Comparison between The ultra-wide band gap semiconductor AlGaN and GaN

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Abstract. The emergence of the ultra-wide band gap semiconductor, whose band gaps considerably wider than 3.4 eV (GaN), opens a new era in many fields because of their many superior property. The major material of the UWBG semiconductor is high Al-content AlGaN and the studies find these material have stunning strengths in ultra-high power and ratio-frequency electronics, deep-ultraviolet optoelectronics, quantum information and electronics for extreme-environment applications. In this article, by comparing GaN and ultra-wide band gap AlGaN, people can know the strengths of AlGaN, lacks of GaN and realize why AlGaN will replace GaN in some applications and why GaN will continually be used by people in some applications.

1. Introduction
GaN is a popular and widely used semiconductor that can be operated under a temperature over 600 °C [3]. However, when the density of temperature-induced intrinsic carriers in GaN surpasses the concentration of dopant-induced carriers at this temperature, the performance of device will degrade. Compared with GaN, ultra-wide band gap semiconductors like AlGaN have a wider band gap, higher levels of breakdown field, better temperature stability and irradiation robustness, so that they can be operated above 1000 °C and tolerate high radiation. Under this background, this article will introduce the properties of GaN and AlGaN and their performance. By analyzing the limitations of GaN, the reasons why AlGaN will replace GaN in some specific fields are discussed.

2. Material
2.1. GaN
Firstly, GaN as the third semiconductor is a hexagonal wurtzite [11] under the barometric pressure and has a stable chemical property even under high temperatures or in the alkaline solution. At the same time, GaN has a small atomic volume and therefore has a good hardness. Secondly, GaN has a low permittivity so it has high RF power level. Thirdly, it has high saturation electron mobility [7] (maximum 3x10^7 cm / s), so it has good carrier transport capability. Finally, GaN has a band gap of up to 3.4 eV, so its inherent carriers are relatively low at high temperatures and high radiation [10].

However, GaN material has still some drawbacks. For example, the heteroepitaxy defect density is high due to the unsolved substrate single crystal problem. There are lots of drawbacks in GaN epitaxial thin films, including points defects caused by growth technology or doping, buffer layer defects and dislocation caused by substrate mismatch. The residual impurities in epitaxial GaN mainly come from H, O, C and N vacancies, while H forms high resistance in the complex compensation holes formed by...
MgO is the shallow donor of GaN and affects carrier concentration. Dislocation limits the thickness of nitride materials with high Al component required for deep uv light.

2.2. AlGaN
As a frontier material, AlGaN has a crystal structure and they are also ternary alloy [12]. Just like other ternary alloys, the major exploit of AlGaN is focus on power of hetero structures and band gap engineering [6]. Compared to GaN, firstly, AlGaN own wider band gap up to 6.0 eV while the GaN wide only 3.4 Ev; secondly, its breakdown field higher than 4 MV cm\(^{-1}\) of GaN; thirdly, AlGaN has higher saturation velocities than \(10^7\) cm s\(^{-1}\); fourthly, it has a high electron mobility [7] up to\(1000\) cm\(^2\) V\(^{-1}\) s\(^{-1}\); fifthly, it’s easier for AlGaN to be doped n-type with Si. Above these are standpoints from electronic perspectives. From the optoelectronics perspective, AlGaN can directly access to emission wavelengths shorter than 365 nm into UV-A; -B; -C. In this area, AlGaN is stronger than GaN. However, just only a few AlGaN has been applied in applications and devices because there are two major problems [9].

The first problem is the controlling over doping. Firstly, when the band gap increase, most dopant ionization energies grow up. But if the ionization energies grow up, the fraction of carriers will decrease so under the room temperature, it is difficult for many UWBG devices to reach the special free carrier concentration. Secondly, the wide band gap make themselves incline to self-trapping carriers because the localized nature of valence band state form easily small hole polarons and this occurrence happens easily to self-trapping because of their lattice dislocation. Thirdly, dopants in semiconductor has a tendency called compensation via impurities, native defects and so on. For instance, n-type doping AlGaN by Si, if the proportion of Si increase continually, the free carrier concentration will increase and it will decrease as it reaches the turning point. This phenomenon is called compensation and lower compensation is better. Considerably, AlGaN/AlN own spontaneous and piezoelectric polarization, people can consider new method such as polarization-induced doping, which can generate limited carriers at the hetero interface but because of the deep-level flaws of the wide band-gap layer, this change is relative.

The second problem is the absence of single-crystal used for epitaxial growth and the lack of scientific understanding of controlling heteroepitaxy on such substrates. The high price and low ability of AlN constrain the development of UWBG electronic and optoelectronic devices. Except for high crystalline quality and large diameter, low lattice bow is necessary. Usually people need a large bow radius but it’s difficult to obtain one. Traditional method is not used because to obtain AlN boules from melt calls for a high pressure, which is difficult to realize in lab. So now the alternative method is vapor-phase and solution growth approach, which can let the microscopic seed regrowth again and again and finally expand the suitable size. However, the expansion speed of this method is slow, as a result, the production is low, while the wafer is expensive. Therefore, the actual production doesn’t take place. Now, some scientists come up with a mixing method such as ammonothermal method, which is validated that it can produce high quality homoexpital HVPE- grown GaN.

3. Devices and applications
The high-power electronics is the widest application for UWBG technology because each application controlled by power switch need high power. When the switch is off, it helps these applications block high voltage and when the switch is on, it helps these applications monitor the current. As people demand more sustainable energy, high-power electronics will play more important role in our lives.

Now GaN-on-Si is the major material used in high-power electronic. Current WBG technology can reduce power switching to a low level, on which the heat dissipation and heat sinks will not encumbered by system design, and reduce waste and cost, so that people will focus on the cost and performance of system instead of that of the device. This semiconductor device can realize a stronger doping under the given break voltage, the reduction of electric conduction and switching and the increase of the efficiency of power transformation. For high voltage, the first consideration is vertical SiC and for low voltage, the first consideration is GaN. Compared to traditional semiconductors, UWBG can applied in higher or
lower voltage. Then, UWBG semiconductor has a higher FOM’s \( \left( \frac{1}{4\epsilon\mu EC^3} \right) \) Based on these properties, it will be applied in electronics and thermal fields.

From continuous and pulsed power, especially in some highest power and voltage application in pulsed power, the UWBG semiconductor will have well performance than WBG semiconductor.

As to continuous power, power grid and some applications such as used in the electric-car and ferry can be impacted by UWBG semiconductor. In general, if UWBG semiconductor want to be applied in these application such as mobile and electric-applications in airline and so on, they should be designed as a vertical structure similar to SiC. The design of vertical AlGaN need a processing technology depended on lateral selective area doping [5]. Compared to traditional WBG semiconductor, a high quality gate insulator can form on the UWBG material because of the stable properties. And another application is Pulsed power including electromagnetic rail guns, electric reactive armor, pulsed microwave sources, directed energy weapons, high-power pulsed lasers, and fusion energy. With the remarkable development of semiconductor, more and more scientists start to investigate high-voltage semiconductor. GaN and SiC are limited to dealing with \( \approx 10^5 \) W. However, the high power applications required \( \approx 10^6 \) w, the UWBG semiconductor which has lower carrier density, robust radiation resistance, and good thermal stability, will be a factor to accomplish this problem.

In the continuous-power application, UWBG can make power switch work under higher frequency then traditional silicon. Because of this, it allows smaller passive element used in the switch and this method can increase integration. This way can increase dramatically property of power switch and finally UWBG can come up more small foot script, lighter weight and operating under high temperature. These advantages will have a huge impact on transportation, military system and aerospace and other fields. In pulsed power, improvement of passive elements need them to follow the potential system of UWBG but the challenge is how to keep passive element good properties under the high-power switching.

Except for high-power electronics, UWBG are widely used in extreme environment and in this section. The following two parts will be discussed: the surrounding environment is extreme such as the presence of radiation and high temperature or pressure or corrosive chemical. However, under this extreme environment, the sensors and electronic-applications are necessary. For some equipment we have talked about before, WBG and UWBG technology possess better robustness than under the high radiation environment. And this kind of high voltage, huge current and radiation resistance mainly
utilized as electronic thrust control actuators of rockets and missiles. WBG and UWBG have robust for high operation, another advantage for space application. Currently, almost all useful commercial GaN power devices are not sufficiently rated for high-voltage power conversion envision by NASA [4]. However, UWBG can replace it because application which UWBG is applied in possess operate in high radiation and high temperature. And UWBG devices may become the important factor in next space generation. The reasons of UWBG has wider band gap which need higher energy of photons or ion clusters to come up ionization of electron-hole in semiconductor. And another reason is UWBG can use material between two different band gaps to form hetero-structure and then form 2DEG area and form channel in HEMT, which is not sensitive to hard radiation [1].

Figure 2. a notional GaN HEMT (right), biased in the off state with 100 V bias on the drain

UWBG material will improve dramatically immunity of HMET transistor to hard radiation and it will get small devices and reduce the volume for collecting radiation-induced charge. Next, for some simple sensors, they can be used in extreme environment, but now we have no devices such as microprocessor and wireless electronics and powering devices can be used in 250°C, even above. Today, acting cooling is used in high temperature for complex electronic devices and in lower temperature, we can not use acting cooling and we can only expend the time of heating. Although, SiC and GaN-based devices can operate under above 600°C but the shortcoming of them is the temperature-induced intrinsic carriers in these materials surpassed the concentration of dopant-induced carriers at these very high temperature (beyond 800°C for SiC and 1000°C), reducing the device performance [3]. Based on the situation, scientists have more incentive to develop UWBG to adapt the extreme environment. Using UWBG need to integral electronic-sensor system and there are so many challenges such as material diffusion, formation between metals and temperature gradient and so on. Another major challenge is how to deliver power to system.

4. Suggestion
AlGaN is one of the important representatives of the third generation of new wide band gap semiconductor materials, whose band gap width can be continuously adjustable in the range of 3.4eV (GaN) to 6.2eV (AIN). AlGaN has more flexibility than GaN in band gap, people can change percentage of Al content in AlGaN and find a percentage of Al that reflects AlGaN’s performance or a performance optimality [8]. With the increase of Al component in AlGaN, the receptor position deepens and the activation energy increases, leading to the decrease of activation efficiency and hole concentration. Scientists can discover the percentage of Al components under different optimal performance conditions. For example, when Al content increase a certain percentage with high break field, high electron mobility [8], this AlGaN can be used in high electronic power.

5. Conclusion
Although GaN still dominant the semiconductor field, scientists have found scientists have found some flaws in the application process. These problems concentrate on doped hetero structures [6], and operating temperatures. However, scientists have found that UWBG with a wider band gap and higher breakdown voltage can solve some problems. But so far, only a handful of laboratories are studying
UWBG, and UWBG is rarely used because ultra-wide band gap semiconductors still face many problems such as high cost and material properties. When these problems are solved, AlGaN will eventually replace GaN in some specific fields.

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