, and lower switching losses and through-state resistance ratios, which have played a huge role in the development and application of information science and technology. GaN semiconductor material application process, on the one hand, we need to keep an eye on the trend of industrialization and scale of related devices; on the other hand, we also need to be used to select new technologies and materials, research and development of new communication power product architecture, to achieve digital social transformation to provide reliable energy security.

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