Theory And Application of Gallium Nitride Based Dilute Magnetic Semiconductors

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Abstract. Semiconductors are key components for the development of Industry 4.0 innovative technologies such as consumer electronics, data centers, intelligent new energy vehicles, and aerospace technology. Academic research on semiconductors can not only promote the development of electronics and electromagnetics, but also meet the demand for high-performance semiconductors in technological development. This paper provides a review of the theoretical and experimental research results on gallium nitride based diluted magnetic semiconductors, and prospects the future application prospects of gallium nitride based diluted magnetic semiconductors. This paper found that the theoretical prediction of gallium nitride based diluted magnetic semiconductors is generally believed to have good temperature conditions and advantages in thermal conductivity, electron mobility, breakdown voltage, and other aspects. The current experimental results also confirm that gallium nitride based diluted magnetic semiconductors can improve the limitations of semiconductors under room temperature conditions. This article believes that this semiconductor material has broad development potential in fields such as intelligent vehicles, aerospace, and cloud computing.

Keywords: Magnetic semiconductors; Gallium nitride; Thermal conductivity.

1. Introduction

As humanity enters the information age, the transmission and processing of digital information has become an important factor affecting the development of the information society. Modern electronic technology relies on the spin property of electrons to store digital information and relies on the charge property of electrons as a tool and carrier for digital information transmission. The rapid development in the field of integrated circuits, especially in achieving nanoscale applications, has brought electronic technology into the atomic age, and further attracted attention to the application of electronic spin properties in the field of information. Spintronic devices have better performance than traditional semiconductors in terms of energy consumption, speed, and non-volatility, and can also achieve smaller volumes [1]. The important condition for achieving the operation of spin electronic devices is to combine the high efficiency of semiconductors and spin electrons. This requires appropriate magnetic materials as the source of injection for spin electrons.

Metal materials were once used to inject spin electrons, but these materials can create a magnetic dead layer at the interface that causes electrons to jump during spin. This leads to low electron injection efficiency and interferes with the normal operation of electronic devices. Although ferromagnetic semiconductors can effectively overcome the issue of conductivity, they cannot achieve large-scale production due to their high temperature requirements (requiring temperatures higher than 20 K Curie) [2].

Subsequently, people shifted their research focus to non-magnetic semiconductors and found that using transition metal elements to replace some of the atoms in the material would convert them into dilute magnetic semiconductor materials. This type of semiconductor has lattice constants and band structures similar to those of semiconductors and can achieve compatibility between magnetic and semiconductor characteristics. This is because this semiconductor material can change the effective g-factor, impurity energy level, and other parameters of the semiconductor material through spin-spin exchange, thereby changing the external magnetic field of the semiconductor and affecting its physical properties. At the same time, the disordered distribution of magnetic ions gives this

semiconductor material many advantages of disordered magnetic alloys [3]. Therefore, dilute magnetic semiconductor materials have become an important research object in the field of spin electrons.

Gallium nitride based diluted magnetic semiconductors are important members of the III-V family in diluted magnetic semiconductor materials. Although the research and application of this semiconductor material has attracted widespread attention in the field of electronics, there is still no unified conclusion on the physical and magnetic properties of this material. Therefore, this paper reviews the current theoretical and experimental research on gallium nitride based diluted magnetic semiconductors and prospects the future development and applications of this semiconductor material.

2. Theory and Mechanism

2.1. Properties of Gallium Nitride

Gallium nitride is a semiconductor material that can achieve direct bandgap. In terms of electrical properties, the optimal electron concentration of gallium nitride can reach 4 without intentional doping × 1016/cm3, the concentration of charge carriers can be considered to be controlled within the effective range of 1014-1020/cm3 and can achieve high compensation. At room temperature, the highest mobility of gallium nitride can be achieved μ N=600cm2/v · s. The doping concentration can be effectively adjusted to the range of 1011-1020/cm3 through the P-type doping program and thermal annealing program. In terms of optical properties, gallium nitride can be widely used in the fields of blue and purple light devices, such as blue LED and laser emission devices. The direct bandgap energy that this substance can achieve is 3.39 eV [4].

There are three crystal structures of gallium nitride, the first being the wurtzite structure (as shown in Figure 1). In this structural state, there are 6 N and Ga atoms in each crystal cell. The data of spatial group structure is P63mc (C46V). The second structure is the sphalerite structure (as shown in Figure 1). In this structural state, gallium nitride produces an atomic distribution structure similar to that of diamond. There are 4 N and Ga atoms in each crystal cell, with lattice constants and c. The data for the spatial group structure is F-43m (T2d) [5]. The third type of structure is rock salt ore structure (as shown in Figure 1). In this structural state, Ga atoms and N atoms exhibit a nested state with each other. Four Ga atoms will surround one N atom, while four N atoms will surround one Ga atom.

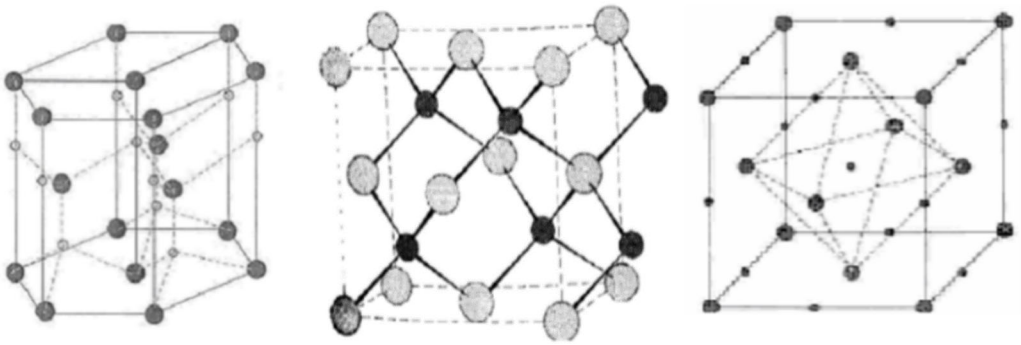


Fig. 1 The Structures of wurtzite, sphalerite, and Rock Salt Mine [5].

In addition, gallium nitride has significant advantages in thermal conductivity, breakdown voltage, and other aspects. At the same time, this material also has the characteristics of high temperature resistance and corrosion resistance. These advantages make gallium nitride widely used in the research and manufacturing of high-density and high-power electronic devices.

2.2. Theoretical research progress

At present, the theory of gallium nitride based diluted magnetic semiconductors can be divided into two categories. The first type of theory views the lattice of semiconductor materials as a regular substitution of doped atoms for the lattice and the formation of new alloys, a process that is stochastic.

The second type of theory suggests that the magnetism of materials comes from small clusters in the lattice.

Based on the Zener model, Dietl et al. (2000) researched, and analysis were conducted on the sources and characteristics of ferromagnetism, and a mean field model was proposed [6]. This model can further explain the relationship between charge carriers and spin momentum and provide a new perspective for further exploration of new ferromagnetic materials. According to the calculation and prediction results of this model, diluted magnetic semiconductors based on gallium nitride and zinc oxide exhibit excellent performance in terms of Curie temperature (as shown in Figure 4) and can be above room temperature. This provides hope for the large-scale production and manufacturing of dilute magnetic semiconductors. Theodoropoulou et al. (2002) analyzed the changes and characteristics of carrier concentration and ferromagnetism using a unified field model and considering the impact of disorder on the experimental results [7]. Their prediction suggests that under the condition of bound magnetic polarons, the concentration of charge carriers required for ferromagnetism becomes lower, while Mn atoms will decrease ferromagnetism under the effect of antiferromagnetic effects. Overberg et al. (2002) set the source of ferromagnetism as Mn clusters [8]. A short-range gravitational force will form between different clusters. 3-5 Mn clusters can form 4-5 μB. The magnetic momentum of b. At the same time, there is competition between antiferromagnetic applications for ferromagnetic interactions. The theory also suggests that an increase in temperature can lead to an increase in cluster size. An increase in the number of Mn atoms will lead to a decrease in magnetic momentum. Overberg et al. (2001) found that ferromagnetism of gallium nitride was calculated using the pseudopotential density function formula, and it is believed that when doped with substances such as V and Mn, gallium nitride will have a stable ferromagnetic state, while when doped with substances such as iron and Co, gallium nitride will appear in a spin glass state [9].

3. Experimental Achievement and Future Application

In 1992, Strite and Morkoc used the molecular beam epitaxy method to grow the material, and it was found that (Ga, Mn) N exhibits antiferromagnetic phenomena below the Curie temperature of 10K. (Article 8) The use of superconducting quantum interference equipment to inspect the counterfeit also revealed the presence of antiferromagnetic features in ions in Mn. By using of the MOCVD method, Fukumura et al. (2001) found that (Ga, Mn) N thin films grown on sapphire were studied, and it was found through experiments that semiconductors based on (Ga, Mn) N can achieve good ferromagnetism at room temperature [10]. Further, Wakano, T. et al. (2001) used molecular beam epitaxy at low temperature, (Ga, Mn) N thin films were grown on sapphire substrate [11]. The growth temperature of the thin film is between 580 ° C and 750 ° C, and the Mn content exceeds 3% but is lower than 5%. The Curie temperature exceeds 900K.

In addition, many scholars have studied the relevant characteristics of gallium nitride diluted magnetic semiconductors formed by using Fe, Cr, and Cu as dopants [12]. Angelescu and Bhatt (2002) found that adding Cr can make the ferromagnetism of semiconductors become ordered [13]. Berciu and Bhatt, however, found that single crystal blocks of (Ga, Cr) N were fabricated at room temperature [14]. A ferromagnetic (Ga, Cu) N thin film was fabricated using ion implantation method at room temperature.

In fact, gallium nitride based diluted magnetic semiconductors have broad application prospects in the following areas.

The first is the new energy vehicle field. With the continuous development of automation trends in new energy vehicles such as autonomous driving, there is a huge demand for safe and efficient semiconductor components in the field of new energy intelligent vehicles. Intelligent new energy vehicles require the production of microcontrollers through semiconductor technology. The microcontroller is responsible for monitoring and analyzing the operating status of various parts of the car, the temperature and humidity inside the car, and the external driving environment of the car. Microcomputers based on semiconductor technology can determine the driving status of a car by

collecting, inputting, and calculating the above information, and issue instructions for further driving actions. The application of gallium nitride based diluted magnetic semiconductors can effectively enhance the computing power of microcomputers, enhance their heat dissipation, and further reduce their volume. This plays a crucial role in improving the autonomous driving ability of new energy vehicles.

The second is the aerospace field. In the aerospace field, communication between ground command centers and satellites and space stations in space relies on high-frequency carrier communication tools. This is because the ground command center is too far away from satellites and space stations in space, requiring higher energy forms for information transmission. The advantages of gallium nitride based diluted magnetic semiconductors in saturation, electron mobility, and drift speed enable them to be used in the manufacturing of microwave devices and power amplifiers required for high-frequency carrier communication tools. With the continuous development of aviation and aerospace industries in various countries, there is a huge demand for this semiconductor material in the aerospace field.

The third is the cloud computing and data center field. As humanity enters the era of big data, both enterprises and individuals need to extensively collect data information from their living environment and carry out effective data computing and data mining. The application of gallium nitride diluted magnetic semiconductors can effectively enhance the computing power of data center electronic computers and improve the thermal consumption of electronic computers. This can effectively enhance the data computing capacity of cloud computing centers, improve the computing efficiency of cloud computing, and further improve the user experience of big data users.

4. Conclusion

This paper analyzes the development background, theoretical prediction, and experimental development of gallium nitride based diluted magnetic semiconductors. At present, both theoretical predictions and experiments have proven that gallium nitride based diluted magnetic semiconductors have good temperature conditions and advantages in thermal conductivity, electron mobility, breakdown voltage, and other aspects. From theoretical research, both the mean field model and the unified field model predict that gallium nitride based diluted magnetic semiconductors have higher Curie temperatures and can better achieve room temperature processing and manufacturing. The stable advantages of gallium nitride based diluted magnetic semiconductors in ferromagnetism are also recognized. In terms of experiments, the Curie temperature, and ferromagnetic characteristics of (Ga, Mn) N thin films cultured on the basis of sapphire confirm the correctness of theoretical research. At present, gallium nitride based diluted magnetic semiconductors have become an important material of concern in the research and manufacturing of third-generation semiconductors. The technological development in the Industry4.0 era requires high-performance and high-efficiency semiconductor components as support. This provides broad application space for gallium nitride diluted magnetic semiconductors, especially in fields such as intelligent car manufacturing, aerospace, and cloud computing. New semiconductor technology can enhance the capabilities of microcomputers, thereby improving autonomous driving performance. The advantages of gallium nitride based diluted magnetic semiconductors in saturation, electron mobility, and drift speed can further optimize the performance of microwave devices and power amplifiers and enhance the computing power of electronic computers. Although current experimental research has focused on the formation of gallium nitride diluted magnetic semiconductors doped with Fe, Cr, Cu and other dopants, there is still limited research on the types and characteristics of dopants. There is also a lack of comparative research on the thermal conductivity, electron mobility, breakdown voltage, and other aspects of different dopants in various experiments. At the same time, there is a lack of further research on the low energy regulation and spin transport properties of magnetism in current research. These properties directly affect the production and manufacturing promotion of gallium nitride diluted magnetic semiconductors and other types of semiconductors.

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