Study on the enhancement of optical and electrical properties of GaN by doping

Weili Liu
Microelectronics Academy, Dalian University of Technology, Dalian, China
Corresponding E-mail: 736081960@qq.com

Abstract—GaN is a hot material of semiconductor devices, and it is extensive researched because of its outstanding performance. At the same time, doping can change the performance of GaN in the expected direction. This paper mainly introduces the main properties of GaN material. Meanwhile, according to the current application of GaN, it focuses on the effects of some common doping-types on the optical and electrical properties of GaN material. Through the doping of different elements, the optical and electrical properties of GaN will be improved in different aspects. For example, c-doping improves the breakdown voltage of AlGaN/GaN devices. Finally, the development prospect of GaN doped materials and devices is described.

1. Introduction
GaN materials include GaN, as well as the alloy with InN and AlN. The material is hard and the chemical property is stable. As a kind of direct band-gap semiconductor material, GaN has the characteristics of high luminescence efficiency due to its high composite probability of electrons and holes. Therefore, GaN material is an ideal luminescent device material. It is widely used in laser diode (LDs), light-emitting diode (LEDs), ultraviolet detector and other Photoelectric device fields. At room temperature, GaN band gap width was 3.4eV and electron mobility was 900cm2/N·s[1]. Without doping, the carrier concentration of GaN is within the range of 1017~1019cm-3[2]. In general, the GaN that is not intentionally doped is of n-type, and the intrinsic carrier concentration is high, ranging from 1018 to 1019cm-3[1]. Although GaN has some innate advantages, it still has many disadvantages in application, such as low carrier mobility in low electric field and the poor high-frequency performance. In recent years, researchers have studied different elements doping to improve the optical and electrical properties of GaN materials devices, so that GaN can meet the requirements of device applications. This paper also aims to find out, how doping affect the electrical properties of GaN and which element is most suitable for doping.

2. Analysis of doping results
2.1. The effect of C-doping
AlGaN/GaN hetero-junction field effect transistor (HFET) has excellent electrical performance, and the current research is very extensive. HFET device based on Si substrate has been implemented, once the technology is mature, it will cause a great impact on the traditional Si-based power devices. However, it will cause the wafer to bend when growing buffer layer due to the large lattice mismatch and thermal mismatch between the Si and nitride layers, coupled with the high conductivity of the AlN/Si interface, the leakage current will increase, the breakdown voltage will decrease, and it is easy to damage the device. Through the research, C doping can effectively solve this problem.
A carbon auto-doping technique (CDT) method has been proposed to increase the breakdown voltage. In 2015, Yiqiang Ni et al. in Sun Yat-sen University studied the influence of the electric properties in different C doping position of AlGaN/GaN system based on Si materials shown in fig. 1 (a), (b). They found all these locations of C doped buffer can improved the breakdown voltage. The GaN buffer and the GaN/AlN buffer with SLs buffer solution were doped with C simultaneously, there was higher breakdown voltage, up to 181 V/μm shown in fig. 2. At the same time, Yiqiang Ni et al. showed that this doping method could produce AlGaN/GaN hetero-structures with high breakdown voltage without changing other properties [3]. In general, the appropriate C doping in GaN improves the breakdown voltage of the device and greatly improves the reliability and working range of the device, which will enhance the future application value of GaN devices and enable GaN to play a role in more high-voltage fields.

Figure 1. (a) Cross-section TEM image of the fundamental GaN/Si(111) (b) Schematic of the GaN/Si(111) [3].
2.2. The effect of As-doping
Electron mobility and carrier concentration are two important indicators in semiconductor performance. Good semiconductor materials are usually accompanied by higher carrier concentration and faster electron mobility, because they can effectively improve the reaction performance of semiconductor devices. Referring to the study of M. Ahoujia et al., it can be concluded that carrier concentration and electron mobility generally increase with the increase of as-doped concentration. In other words, As-doped can improve the performance and work efficiency of GaN devices [4].

However, a problem arise, M. Ahoujia et al. found that two deep electron trap energy levels is 0.22ev and 0.60ev, could be observed in GaN samples before doping As. However, in the samples doped with As, the energy level of 0.22ev was not observed, and only a deep energy level of 0.60ev existed [4]. M. Ahoujia et al. did not give an explanation, and speculated that this was because the As atom occupied the site of 0.22ev. Based on this hypothesis, we can assume that deep energy level is easy to introduce deep energy level impurities. Due to the existence of deep energy level, these impurities have less significant influence on carrier concentration and conduction type than shallow energy level impurities, but the compound effect on carriers is stronger than shallow energy level impurities, and the deep energy level impurity is called the recombination center. The presence of a recombination center will reduce the lifetime of non-equilibrium carriers to some extent, as opposed to the current goal of increasing the lifetime of nonequilibrium carriers. However, in general, the number of deep level impurities is small and the effect is limited. In this experiment, a large amount of As doping can make us ignore influence of deep level impurities, and carrier concentration and electron mobility are significantly improved. Therefore, we can speculate that the result of this doping will effectively improve the operating frequency and speed of GaN devices, and will be very popular in the field of high-frequency technology and devices.

2.3. The effect of F-doping
Transistors include diodes, audions, and other devices that have the functions of rectification, amplification, and switching. Particularly, transistors can be used as variable current switches.
Switching speed is also an important parameter in transistors. Therefore, when using semiconductor transistors, the transistor uses the electrical signal to control its own opening and closing. The faster the switching speed is required, the better.

In 2015, J.W. Roberts et al. completed the experiment of using F doping to control threshold voltage to accelerate the switching speed. In AlGaN/GaN metal-insulator-semiconductor hetero-junction FET, F doping can achieve uniform distribution. The most important reason is that F doping can effectively reduce the capacitor hysteretic effect of GaN semiconductor devices when they are capacitors. At the same time, compensation is made for the positive trap in the oxide to reduce the positive charge in the gate oxide and offset the threshold voltage [5]. According to the data given by J.W. RBTS et al., the average positive threshold voltage deviation of GaN-based transistors is between 0.75 and 1.36v, which is a large numerical change compared to the transistor threshold voltage [5]. By shifting the threshold voltage, the speed of the switch is increased and the operating speed of the device is also increased.

2.4. The effect of Cr-doping
Semiconductor materials have unique optical properties. The resistivity of semiconductor materials is photosensitive. Therefore, by using this property, photodiode, phototransistor and silicon photocell devices can be made. At the same time, the response of the semiconductor optical performance degree can be different because receives the light of different wavelengths, in the use of pure GaN made one-dimensional nanowires, photo-luminescence peak can be measured at 378nm and 464nm, the GaN material absorb these two light wavelengths more than the nearby [7].

In this experiment, Rongna Chen used the same method to grow GaN one-dimensional nanowires, the only difference is that be doped with Cr this time. After the growth was completed, detect again, and it could be seen from the PL diagram that an extra weak luminescence peak of 602nm was added shown in fig. 3 [2]. This phenomenon could be caused by the transition from the conduction band to the Cr-deep energy level acceptor, but the transition of the deep energy level acceptor is more difficult than that of the shallow energy level acceptor, so only the weak luminescence peak could be obtained. Thus, the optical response of GaN material was enlarged, the utilization rate of optical signal was increased, and the optical performance was improved.

![Figure 3. PL spectra of GaN nanowires with Cr source of 0.5g](image)

3. Future development prospects and direction of GaN doped devices
After years of development, GaN is widely used in semiconductor devices and can effectively improve its own optical and electrical properties through doping. At present, GaN doping research is a hot spot
of GaN devices, GaN still has great development and application opportunities. For example, Sihao Xia et al. of Nanjing University of Science and Technology had used the way of simulation and calculation, and the quantum efficiency of this exponential-doping GaN nanowire photocathode is obtained recently. Find the best optimal incident angle, GaN nanowire can effectively enhance the escaping of carriers from the top surface and reduce the escaping of electrons from the side face under the action of the internal electric field [6]. This result has a guiding significance for the preparation of the photocathode. In addition, there are many examples to improve the performance of GaN devices through doping, which can show that the research on GaN will have great practical significance. Further studies are likely to lead to further achievements.

4. Conclusion
In general, this paper summarizes the main optical and electrical properties of pure GaN, a central point is presented that doping can improve the performance of GaN devices. And details in several kinds of different elements on the GaN doping are introduced. It is found that different doping ions can affect the different properties of GaN. For example, as mentioned in the paper, carrier mobility of GaN devices can be improved through doping, thus improving high-frequency performance. At the same time, the breakdown voltage, switching speed, light response range can also be improved by doping. Hence, it can be speculated that the photoelectric performance can be improved by doping in the future. Finally, the realistic significance and prospect of GaN doping research are emphasized.

All in all, as long as the doping control is effective and the performance of the device is improved to the expected level, there is an opportunity to create better devices.

References
[1] Song F Study on synthesis, doping and luminescence properties of GaN nanometer materials pp 14-15
[2] Chen R 2014 Preparation of gallium nitride via chemical vapor deposition method and its optical property research (Qinhuangdao: Yanshan university) p 7
[3] Ni Y, Zhou D, Chen Z, et al. 2015 Influence of the carbon-doping location on the material and electrical properties of a AlGaN/GaN heterostructure on Si substrate Semiconductor Science and Technology vol 30(10) pp 105037.
[4] Aboujia M, Yeo Y-K, Hengehold R L, et al. 2002 Influence of arsenic doping on the electrical properties of GaN epitaxial layers grown by MOCVD International Semiconductor & Insulating Materials Conference IEEE Canberra Australia p 27-30
[5] Roberts J W, Chalker P R, Lee K B, et al. 2016 Control of threshold voltage in E-mode and D-mode GaN-on-Si, metal-insulator-semiconductor heterostructure field effect transistors by, in-situ fluorine doping of atomic layer deposition, Al2O3 gate dielectrics Applied Physics Letters vol 108(7) pp 072901
[6] Xia S, Liu L, Diao Y, et al. 2017 Research on quantum efficiency and photoemission characteristics of exponential-doping GaN nanowire photocathode Journal of Materials Science vol 52(9) pp 12795-12805
[7] Chen R 2014 Preparation of gallium nitride via chemical vapor deposition method and its optical property research (Qinhuangdao: Yanshan university) p 80-81