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Thermally Stable Ti/Al/W/Au Multilayer Ohmic Contacts on n-Type GaN

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As a multilayer ohmic contact scheme, Ti/Al/W/Au has been deposited on n-GaN, and the effect of the contact on the thermal stability and the ohmic contact resistivity was investigated. The multilayer contact showed high thermal stability for annealing temperatures from 600 °C to 900 °C by not showing an increase in surface roughness or lateral diffusion. Also, the specific contact resistivity decreased with increasing annealing temperature, and a contact resistivity of 6.9×10^{-6} $\Omega\cdot cm^2$ could be obtained by the annealing at 900 °C for 30 seconds. The increase on the thermal stability of the multilayer contact was caused by the high diffusion barrier of tungsten preventing interdiffusion between Al and Au and especially preventing the lateral diffusion of Al.

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I. INTRODUCTION

Group III-nitride semiconductors, especially GaN, are highly attractive materials for optoelectronic devices such as light-emitting diodes (LEDs) and laser diodes (LDs) in blue and ultraviolet wavelength ranges and for high electron mobility transistors (HEMTs) [1–5]. However, the utilization of GaN-based devices is limited by engineering problems, including the difficulty in making low resistive the thermally stable Ohmic contacts to both p-type and n-type GaN.

In general, to form an Ohmic contact to n-GaN, Ti has been used in various Ohmic contact schemes, including Ti [6–8], TiN [8,9], Ti/Al [10–15], Ti/Al/Ni/Au [11,16], Ti/Ni [17], Ti/Ag [18], Ti/TiN [19], Ti/Al/Pt/Au [20], and Ti/Al/Mo/Au [21]. Investigations on these contacts have indicated that the formation of TiN at the interface may be important for Ohmic contact formation due to its low work function and the formation of nitrogen vacancies in the GaN below the contact layer by a reaction of Ti with GaN. The use of Ti/Al instead of Ti decreases the contact resistivity further by forming AlN at the interface in addition to TiN [9,13]. However, the use of Ti/Al can lead to an instability in the GaN devices due to the lateral diffusion of Al and an increase in the surface roughness by Al reflow during the contact annealing process. Diffusion barrier materials, such as Mo and Ni, have been used to decrease the unstability. However, in the case of Mo, Al reflow and an increase of surface roughness was observed due to the lack of wetting between Al and Mo, and in the case of Ni, mixing between Ni and Au was observed when Ti/Al/Ni/Au was used as the multilayer contact scheme [11,16,21]. In this study, as a different diffusion barrier material, W, which has a higher melting point, was used in the multilayer Ohmic contact scheme of Ti/Al/W/Au on n-GaN, and the characteristics of thermal stability and ohmic contact of the multilayer contact were investigated as functions of the annealing temperature.

II. EXPERIMENT

The epitaxial GaN layers were grown by using on (0001) sapphire substrates metal-organic chemical vapor deposition (MOCVD). As the epitaxial GaN layers, undoped GaN buffer layers (100 nm) were grown on sapphire substrates, followed by the growth of Si-doped n-type GaN layers (2 μm). The epitaxial GaN layers had a net n-type carrier concentration of 1.7×10^{-18} cm^{-3}. After the growth of the GaN films, mesa regions for the transmission line method (TLM) measurements were defined by using reactive ion etching (RIE) to etch the n-type GaN layer down to the undoped GaN buffer layer. The linear metallization pattern of the contact pads, which consisted of six square contact pads (area: 100×200 μm^2) separated by designed gap spacings, was defined on the mesa regions by using a photoresist for the TLM measurements. The gap spacings between the contact pads were 5, 10, 20, 40, 80 and 160 μm. Prior to deposition of the multilayer contact metal, the samples were cleaned in a diluted HF solution (HF : H_2O = 1

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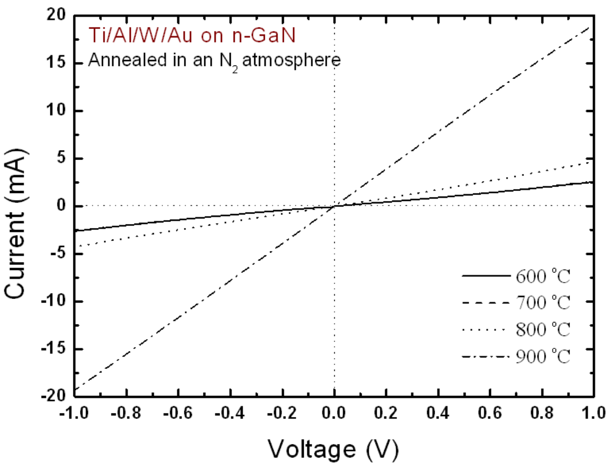

Fig. 1. I-V characteristics of Ti/Al/W/Au contacts on n-GaN measured as a function of annealing temperature from 600 °C to 900 °C for 30 seconds.

: 10) for 1 min to remove the native oxide on the n-type GaN surface. Ti/Al/W/Au (12/60/20/50 nm) was sequentially evaporated using an electron-beam evaporator. The TLM patterns for contact resistivity measurements were formed using a lift-off technique. The annealing of the contact was carried out using rapid thermal annealing (RTA) in a nitrogen environment at temperatures in the range from 600 °C to 900 °C for 30 seconds.

The current-voltage (I-V) characteristics of Ti/Al/W /Au contacts on n-GaN were measured before and after annealing by using a semiconductor parameter analyzer (HP4145A). The diffusion characteristics of the contact multilayer metal layers were investigated using the depth profile of Auger electron spectroscopy (AES, Perkin-Elmer Model660). The surface roughness of the annealed contact metal was measured by using atomic force microscopy (AFM, Auto probe CP-Research), and the lateral diffusion was observed by using scanning electron microscopy (SEM, Hitachi S-4700).

III. RESULTS AND DISCUSSION

Figure 1 shows the I-V characteristics of the annealed Ti/Al/W/Au contacts on n-GaN. The annealing temperature was varied from 600 °C to 900 °C. As the figure shown, all of the contacts showed Ohmic characteristics after annealing. An increase in the annealing temperature decreased the contact resistance, and the lowest specific contact resistivity calculated using the TLM patterns was 6.9×10^{-6} $\Omega\cdot$cm^2 for annealing at 900 °C. The decrease in the contact resistance with increasing annealing temperature is believed to be from an increase in thermal interdiffusion at the interface between the deposited metals and GaN.

Figure 2 shows the AES depth profile of the annealed contacts at temperatures from 600 °C to 900 °C. As Figure 2(a) shown, when the annealing temperature is 600 °C, no significant diffusion of nitrogen from GaN to Ti is observed; however, as the annealing temperature is increased to 900 °C, more significant diffusion of nitrogen to Ti and Al is observed in addition to the diffusion of Ti and Al to GaN. The diffusion of nitrogen to Ti and Al forms nitride compounds, such as TiN and AlN, at the interface, and the decrease in the contact resistivity with increasing annealing temperature is believed to be related to the formation of nitrogen vacancies at the GaN interface. The nitrogen vacancies in GaN are known to act as donors and to increase the electrical conductivity of n-GaN, which results in a decrease in the contact resistivity [21]. One interesting phenomenon shown in Figure 2 is the AES depth profile of tungsten. The increase in the annealing temperature did not change the AES depth profile of tungsten located between Al and Au, indicating no significant diffusion, while other metals diffused significantly to adjacent area with increasing of annealing temperature. Therefore, the tungsten layer acted as a diffusion barrier between Al and Au and prevented the outdiffusion of Al and the indiffusion of Au. These diffusion behaviors lead to a degradation of the contact property due to both the formation of Al-oxide over the contact metal layers and poor wetting of Au to GaN.

The thermal expansion coefficient of tungsten (4.5×10^{-6} K^{-1} at 0 $\sim$ 100 °C) is much lower than those of Al and Au (23.5 and 14.1×10^{-6} K^{-1} at 0 $\sim$ 100 °C, respectively); therefore, a higher thermal stability of the contact could be obtained by using tungsten in the multilayer contact scheme. Figure 3 shows the RMS surface roughness of the contact measured as a function of the annealing temperature by using AFM. As the figure shown, annealing at temperatures up to 900 °C for 30 seconds did not change the surface roughness, and the surface roughness remained in the range from 5 to 7 nm. If a good Ohmic contact to n-GaN is to be obtained, high temperature annealing is required for a solid state reaction, and, in general, an increase in the annealing temperature increases the surface roughness, especially when Al is used in the multilayer contact metal scheme. The use of Ti/Al decreases the contact resistivity significantly; however, due to the low melting point of Al, the surface roughness is increased by annealing. However, if a good contact pattern definition in addition to reproducibility and uniformity of the contact resistivity is to be guaranteed, the contact surface morphology must be smooth. In the case of a multilayer metal scheme such as Ti/Al/Mo/Au, the annealing at 850 °C for 30 seconds increased the surface roughness from 1 nm to 17 nm [19]. Even though the use of Mo in the multilayer contact scheme showed a good thermal property by preventing the reflow of Al, the use of tungsten used in our experiment showed a better thermal property by having a lower surface roughness at the higher annealing temperature.

The use of Al in the multilayer contact metal scheme

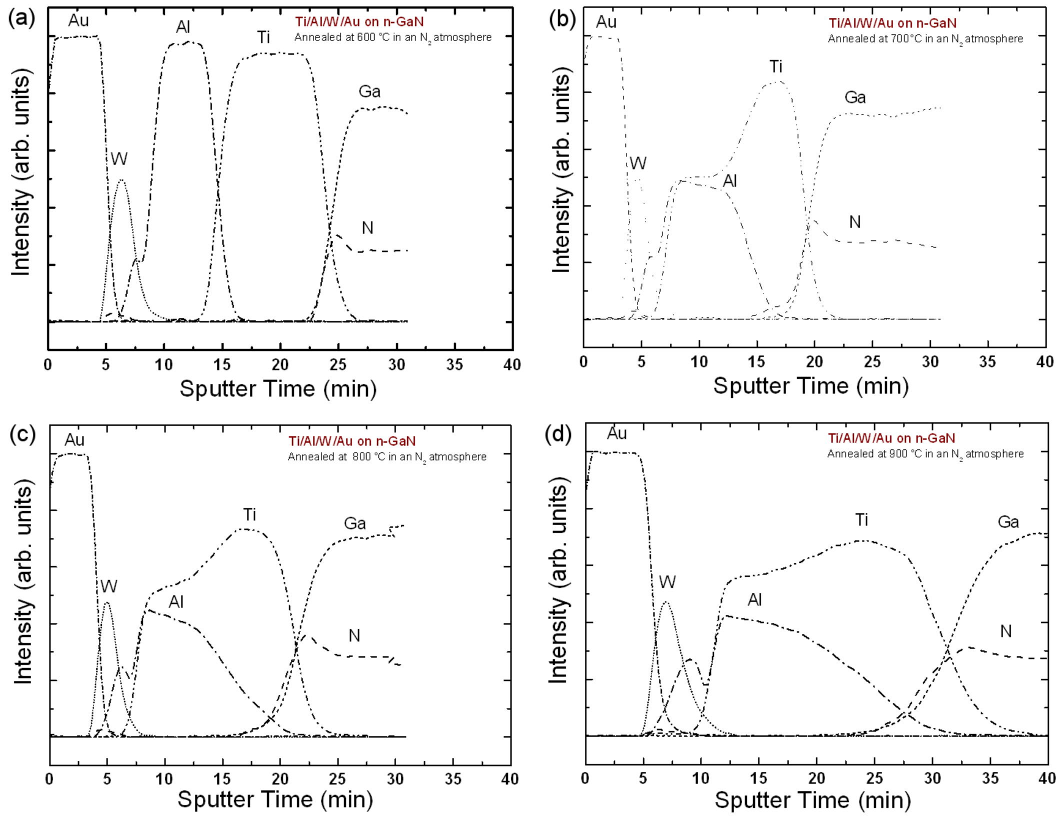

Fig. 2. AES depth profiles of the Ti/Al/W/Au(12/60/20/50 nm) contact on n-GaN annealed at (a) 600 °C, (b) 700 °C, (c) 800 °C and (d) 900 °C.

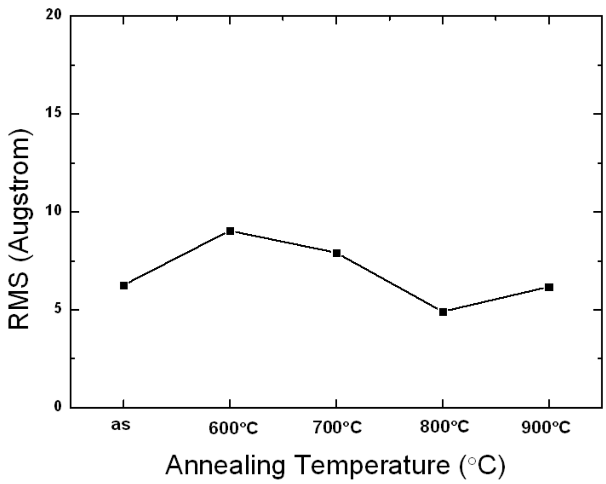

Fig. 3. RMS surface roughness of the contact measured as a function of the annealing temperature by using AFM.

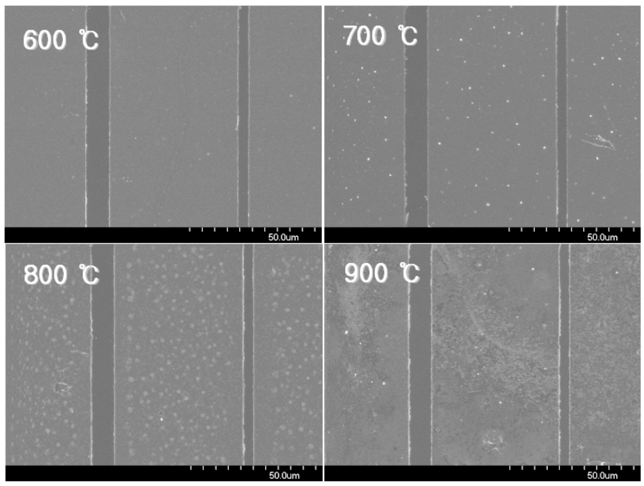

Fig. 4. Top view of TLM patterns of the annealed Ti/Al/W/Au contact observed using SEM after annealing at temperatures from 600 to 900 °C. The two narrow vertical lines in the SEM micrographs are the GaN surface between the contact metals.

can present an additional problem, such as lateral diffusion during the annealing due to the low melting point. Especially, when Ti/Al is used as the multilayer gate electrode of a HEMT device, the lateral diffusion of Al occurring during the annealing can short the device or decrease the performance of the device significantly. Figure 4 shows top views of the TLM patterns observed using SEM after annealing at temperatures from 600 to 900 °C. In the micrographs, the narrow vertical lines are the GaN surface between the contact metals. As the micrographs shown, no lateral diffusion of Al could be observed, even after annealing at 900 °C. Therefore, Ti/Al/W/Au as the multilayer contact metal scheme showed a very stable thermal property in addition to low contact resistivity due to the thermal stability of tungsten compared to other metals. Due to the high temperature stability, we believe that this metal scheme can be successfully applied to various GaN devices, such as the optical devices requiring high-temperature processes and HEMT devices.

IV. CONCLUSION

In this study, multilayer metal composed of Ti/Al/W/Au (12/60/20/50 nm) was used as the contact metal to n-GaN, and the effects of the multilayer contact metal on the contact resistivity and the thermal stability were investigated for annealing at temperatures from 600 °C to 900 °C for 30 seconds. The contact resistivity decreased with increasing annealing temperature, and contact resistivity of 6.9×10^{-6} Ω·cm^2 could be obtained by annealing at 900 °C for 30 seconds. Also, annealing a temperature up to 900 °C for 30 seconds did not change the surface roughness of the contact, and no lateral diffusion of Al could be observed by using SEM. The low contact resistivity and the high thermal stability of the multilayer metal composed of Ti/Al/W/Au (12/60/20/50 nm) are believed to be related to the high thermal stability of tungsten located between the Al and the Au. By preventing Al outdiffision through the tungsten layer, the formation of Al_2O_3 was prevented and, due to high the thermal stability of the tungsten, no increase in the surface roughness or in the lateral diffusion caused by the low melting point Al layer could be observed, even after annealing at 900 °C.

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