Electrical properties and reliabilities of Pt, PtAu, NiAu, and TaTi Ohmic contact materials for *p*-GaN

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GaN-based III-nitride materials have been successfully used in fabrication of blue and ultraviolet light emitting devices and high-power microwave devices. Thermally stable, low resistance Ohmic contacts are essential for improving further the electrical and optical properties of these devices. Since the reliability of blue laser diodes (LDs) has not yet satisfied the engineers' requirement, development of reliable Ohmic contacts with specific contact resistance (ρ_c) lower than 10^{-4} Ω-cm^2 for *p*-GaN is crucial to manufacture the blue LDs.

Extensive efforts have been carried out to prepare such the Ohmic contacts for p-GaN for more than 10 years. However, within our knowledge, a reproducible fabrication process of p-type Ohmic contacts usable in the manufacturing LDs is not yet established. Our group has also challenged to prepare such the reliable low resistance Ohmic contacts for *p*-GaN.[1] Ishikawa *et al*.[2] found that surface cleaning of the GaN epilayer prior to metal deposition was an important process for preparation of such Ohmic contacts, and various methods to remove a contamination layer native on the GaN surface were developed. The best method to provide low contact resistance was to remove the contamination layer by depositing Ni or Ta (which reactes with oxide contamination) directly on the GaN and annealing them at temperature of 500 °C. Further reduction of the contact resistance was made by annealing the contact metals at 500 ~ 600 °C in a N_2 and O_2 mixed gas ambient.[3] The contact resistances of Au-based contacts (Co/Au, Ni/Au, Pt/Au, Pd/Au, and Cu/Au, where a slash "/" between the metals indicates the deposition sequence) were reduced by a factor of ~3 by annealing in a partial O_2 ambient compared with those prepared in N_2 annealing.[3] The reason was believed to be due to formation of an intermediate semiconductor layer (ISL) with high hole concentrations, induced by removing hydrogen atoms which bonded with Mg or N atoms in the *p*-GaN epilayer. After annealing the Ni/Au contacts in the partial O_2 ambient, a NiO was formed at the top surface.[3] Maeda *et al*.[4] investigated the effects of the NiO layers on the electrical properties of the Ni/Au-based Ohmic contacts for *p*-GaN and found that the NiO layer which was formed between Au and GaN did not reduce the barrier height at the interface. They concluded that reduction of the ρ_c value after annealing in the O_2 ambient was due to formation of the ISL with high hole concentration.

Suzuki *et al.*[5] produced the ρ_c values as low as 3×10^{-5} Ω-cm^2 after annealing Ta/Ti Ohmic contacts at 800 °C. The formation mechanism of this contact was believed to be due to enhancement of out-diffusion of hydrogen from the GaN to the contact metals, which increased the hole concentration in the *p*-GaN epilayer.[6] The hydrogen out-diffusion model explained nicely the electrical properties of the Ta/Ti Ohmic contacts for *p*-GaN, but not explained a reason why the ρ_c value of the binary Ta/Ti contact was smaller than that of a single element Ta or Ti contact. Another possible formation mechanism for the low resistance Ta/Ti Ohmic contact was reduction of the Schottky barrier height (SBH) value between the *p*-GaN and Ta/Ti by annealing at elevated temperatures. However, Kawakami *et al.*[7] measured the SBH values of Ta/Ti and Ta_xN contacts to *p*-GaN and concluded that the SBH of the Ta/Ti contact did not change before and after annealing. Thus, we believe that reduction of the contact resistances of the Ta/Ti contact was due to increase of the hole concentrations in the *p*-GaN epilayer induced by out-diffusion of hydrogen from the GaN. From our previous studies, the Ta/Ti contacts provided reproducibly the ρ_c values lower than those of the Pt and Ni/Au contacts prepared by annealing in the O_2 ambient. However, the ρ_c values of the Ta/Ti Ohmic contacts increased during room temperature storage and upon injecting current,[7] which is in our serious concern for application of these contacts to the blue LDs.

The purpose of this paper was to select the most reliable Ohmic contact metals among the Pt, Pt/Au, Ni/Au, and Ta/Ti contacts (which were developed in our laboratories) for *p*-GaN. We investigated stabilities of the electrical and microstructural properties during storage at room temperature and upon injecting high current which are required for the commercial GaN-based blue LDs.

Undoped (0001)-oriented GaN and Mg doped *p*-type GaN epilayers were successively grown by metal-organic vapor phase epitaxy on the (11-20)-oriented α-Al_2O_3 substrates using a thin AlN buffer layer. The hole concentrations of the *p*-GaN layers were in the range of 6 ~ 7×10^{17} cm^{-3}. The circular and annular electrode patterns were prepared on the *p*-GaN epilayers by the conventional photolithographic technique. Ta, Ti, Ni, and Pt were deposited in an electron beam evaporator and Au was deposited with a resistance heater in the same chamber. After lifting-off the photoresists, annealing was carried out for the Ta/Ti contacts at temperatures ranging from 500 to 800 °C for 5 to 20 min in vacuum lower than 4.0×10^{-4} Pa. For the Pt, Pt/Au, and Ni/Au contacts, annealing was carried out at temperatures ranging from 300 to 600 °C in O_2 and N_2 mixed gas ambient, where the O_2 concentration was controlled in the range between 0 and 100 %. The electrical properties of these contacts before and after annealing were evaluated using a current-voltage (I-V) method and transmission line method (TLM) at room temperature. Stabilities of these contacts during room temperature storage and upon injecting the electric current were investigated by analyzing changes of the electrical properties. Surface morphology was observed by an optical microscope and a scanning electron microscope (SEM).

Table I summarizes the stabilities of Ohmic contact properties of the Pt(O_2), Pt/Au(O_2), Ni/Au(O_2), Ni/Au(N_2), and Ta/Ti contacts, where Pt(O_2), Pt/Au(O_2), and Ni/Au(O_2) denote the Pt, Pt/Au, and Ni/Au contacts annealed in the partial O_2 ambient, and Ni/Au(N_2) denotes the Ni/Au contacts annealed in the N_2 ambient. All contacts are compared with an "ideal" contact by marking each property by a "+" or "−" sign in Table I, where the "+" sign indicates the satisfied property and the "−" sign indicates the unsatisfied property. The Ta/Ti contact has the ρ_c value lower than 10^{-4} Ω-cm^2 [Refs. 5 and 6]. However, the ρ_c values of the Pt(O_2), Pt/Au(O_2), and Ni/Au(O_2) contacts are mid-10^{-3} Ω-cm^2 which do not satisfy the requirements for the blue LDs. The Pt(O_2), Pt/Au(O_2), Ni/Au(O_2), and Ni/Au(N_2) Ohmic contacts showed no deterioration during storage at room temperature and current injection, which was required for the blue LDs. However, both the electrical properties and the surface morphology of the low-resistance Ta/Ti contact deteriorated, which was in our serious concern to use this contact material in the manufacturing LDs. In addition, the Pt(O_2) and Pt/Au(O_2) contacts have strong adhesion with GaN, but the Ni/Au(O_2) contact had poor adhesion. Judging from the results listed in the Table I, the Pt(O_2) and Pt/Au(O_2) contacts were believed to be the best Ohmic contact materials for *p*-GaN among these four contacts. Unfortunately, the ρ_c values of the Pt(O_2) and Pt/Au(O_2) contacts were higher than the target value of 10^{-4} Ω-cm^2.

There are two approaches for development of the reliable, low-resistance Ohmic contact materials for *p*-GaN. One is to develop a *p*-type doping technique which generates high hole concentration during epitaxial growth of the *p*-GaN epilayers or by diffusion from the contact metals in order to reduce the ρ_c values of the Pt(O_2) and Pt/Au(O_2) contacts. If the hole concentration was higher than around 3×10^{18} cm^{-3} in the *p*-GaN epilayer, the ρ_c value lower than 10^{-4} Ω-cm^2 would be achieved.[3, 7] This target value of the hole concentration is believed to be the realistic value which is 4~5 times greater than the typical hole concentration obtained by doping with Mg. Another approach is to understand the deterioration mechanism of the contact resistance for the Ta/Ti contact during room temperature storage and current injection in order to search a method to improve the stability of this contact. The efforts to obtain the high-p^+-GaN epilayer and to understand the deterioration mechanism should be continued.

References

1 M. Murakami and Y. Koide, Crit. Rev. Solid State Mater. Sci. **23**, 1 (1998).
2 H. Ishikawa, S. Kobayashi, Y. Koide, S. Yamasaki, S. Nagai, J. Umezaki, M. Koike, and M. Murakami, J. Appl. Phys. **81**, 1315 (1997).
3 Y. Koide, T. Maeda, T. Kawakami, S. Fujita, T. Uemura, N. Shibata, and M. Murakami, J. Electron. Mater. **28**, 341 (1999).
4 T. Maeda, Y. Koide, and M. Murakami, Appl. Phys. Lett. **75**, 4145 (1999).
5 M.Suzuki, T. Kawakami, T. Arai, S. Kobayashi, Y. Koide, T. Uemura, N. Shibata, and M. Murakami, Appl. Phys. Lett. **74**, 275 (1999).
6 M. Suzuki, T. Arai, T. Kawakami, S. Kobayashi, S. Fujita, and Y. Koide, Y. Taga, and M. Murakami, J. Appl. Phys. **86,** 5079 (1999).
7 T. Kawakami, Y. Koide, and M. Murakami, J. Appl. Phys. to be submitted.

Table I. Comparison of electrical and microstructural properties among various Ohmic contacts for p-GaN

		Ideal	Pt(O_2) and Pt/Au(O_2)	Ni/Au(O_2)	Ni/Au(N_2)	Ta/Ti
Formation	ρ_c	$< 10^{-4}$ Ω-cm^2	−	−	−	+
	Adhesion	strong	+	−	−	+
Deterioration	Storage	no	+	+	+	−
	Current-induced	no	+	+	+	−
	Failure	no	+	+	+	−