PERGAMON

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Solid-State Electronics 47 (2003) 1843–1846

SOLID-STATE ELECTRONICS

www.elsevier.com/locate/sse

GaN-based light-emitting diodes with Ni/AuBe transparent conductive layer

Lung-Chien Chen [a,*], Chin-Yuan Hsu [b], Wen-How Lan [c], Sheng-Yuan Teng [d]

[a] Department of Electro-Optical Engineering, National Taipei University of Technology, 1, Sec. 3, Chung-Hsiao E. Road, Taipei 106, Taiwan, ROC
[b] Department of Materials and Engineering, National Chiao Tung University, Hsinchu, Taiwan, ROC
[c] Department of Electrical Engineering, National University of Kaohsiung, Kaohsiung, Taiwan, ROC
[d] Formosa Epitaxy Incorporation, 99, Lung Yuan 1st Road, Lung-Tan, Taoyuan, Taiwan, ROC

Received 28 February 2003; accepted 17 March 2003

Abstract

Ni/AuBe as p-type ohmic contact to p-GaN in the heat treatment process are reported. By selection of an optimum condition, the best construction of Ni/AuBe bi-layers is 5 nm/5 nm thick. The light-transmission is about 75% for 470 nm blue light and the lowest specific contact resistance obtained is $2 \times 10^{-3}\ \Omega\,cm^2$ examined by transmission line model after heat treatment process at 500 °C alloying temperature during 10 min in nitrogen ambient. The Be atom may plays an important role in the formation of good ohmic contacts. On the other hand, Ni/AuBe bi-layers are also applied to GaN-based light-emitting diodes (LEDs) as p-type ohmic contact electrode. The typical *I–V* characteristics of the GaN-based LEDs with 5 nm/5 nm-thick Ni/AuBe TCL exhibit a forward-bias voltage of 3.41 V at injection current of 20 mA.

Keywords: GaN; Light-emitting diode; Ni/AuBe

1. Introduction

The III–V nitrides are large and direct energy gap semiconductors, which attract a lot of interest as optimum materials for short wavelength optoelectronic and high temperature electronic applications such as visible light-emitting diodes (LEDs) [1–3], laser diodes [4], hetero-structure field effect transistors [5], and photodetectors [6–9]. However, the p-type GaN is a kind of material having high resistance and wide bandgap such that it is hard to make a good ohmic contact and to acquire a good current spreading layer in LED's application. Investigation of p-type ohmic contacts on GaN and current spreading is important both for material characterization and device fabrication [1–5,10–14]. Since the bi-layered Ni/Au has best device performance so far, it is most common metal frame for transparent contact layer (TCL) in the GaN-based LED process. However, in order to improve the reliability of GaN-based LED, it should be lower down the power consumption as possible. Reducing the serial resistance is one aspect to improve the device performance.

In this paper, we study the contact behavior and the transparent property for blue light of Ni/AuBe metal frame in various conditions in nitrogen ambient, and examine the specific contact resistance (ρ_c) of Ni/AuBe deposited on p-type GaN epitaxial layer by using electron-beam evaporator and then undergone a heat treatment. Besides, the Ni/AuBe metal frame with optimum thickness is used for TCL of the GaN-based LED in according to the optimum alloying condition to reduce the serial resistance and forward voltage of the GaN-based LED. Finally, we compare the GaN-based

* Corresponding author. Tel.: +886-2-2771-2171; fax: +886-2-8773-3216.
E-mail address: ocean@ntut.edu.tw (L.-C. Chen).

0038-1101/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0038-1101(03)00129-1

LED having 5 nm/5 nm- and 5 nm/10 nm-thick Ni/AuBe transparent conductive layers with that having 5 nm/8 nm-thick Ni/Au transparent conductive layers.

2. Experiments

In the study of Ni/AuBe transparent conductive layer, the 2 μm Mg:GaN epitaxial layer were grown on (0 0 0 1)-oriented sapphire substrate with GaN buffer layer by metal-organic chemical vapor deposition (MOCVD) technology. Subsequently, heat treatment were completed at 650 °C during 10 min in nitrogen ambient so as to activate the p-type dopant [1–3]. The p-GaN epitaxial layer was examined by Hall measurement, and the hole concentration and the mobility of p-GaN was 1×10^{17} cm^{-3} and around 8 cm^2/V s, respectively. The bi-layered Ni/AuBe (Au:Be = 99:1) with 50 nm/50 nm, 50 nm/100 nm, 50 nm/150 nm, 50 nm/200 nm, 50 nm/250 nm, respectively were formed on the p-GaN epitaxial layer. Ni and AuBe were deposited by using electron-beam evaporator. Multiple annular patterns with interspacing of 5, 10, 15, 20, 30, and 40 μm were used to measure the ρ_c values by a transmission line model method [15,16] after evaporation, photolithography process, and alloy was carried out at temperature in the range of 400–600 °C during 10 min in nitrogen ambient. Circular patterns with interspacing of 5 μm were used to measure most of the current–voltage (I–V) characteristics.

Next, in the study of GaN-based LED's performance, the 3 μm Si:GaN, five pairs of undoped InGaN/GaN multiple-quantum-well, and 0.5 μm Mg:GaN in this order were grown on (0 0 0 1)-oriented sapphire substrate with GaN buffer layer by MOCVD technology. Subsequently, heat treatment were completed at 650 °C during 10 min in nitrogen ambient so as to activate the p-type dopant. After there, fabrication of LED chips was accomplished. The surface of p-type GaN layer was partially etched until the n-type GaN layer as exposed. Next, Ni/AuBe TCL was evaporated onto the p-type GaN layer, and Ti/Al/Ti/Au (15 nm/50 nm/100 nm/1000 nm) electrode was formed on the Ni/AuBe TCL and the exposed n-type GaN layer at same time, respectively. The cross section of the completed structure was shown in Fig. 1. Subsequently, the LED chip was boned on TO-18 can to measure the current–voltage (I–V) characteristics. The current–voltage (I–V) characteristics were measured in HP4145B semiconductor parameter analyzer. The light-transmission characteristics of Ni/AuBe transparent conductive layer were measured by using Hitachi U3010 spectrum meter. All measurements were performed at room temperature.

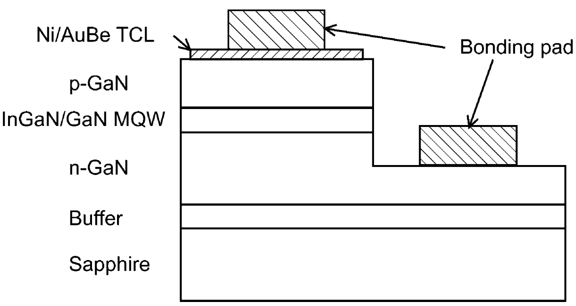

Fig. 1. The cross section of the completed structure of the GaN-based LEDs grown on the sapphire substrate.

3. Results and discussion

Fig. 2(a) and (b) shows the current–voltage (I–V) characteristics of Ni/AuBe having respectively the thickness of 5 nm/5 nm and 5 nm/10 nm deposited on p-GaN layers at alloying temperature ranging from 400 to 700 °C. The diameter and interspacing of pattern for the

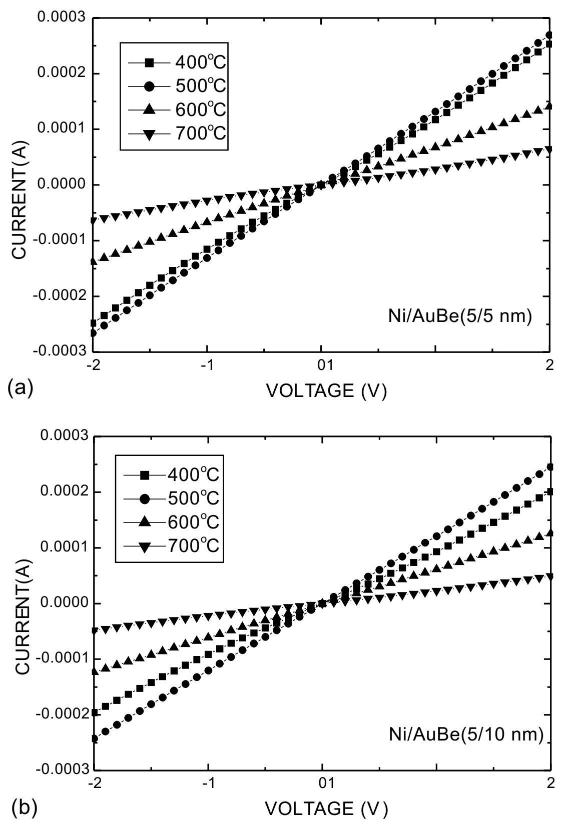

Fig. 2. (a,b) The I–V characteristics of Ni/AuBe having respectively the thickness of 5 nm/5 nm and 5 nm/10 nm deposited on p-GaN layers at alloying temperature ranging form 400 to 700 °C.

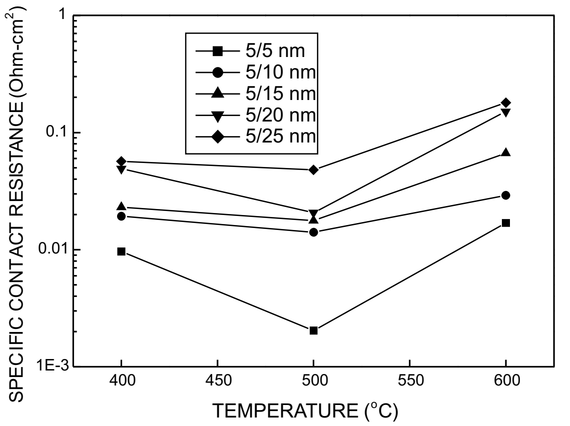

Fig. 3. The specific contact resistance of Ni/AuBe having respectively 50 nm/50 nm, 50 nm/100 nm, 50 nm/150 nm, 50 nm/200 nm, and 50 nm/250 nm deposited on p-GaN at alloying temperature ranging from 400 to 600 °C.

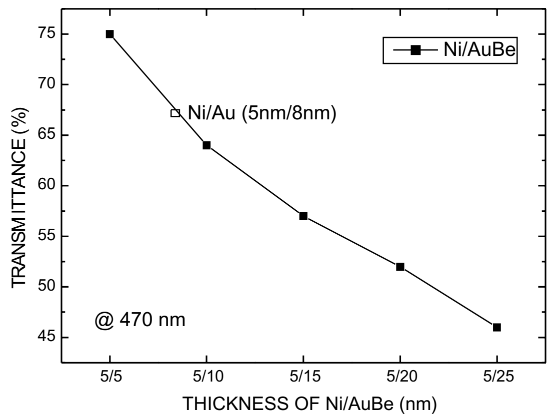

Fig. 4. The measured light-transmission as a function of various thickness of Ni/AuBe bi-layers for 470 nm blue light at 500 °C alloying temperature during 10 min.

I–V characteristics were 5 and 100 μm, respectively. As shown, the 500 °C alloyed sample exhibited the best *I–V* characteristics among all samples. However, when alloying temperature increase up to 600 and 700 °C, a near non-linearity are observed. Besides, the *I–V* characteristics of Ni/AuBe having respectively the thickness of 5 nm/15 nm, 5 nm/20 nm, and 5 nm/25 nm deposited on p-GaN has similar behaviors. Fig. 3 shows the specific contact resistance of Ni/AuBe having respectively 50 nm/50 nm, 50 nm/100 nm, 50 nm/150 nm, 50 nm/200 nm, and 50 nm/250 nm deposited on p-GaN at alloying temperature ranging from 400 to 600 °C. The specific contact resistance decreases from 9.67×10^{-3} to 2×10^{-3} $\Omega\,cm^2$ as temperature increase from 400 to 500 °C in the case of 50 nm/50 nm-thick Ni/AuBe. The lowest specific resistance as low as 2×10^{-3} $\Omega\,cm^2$ can be achieve for 50 nm/50 nm-thick Ni/AuBe alloyed at 500 °C. However, while the alloying temperature increase up to 600 °C, the specific contact resistance increase and the degradation of the contact behaviors can be observed. On the other hand, the specific contact resistance degrade from 2×10^{-3} to 4.8×10^{-2} $\Omega\,cm^2$ when thickness of AuBe increase from 5 to 25 nm in the case of 500 °C alloying temperature.

The improvement of linearity in the *I–V* characteristics of Ni/AuBe in low voltage may be attributed to the atomic diffusion of Be during the process. Because Be atom is quire small, the interdiffusion of Be atoms into the GaN can be expected in the alloying process. Be atom is a p-type dopant for GaN such that the diffusion of Be atoms into GaN may increase the effective hole concentration and thus reduce the specific contact resistance in the metal–semiconductor interface. And the interfacial reactions taking place between Ni, Au, and GaN so that a new microstructure of a mixture of crystalline NiO, Au, and an amorphous is formed [10,13,14]. However, as the alloying temperature increase to 600 °C even up to 700 °C, Be and Ni diffuse deeply into GaN, thereby resulting in the specific contact resistance increase in the metal–semiconductor interface. On the other hand, the thicker AuBe metal layer may be result in Ni atoms harder to react with oxygen to form crystalline NiO. Thus, the alloying temperature is higher than 600 °C or AuBe metal layer is formed more thicker than 10 nm, the specific contact resistance become degradation.

Next, Fig. 4 shows the measured light-transmission as a function of various thickness of Ni/AuBe bi-layers for 470 nm blue light at 500 °C alloying temperature during 10 min. In this study, Ni/AuBe bi-layers were deposited on backside-polished sapphire substrates with p-type GaN film thereon. The backside-polished sapphire substrates with p-type GaN film thereon were used as the reference to calibrate the light-transmission measurements. As shown in Fig. 4, the light-transmission is about 75% for the 5 nm/5 nm-thick Ni/AuBe bi-layer after heat treatment at 500 °C alloying temperature in the case of 470 nm blue light. However, the light-transmission decreases as the thickness of Ni/AuBe bi-layers is increased. In the case of the 5 nm/25 nm-thick Ni/AuBe bi-layer, the light-transmission is had only about 47% in the case of 470 nm blue light. In Fig. 4, square mark presents the light-transmission of the 5 nm/8 nm-thick Ni/Au bi-layer in the same process. Therefore, the ohmic contact behaviors of Ni/AuBe bi-layers are similar to Ni/Au bi-layer from Fig. 4.

Typical *I–V* characteristics of the LEDs in forward bias are shown in Fig. 5. It can be seen that the LEDs with 5 nm/8 nm-thick Ni/Au TCL, and 5 nm/5 nm- and 5 nm/10 nm-thick Ni/AuBe TCLs has forward-bias voltage (at injection current of 20 mA) of about 3.4,

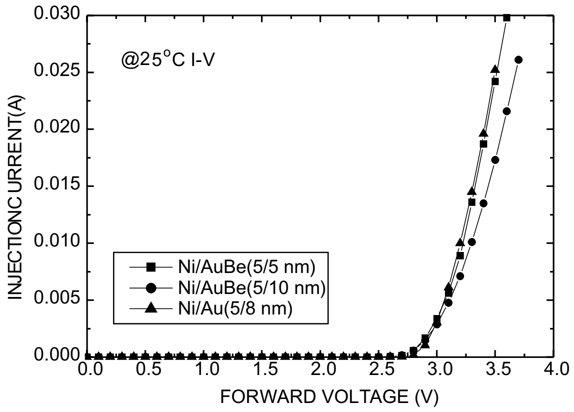

Fig. 5. Typical *I–V* characteristics of the LEDs in forward bias.

3.42, and 3.51 V, respectively. In this case, the LED with 5 nm/8 nm-thick Ni/Au TCL have a lower operating voltage than that of the LED with 5 nm/5 nm-thick Ni/AuBe TCL even less thickness of TCL and poorer light-transmission. Au layer have a function of current spreading laterally. The lateral resistance of Au or AuBe layer decreases when the thickness of Au layer is thicker, but the specific contact resistance of Ni/Au or Ni/AuBe layers with p-GaN increases due to the reactive probability of Ni with oxygen reduces. Accordingly, as above statement, the thickness of TCL is tradeoff to achieve best LED's performance.

4. Conclusion

Ni/AuBe as p-type ohmic contact to p-GaN in the heat treatment process were studied. The optimum construction of Ni/AuBe bi-layers is 5 nm/5 nm-thick. The light-transmission is about 75% for 470 nm blue light. The lowest specific contact resistance as low as $2 \times 10^{-3}\ \Omega\,\mathrm{cm}^2$ were caused by the Be atom diffusion and the crystalline NiO formed at 500 °C during 10 min. The Be atom may plays an important role in the formation of good ohmic contacts in the heat treatment process. On the other hand, Ni/AuBe bi-layers were also applied to LED's process as p-type ohmic contact electrode. The typical *I–V* characteristics of the GaN-based LEDs with 5 nm/5 nm-thick Ni/AuBe TCL exhibit a forward-bias voltage of 3.41 V at injection current of 20 mA.

Acknowledgement

The authors would like to thank Formosa Epitaxy Incorporation for process equipment support.

References

[1] Nakamura S, Mukai T, Senoh M. Appl Phys Lett 1994;64:1687.
[2] Nakamura S, Senoh M, Iwasa N, Nagahama S, Yamada T, Mukai T. Jpn J Appl Phys 1995;34:L1332.
[3] Mukai T, Yamada M, Nakamura S. Jpn J Appl Phys 1999;38:3976.
[4] Nakamura S, Senoh M, Nagahama S, Iwasa N, Yamada T, Matusshita T, et al. Appl Phys Lett 1998;72:2014.
[5] Lee J-S, Kim J-W, Jung D-C, Kim C-S, Lee W-S, Lee J-H, et al. Jpn J Appl Phys 2001;40:L198.
[6] Carrano JC, Li T, Grudowski PA, Eiting CJ, Dupuis RD, Campball JC. J Appl Phys 1998;83:6148.
[7] Li T, Beck AL, Collins C, Dupuis RD, Campbell JC. Appl Phys Lett 1999;75:2421.
[8] Su Y-K, Chiou Y-Z, Juang F-S, Chang S-J, Sheu J-K. Jpn J Appl Phys 2001;40:2996.
[9] Jiang H, Nakata N, Zhao GY, Ishikawa H, Shao CL, Egawa T, et al. Jpn J Appl Phys 2001;40:L505.
[10] Chen L-C, Ho J-K, Chen F-R, Kai J-J, Chang L, Jong C-S, et al. Phys Stat Sol (a) 1999;176:773.
[11] Jang J-S, Chang I-S, Kim H-K, Seong T, Lee YS, Park S. J Appl Phys Lett 1999;74:70.
[12] Suzuki M, Kawakami T, Arai T, Kobayashi S, Koide Y. Appl Phys Lett 1999;74:275.
[13] Ho J-K, Jong C-S, Chiu C-C, Huang C-N, Chen C-Y, Shih K-K. Appl Phys Lett 1999;74:1275.
[14] Sheu J-K, Su Y-K, Chi G-C, Koh P-L, Jou M-J, Chang C-M, et al. Appl Phys Lett 1999;74:2340.
[15] Marlow GS, Das MB. Solid-State Electron 1982;25:91.
[16] King DJ, Zhang L, Ramer JC, Hersee SD, Lester LF. Mater Res Soc Symp Proc 1997;468:421.