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The Intrinsic Origin and Technological Challenges of p-Type GaN Doping in Blue LEDs

Jie Su

Guangzhou Ulink International School, Guangzhou, China
13112906688@163.com

Abstract. The blue light-emitting diodes (LEDs) are significant in the current lighting technology due to their energy saving and lifetime of work. The most important material is GaN in the production of blue LEDs, but p-type GaN remains a challenge since it can hardly be produced with good conductivity. This paper will be discussed through the use of a literature review approach, where the main causes of this issue are presented. The argument is centered on the low level of acceptor Mg, passivation by hydrogen, and self-compensation by native defects. Also considered in the paper is the impact of these issues on the materials that affect the performance of blue LED devices, such as resistance, hole injection, and efficiency of light emission. Moreover, there are various ways of improving them, which include annealing, growth control, delta doping, superlattice structure, and tunnel junctions. It has been discovered in the paper that the nature of GaN itself, as well as the effect of its defects during growth, makes the p-type GaN difficult to produce. Understanding this aspect is also essential for enhancing the blue LEDs and the micro-LEDs in the future.

Keywords: Blue LED, GaN, Micro-LED, p-type GaN

1. Introduction

Blue light-emitting diodes (LEDs) are an important part of modern lighting and optoelectronic devices. Compared with traditional lighting, LEDs use less energy and usually last longer. The development of efficient blue LEDs was a very important step in solid-state lighting because it made it possible to produce white light with semiconductor devices. Because this technology had a strong effect on energy-saving lighting, the invention of the blue LED was recognized by the Nobel Prize in Physics in 2014 [1]. Among the semiconductor materials used in LEDs, gallium nitride (GaN) has become the main material for blue light emission. GaN has a wide bandgap of about 3.4 eV. Because of this, it is suitable for short-wavelength optoelectronic devices and high-power use [2].

In GaN-based LEDs, the light is generated through the recombination of the electrons and holes in the active part of the device. The semiconductor structure should have a p-n junction to ensure that this process can occur effectively. It is possible to produce N-type GaN with considerable ease, as it is silicon-doped. But there is still no way to make reliable p-type GaN. This issue has been addressed by many previous works [3]. noted that the most popular acceptor dopant used in GaN is magnesium (Mg), which creates a relatively deep level of acceptors. Its energy of activation is approximately 200 meV. In other words, at room temperature, only a few of the acceptors are

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ionized. Consequently, the concentration of holes remains minimal. One of the reasons why hydrogen passivation is another factor. Mg and H atoms may react with each other and create Mg-H complexes when introduced during growth. Such compounds cause Mg acceptors to be non-reactive and decrease the efficiency of p-doping even more [4]. Moreover, some holes created due to the Mg doping will also be neutralized by native defects like nitrogen vacancies [5].

This paper is based on these studies, which are the physical causes that prevent p-type doping in GaN blue LED. It focuses primarily on the effects of deep acceptor levels, hydrogen passivation, and compensation of defects. They can be used to explain why it has been hard to achieve p-type GaN. As a rule, one should have a better idea of such problems so as to enhance carrier injection and facilitate the future progress of LEDs and micro-LEDs.

2. Electronic structure of GaN and basic doping physics

The semiconductor that is a wide-bandgap material is GaN. Its bandgap has a value of approximately 3.4 eV. This figure is far higher than silicon. Due to this, it is common to use GaN in blue and ultraviolet optoelectronic components. The same can be said about GaN as being important in the research on the blue LED. GaN is mostly a wurtzite crystal structure. It is this type of crystal structure that influences the optical and electrical characteristics of the material. It also changes the manner of doping in GaN [2, 6].

Doping is used to change the carrier concentration in a semiconductor. Donor dopants provide electrons. Acceptor dopants produce holes. So donor doping makes the material n-type, and acceptor doping makes it p-type. In GaN, silicon is usually used for n-type doping. This process is not very difficult, and it can give a high electron concentration. The situation is different for p-type doping. Magnesium, or Mg, is the most common acceptor dopant in GaN. When Mg enters the GaN lattice, it forms an acceptor level above the valence band. In theory, this can leave holes in the valence band and help electrical conduction [6].

The problem is that Mg does not work well enough in GaN. The acceptor level of Mg is relatively deep. This means that Mg is hard to ionize at room temperature. Earlier studies showed that the activation energy is around 200 meV. This value is much higher than normal thermal energy at room temperature. So only a small part of the Mg acceptors can really produce free holes. Because of this, the hole concentration stays low. This is one main reason why p-type GaN is difficult in practice. Even if the Mg concentration is high, the number of free holes may still be limited [3, 7].

The p-type problem in GaN is not only caused by Mg alone. It is also related to the fundamental electronic structure of GaN and the formation of native defects. The next section will discuss these limiting factors.

3. Fundamental reasons for the difficulty of p-type GaN

The difficulty of p-type GaN does not come from only one reason. It comes from several problems working together. The first and most important one is the deep acceptor level of Mg. Magnesium is the most common acceptor dopant in GaN, but it does not work very efficiently. Earlier studies showed that the activation energy of Mg in GaN is about 200 meV. This value is much higher than the thermal energy at room temperature. Because of this, only a small number of Mg acceptors can be ionized. As a result, the number of free holes remains low. This is one of the main reasons why p-type GaN is difficult to realize in real devices [8, 9].

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This issue is significant since it demonstrates that the challenge begins with the material. In most instances, the Mg concentration is already large, and yet the hole concentration remains much smaller than anticipated. The issue is not merely that there is insufficient dopant. It is the inability of the dopant to generate sufficient free holes. One of the key reasons why this result occurs is due to the wide bandgap of GaN. It increases the difficulty of acceptor ionization and decreases the final hole concentration [6, 7].

The second reason is hydrogen passivation. The process of the growth of p-GaN may also lead to hydrogen incorporation in the material. Such hydrogen atoms have the ability to react with Mg and create Mg-H complexes. In this case, the Mg acceptors will be inactive. That is, there is no Mg in the material, but it does not give holes as effectively as before. This is the reason why annealing is generally required after growth. Annealing is able to break the bonds between some Mg-H and activate the part of the acceptors. Nevertheless, the effect of hydrogen passivation cannot help to improve the efficiency of the p-type doping and exacerbate the situation [4, 5].

Self-compensation also plays an important role. If the Mg concentration is increased, native defects could be more easily to form in the crystal. Some of them, e.g., nitrogen vacancies, act as donor-like defects, reducing the number of free holes and thus compensating acceptor doping. Therefore, the increase of Mg concentration does not necessarily lead to better p-type conductivity but, in some cases, even to stronger compensation [5, 6].

Therefore, the difficulty of p-type GaN has to be interpreted as a combined effect: deep acceptor levels decrease the hole generation, hydrogen passivation renders some Mg acceptors inactive, and self-compensation decreases the final hole concentration again. These issues are closely related and altogether make p-type GaN one of the major bottlenecks in GaN-based blue LEDs [3-6].

4. Impact on blue LED device performance

The difficulty of p-type GaN does not stay only at the material level. It also affects the performance of blue LED devices. In a GaN-based LED, electrons come from the n-type side, and holes come from the p-type side. They recombine in the active region and produce light. If the hole concentration is low, this process cannot work well. So the p-type problem directly influences the quality of the pn junction and the final light output [2, 6].

One clear result is higher resistance in the p-type region. Because the hole concentration is low, p-GaN usually has poor conductivity. This increases the series resistance of the device. When the resistance becomes larger, the forward voltage also becomes higher. More electrical power is then lost as heat. This is not good for LED performance, especially under high current conditions [2, 10].

The other issue is inadequate hole injection. The holes are not easy to inject into GaN-based LEDs as compared to the electrons. It is also possible that the number of electrons and holes within the active area is unbalanced. In the absence of sufficient holes, numerous electrons will not be able to recombine with each other effectively. This reduces the efficiency of the light-emitting device. Such issues may become even more apparent in small devices like micro-LEDs due to the fact that the distribution of carriers depends on the structure of the device and the spreading of current [11, 12].

The efficiency droop and the current crowding are also associated with the p-type problem. The carriers do not necessarily spread equally in the device as the current increases to a high value. In such circumstances, there are local regions that have more of the current than others. This is known as current crowding. Simultaneously, the intensity of light emission can be reduced when the density of the current rises. This phenomenon is referred to as efficiency droop. Not only p-GaN but also low hole injection and large resistance on the p-type cause these issues [10, 12].

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Because of this, the hardness of p-type GaN is not a material problem only. It is also a device issue. It simultaneously influences carrier balance, electrical resistance, and light emission. This is why it is important to enhance p-type GaN in terms of material research as well as the practical performance of blue LEDs and future micro-LED devices.

5. Technological strategies and emerging perspectives

Since p-type GaN is not easy to achieve, many studies have sought to improve it through various approaches. There are some attempts to activate additional Mg acceptors. Other approaches attempt to lower the defects. The methods which do not actually address the issue of p-type but attempt to decrease its effect on the device are also used. And that work in this field does not only concern a better material. It is also a design that is improved [6, 10].

One common method is annealing after growth. In Mg-doped GaN, hydrogen can form MgH complexes and make some acceptors inactive [4, 5]. Annealing is used to break these complexes and activate more Mg atoms. This method is already common in p-GaN processing. Growth control is also important. In MOCVD, conditions such as temperature and gas ratio can affect hydrogen and defect formation. So better growth conditions can help improve p-type conductivity, even though the main material limit is still there [4, 10].

Another approach is to modify the structure. Some works employ delta doping or superlattice structure to enhance p-type behavior [13]. Such methods rely not merely on increasing the amount of Mg but also attempt to modify the distribution of dopants and carriers in the material, which in some cases assists hole transport and reduces the resistance. This does not completely alleviate the issue of deep acceptors, but nevertheless may improve device performance [6, 13].

A tunnel junction is another key concept. It doesn't address the fundamental p-type issue but can mitigate its impact in terms of device design, aiding hole injection and alleviating the issue of a resistive p-type contact. This concept is beneficial for regular LEDs, and is even more crucial for micro-LEDs since smaller devices are more susceptible to current spreading and resistance [11, 12, 14].

Future work will likely proceed along these directions. One is improved defect control; the other is improved device structure. Thus, the future of p-type GaN research is not just about making the material better, but also about finding practical ways to circumvent the limitations that are already present in the material.

6. Conclusion

The primary causes of p-type GaN in blue LEDs were considered in this paper. It was demonstrated that the issue is highly associated with the fundamental characteristics of GaN itself. The bandgap of GaN is wide, and it complicates the ionization of acceptors. Mg is the most used acceptor dopant that has a deep acceptor level, hence it cannot generate sufficient free holes at room temperature.

The paper also demonstrated that the complexity does not lie in the deep acceptor level. Some Mg acceptors can be made inactive by hydrogen passivation, and self-compensation may further decrease the final hole concentration. Due to this, p-type GaN is still challenging even when the Mg concentration is already high. These issues then impact blue LED devices in various ways. They have the potential to enhance resistance, weaken hole injection, and lower light emission efficiency.

As this study is primarily based on a literature review, certain limitations remain. Although the study focuses on exploring a number of general mechanisms, it does not cover all aspects of p-type GaN research. In some cases, the text does not include detailed experimental results or quantitative

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comparisons. Furthermore, as this study does not provide any new experimental data, its discussion is based primarily on previous research and is limited to relatively general.

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