Recent research on ohmic contacts on GaN-based materials

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Abstract. The most important components in most of the electronic products today, such as computers, mobile phones or digital recorders, are closely related to semiconductor. Semiconductors have a long history. Currently, there are some obstacles in the way of the further development of this material. Therefore, this paper mainly focuses on the ohmic contacts between metals and semiconductor with the help of recent research. In the end, a general conclusion is drawn on the electrical behavior of metal contacts on GaN for further advances in this field of GaN-based devices and materials.

1. Introduction
Semiconductors that can work at external temperatures over 150 °C without external cooling have broad application areas, such as automobiles, aircrafts, gas turbines, oil exploration, and space exploration industries[1]. However, there is a large voltage drop at the interface between GaN material and metal, which leads to poor electrical performance and stability of the devices [3]. Low resistance ohmic contact between metal and n-type and P-type GaN is one of the main solutions. Therefore, ohmic contact to GaN is the key technology for preparing commercial GaN devices, and is also the basis for further improving the performance of GaN devices.

This paper summarized some results achieved on ohmic contacts to GaN-based materials. In the first part, the basic principle and concepts of semiconductor-metal contacts are briefly introduced, and the most common methods to evaluate ohmic contacts will be presented. In the second part of the paper, the common approached for ohmic contacts to n-GaN and p-GaN will be presented. For n-GaN, particular emphasis will be given to Ti/Al series contacts and non-alloyed contacts. And for p-GaN, Ni/Au stacks will be discussed, and a new method which is InGaN/AlGaN superlattices to reduce resistance of p-GaN contacts as well as the effect of surface treatments will be presented.

2. Basic principle of semiconductor-metal contacts
Because of the rectification or excess power dissipation caused by the voltage thresholds, the low resistance of ohmic contacts leads to the easy flow of charge in both directions inside the two conductors[3]. Fig. 1 shows the band diagram when metal contact to n-GaN and metal contact to p-GaN. Generally, metals with appropriate work functions are chosen to accomplish no barrier to the majority carrier [21]. According to the calculation, to achieve the ohmic contacts, the work function of metal should be equal to or smaller than that of the n-type semiconductor ( or bigger than the P-type semiconductor) [2]. As can be seen in fig. 2, Titanium (Ti) and Aluminium (Al) are in principle the materials of choice for ohmic contacts to n-type GaN[2]. Further more, in the terms of p-GaN, Ni, Au, Pt, Pd are the most suitable metals for the triggering of ohmic contacts.
Figure 1. (a) metal contact to n-type semiconductor (b) metal contact to p-type semiconductor

Figure 2. Survey of literature results of Schottky barrier height $\Phi_B$ values as a function of the metal work function $\Phi_m$ for different metals on both n-type and p-type GaN. Data are taken from Ref. [4] for n-type GaN and Ref. [5] and [6] for p-type GaN.

At present, the transmission line model (TLM) is commonly used to measure the specific contact resistance, which can evaluate the ohmic contacts. It includes rectangular, circular and circular transmission line models. It have proved that the rectangular and circular transmission line models have large errors, and the measured values are inaccurate. The circular transmission line model can eliminate the errors caused by terminal resistance, and has good operability, accuracy and repeatability.

3. Ohmic contacts to n-GaN
The valence bond of GaN shows obvious ionicity, and there is no high surface density of states at the interface between metal and GaN, so the height of contact barrier mainly depends on the work function of the metal. For n-GaN ohmic contact, as discussed in the last section, the preferred method is to select metal with small work function, of which Al ($\approx$-4.28eV) and Ti ($\approx$-4.33eV) are the two most commonly used metals.

3.1. Al, Ti Series Ohmic Contacts
Al is one of the metals which was studied at first to used as contacts. This kind of ohmic contacts can be formed by single layer Al/n-GaN contact. The contact resistivity of n-GaN grown on sapphire substrates by ECR-MBE method is $1.2*10^{-4.4*10}$ cm$^2$ after 575°C and 10 min annealing. It is worthy
to note that long annealing at high temperature will decrease the contact properties, which may be because of the oxidation of Al to Al2O3, and formed a high resistance layer. For single layer Ti/n-GaN ohmic contact, high temperature annealing is usually required. When annealing temperature rises to 900-950°C, the contact resistivity between Ti and n-GaN decreases from 2*10^7 to 7*10^6 Ω cm² [7]. This is because TiN is formed by the reaction of Ti and GaN at high temperature, and N vacancies are formed at the boundary between GaN and metal, which will cause heavy doping and formed tunneling current, which reduces resistivity.

However, Ti is more easily oxidized than Al at room temperature, so single-layer Al or Ti contact is not feasible for devices requiring stable and high performance. An improvement to the conventional Ti/Al/Ti/Au contact scheme has been developed to achieve better ohmic contact properties to n-GaN using a Ti/Al multi-layered structure [8]. Ti is used as the contact layer in the lower layer and Al as the cap layer. S. Ruvimov et al. reported [9] that the contact resistance of Ti/Al with n-GaN (grown on sapphire substrates by MBE method) reached 8*10^6 cm² after 900 °C and 30 s annealing.

In order to further improve the contact performance of Ti/Al, a layer of less resistive and less oxidizable Au can be added to Ti/Al. In order to prevent the reaction between Au and Ti/Al, a barrier layer should be added. Recently, Ti/Al/Ti/Au, Ti/Al/Pt/Au, Ti/Al/Ni/Au and other multi-layer structures have also been extensively studied [10]. Fig3[2]. Shows a schematic of the multilayer used to fabricate ohmic contact to n-GaN.

![Figure 3. schematic of the multilayer used to fabricate ohmic contact to n-GaN](image)

3.2. Non-alloy ohmic contact
In order to effectively reduce the barrier height of gold semi-contact and obtain low ohmic contact, a thin epitaxial layer with narrow band-gap can be grown during crystal growth. InN, InGaN, and InAlN are ideal narrow band-gap materials for GaN-based devices.

Although InN (Eg=1.9eV) can effectively reduce the contact barrier with metal, the abrupt heterojunction barriers of InN and epitaxy GaN still have adverse effects on ohmic contact. To solve this problem, a layer of InN/GaN short-period superlattice (sps) is grown between the top layer of InN and GaN, which can reduce the heterojunction barrier between GaN and InN. After depositing 200 nm Ti and 100 nm Al on the top layer of InN without annealing, the contact resistivity can reach 6*10^-5 cm²[11].

4. Ohmic contact to p-GaN
4.1. metal alloy
The predicted value of work content of p-GaN is approximately 6.6 eV, which is higher than that of any other pure metals[13]. However, in the reality, the studies about the ohmic contacts between metal
and p-GaN are still scarce and not under the consideration of all the conditions, in comparison to the conductivity of these contacts relies on the electronic properties of the materials[13].

In general, a p-type semiconductor like NiO, can be formed during the annealing at the contact/GaN interface region[14]. Therefore achieving proper conductivity can be realized by annealing the Ni/Au contact in an oxygen-containing ambient atmosphere[14]. And because of the binding of H atoms from the GaN lattice with help of the reaction with the ambient oxygen, which releases Mg dopant atoms that are passivated by forming Mg-H bonds in p-GaN. Hence, metals such as La in a Ni-La, which can absorb H contact, are put into use for p-GaN contact metal schemes[15].

According to He et al. (2016), the decrease of the ohmic contact resistance to p-GaN through the application of InGaN/AlGaN superlattice is obviously[19]. The strain-induced piezoelectronic field or the large valence-band discontinuity between GaN and InGaN can lead to an increase in the hole concentration, which can reach $1 \times 10^{19}$ cm$^{-3}$[16]. High concentration of two-dimensional hole gas(2DHG) not only helps to reduce contact resistance, but also serves as a current spreading layer. The application of InGaN/AlGaN superlattice can realize the positive ohmic contact of p-type GaN that is with the specific contact resistance of 7.27 *10-5cm$^2$[17]. The reason for that lies in the following two advantages of InGaN/AlGaN superlattice: one is that the InGaN/AlGaN superlattice can improve the ionization rate of Mg impurities to obtain higher void concentration. The other is the strong space restriction effect on voids and enhancement of the void expansion performance.

4.2. Metal oxide

ITO (indium-tin oxide) with a relatively high resistivity ($10^{-1}$ Ω cm$^2$) when directly contact to p-GaN becomes the most frequently used transparent contact material[13]. As a result, the combination of ITO with other materials has been studied, including those with Ni/Au, Pt, Zn-Ni[13]. In contrast to the Ni/Au/ITO and Pt/ITO contacts, the Zn-Ni/ITO contact has the lowest specific resistivity for the H-absorbing tendency of Zn-Ni[13]. With Ni layer between ITO and GaN, an ohmic contact with a specific resistivity of $8.6 \times 10^{-4}$ Ω cm$^2$ can be conducted[13]. This is required the proper conductivity, in addition to the formation of NiO in the contact[13].

Through the investigation of using other metals as p-GaN contacts it is found that the transparent conductor ZnO can be probably used as a p-GaN contact material for its lattice constant mismatch with the Wurtzite structure of GaN is small (1.8%) [18].

Compared to n-GaN, the preparation of effective ohmic contacts on p-GaN still remains a problem[20]. The main difficulties are as follows.

Firstly, there is a lack of metal with a high enough work function. GaN has a bandgap of 3.4 eV, and the work function of p-GaN was predicted to be about 6.6 eV,[12] but the work function of metal is generally less than 5eV, which is lower than p-GaN.

The second is the difficulty in growing heavily doped p-GaN, which means the carrier concentration should over $10^{18}$. When doping p-GaN by Mg, the concentration of Mg is usually at the level of $10^{17}$ cm$^{-3}$ [16], which makes it difficult for the carrier concentration to exceed $10^{18}$ cm$^{-3}$.

Thirdly, the formation of N vacancies on GaN surface is easy to occur during the process, which makes the p-GaN surface possibly turn into n-type conductance.

5. Conclusion

The n-GaN ohmic contact using Ti/Al metal (alloy) and non-alloy as electrode has been studied in this paper. The contact resistivity can reach 10-5–10-8cm$^2$, which can meet the requirements of commercialization of devices. As being discussed before, through there are some achievements on making p-GaN ohmic contacts, it is still a practical and technological subjects to prepare ohmic contacts to p-GaN. Surface treatment, suitable metal or alloy system and suitable alloying process are the main methods to improve p-GaN ohmic contact performance.

Except the low resistance, a good ohmic contact should also have many other properties. Although many achievements have been made, there are some aspects on ohmic contacts that are not discussed in
this paper, such as the mechanism of action, the impact of various surface treatment technologies on contact, reliability, repeatability as well as antioxidation, which need to be further studied.

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