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Formation of ohmic contacts to *n*-Al$_x$Ga$_{1-x}$N:Si layers with a high aluminum content

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Abstract. The paper describes the results of optimizing rapid thermal annealing (RTA) of ohmic contacts to AlGaN:Si layers with a high aluminum content (70 mol%) and various electron concentration. The contact characteristics were measured using the transmission line method (TLM). It has been found that for highly doped Al$_{0.7}$Ga$_{0.3}$N:Si layers ($>10^{18}$cm^{-3}), the RTA annealing of Ti(25nm)/Al(80nm)/Ti/Au contact at a temperature 900 °C for 60 s makes it possible to obtain the minimum contact resistance of 8 Ω×mm and specific contact resistivity of 9×10^{-4} Ω·cm^2 with high uniformity over the surface of a 2-inch substrate. For lightly doped Al$_{0.7}$Ga$_{0.3}$N:Si layers ($<10^{17}$ cm^{-3}), almost the same contact characteristics can be achieved at a higher RTA temperature of about 1000C and an increase in the thickness of the Al contact layer to 250 nm.

Keywords: AlGaN solid alloys, contact resistance, transmission line method, rapid thermal annealing, ohmic contacts

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Формирование омических контактов к слоям *n*-Al$_x$Ga$_{1-x}$N:Si с высоким содержанием алюминия

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Аннотация. Статья описывает результаты оптимизации быстрого термического отжига (RTA) омических контактов к слоям AlGaN:Si с высоким содержанием алюминия (70 мол.%) и различной концентрацией электронов. Контактные характеристики были измерены с использованием метода TLM. Установлено, что для сильнолегированных слоев Al$_{0.7}$Ga$_{0.3}$N:Si ($>10^{18}$см$^{-3}$) отжиг контакта Ti(25нм)/Al(80нм)/Ti/Au при температуре 900 °С в течение 60 с позволяет получить минимальное контактное сопротивление 8 Ом×мм и удельное контактное сопротивление 9×10^{-4} Ом·см^2 при высокой однородности по поверхности 2-дюймовой подложки. Для слаболегированных слоев Al$_{0.7}$Ga$_{0.3}$N:Si ($<10^{17}$ см$^{-3}$) практически такие же контактные характеристики могут быть достигнуты при более высокой температуре RTA-отжига (~1000 °C) и увеличении толщины контактного слоя Al до 250 нм.

Ключевые слова: твердые растворы AlGaN, контактное сопротивление, TLM-метод, быстрое термическое вжигание контактов, омический контакт

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Introduction

Photodetectors operating in the solar-blind ultraviolet (UV) wavelength range of less than 290 nm, are typically based on diode structures containing Al$_x$Ga$_{1-x}$N layers with a high content of Al ($x \geq 0.5$) [1, 2]. Due to the difficulty of *p*-type doping such layers in *p-i-n* photodiodes, Schottky photodiodes with only *n*-type AlGaN:Si layers are an attractive alternative [3]. However, the performance of these devices deteriorates greatly with an increase in both the resistivity of bulk layers and the resistivity of ohmic contacts to them. In AlGaN alloys with $x \geq 0.6$, the former effect is due to an increase in the donor activation energy and enhanced generation of compensating defects in the layer [4–5]. Titanium and aluminum with low work functions (~4.3 eV) are commonly used to make ohmic contacts to III-N compounds. The difficulties in obtaining low contact resistance with increasing Al content in the AlGaN:Si layers are associated with a decrease in their electron affinity to values much lower than the work function of titanium contact layer. This leads to the formation of a potential barrier for electrons, which determines the non-ohmic behavior of the standard multi-layer contact Ti/Al/Au/Ti. Only rapid thermal annealing (RTA) of this metal stack at temperatures above 700 °C allows to achieve low-resistive ohmic contacts even for Al$_x$Ga$_{1-x}$N layers with $x > 0.6$. This occurs due to reaction of Ti with nitrogen in the AlGaN layers, resulting in a formation of Ti-N and Ti-Al-N layers, which increases the electron concentration at the interface [5–7]. However, both titanium and aluminum are highly reactive and tend to oxidize even at room temperature. To solve this problem, a thin layer of Au is usually used to prevent oxidation [5]. To prevent the Au diffusion and the formation of the Al$_2$Au, a barrier layer is added, which is most often one of these metals: Ti, Ni, Mo, or Pt. [5, 8].

Studies of the above processes have shown that the contact resistance most significantly depends on the Ti/Al thickness ratio and its optimal value for GaN layers and AlGaN layers with a low Al-content is ~1/2.5 [8]. Since there is no general theory of contact to ternary AlGaN, especially for layers with a high Al-content ($x > 0.6$), there is an urgent need for experimental studies of contact resistance in this material.

This paper describes the formation of ohmic contacts to Al$_{0.7}$Ga$_{0.3}$N:Si layers with different electron concentration using the standard metallization Ti/Al/Ti/Au with different Al thickness and parameters of rapid thermal annealing (RTA) varied to minimize the contact resistance.

Materials and Methods

Si-doped Al$_{0.7}$Ga$_{0.3}$N layers with a thickness of about 600 nm were grown by plasma-assisted molecular beam epitaxy on AlN/c-Al$_2$O$_3$ templates with a threading dislocation density of less than $5 \cdot 10^9$ cm^{-2}, as described in [9]. The layers were grown at metal-rich conditions with periodic growth interruptions to achieve an atomically smooth droplet-free surface of AlGaN layers [10]. The temperatures 1240 and 1290 °C of a solid-state Si effusion cell were used to change the electron concentration in the layers.

Mesa-structures for measuring contact resistance by Transmission Line Method (TLM) were fabricated using contact photolithography and reactive ion-plasma etching in an inductively coupled plasma reactor with a high concentration of reactive ions and BCl_3 radicals. The structures were metallized using explosive (reverse) photolithography. Metal stacks Ti(25 nm)/Al(80–250 nm)/Ti(60 nm)/Au(100 nm) were deposited by a vacuum thermoresistive sputtering setup. The deposited metal stacks were annealed using STE RTA 100 setup with the annealing temperature varied within 700–1000 °C and the duration 30–180 s. The electron concentrations (n) in the AlGaN:Si layers were determined from CV measurements. For measurements of the resistances by TLM, a Keysight B2901A was used. Fig. 1, *a*) shows identical rectangular pads with the same length d = 100 μm, width W = 300 μm, and different distances between the contact pads L_i = 100, 80, 40 and 20 μm.

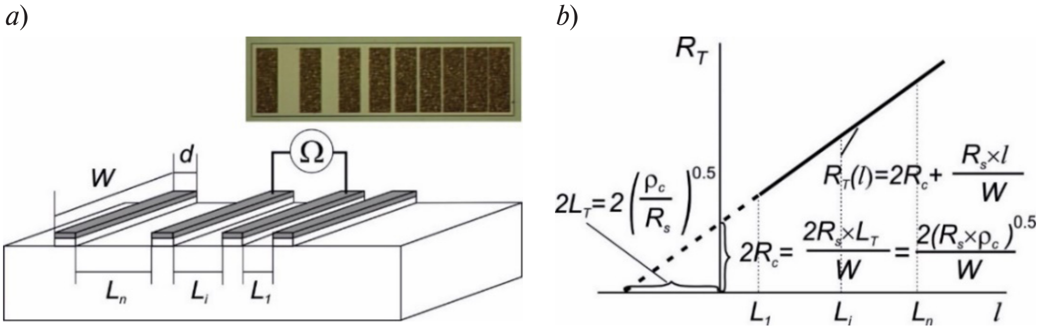

Fig. 1. Schematic illustration of TLM and optical microscope image of the contact pads used in this method (*a*); the dependence of the measured resistances on the distance between the pads (*b*)

Fig. 1, *b* shows the measured total resistance as a function of inter-contact distance $R_T\left(\ell\right) = 2R_C + \frac{R_S\ell}{W}$, where $R_C = \frac{R_S L_T}{W}$ is the measured contact resistance, R_S is the sheet resistance of the AlGaN layer, and L_T is the so-called "transfer length" measured from the intersections of interpolation line of $R_T(\ell)$ with abscissa axis [11]. The assumptions of a uniform distribution of R_S over the measurement area and the validity of the inequalities $2L_T < d$, $W >> d$ enabled the relationship for the specific contact resistance $\rho_c = R_S \cdot L_T^2$ Ohm·cm^2 to be invoked. The value $r_c = R_C W$ Ohm·mm was also used to characterize the contact resistance.

Result and discussion

The $Al_{0.7}Ga_{0.3}N$:Si layers grown at the highest temperature of Si-cell of 1290 °C demonstrated electron concentrations above 10^{18} cm^{-3}. Initially, we studied the layers with the contacts having a standard Ti/Al thickness ratio of 1/2.5. The unannealed layers did not demonstrate ohmic contact characteristics. Fig. 2, *a*, *b* show the dependences of r_c and ρ_c of these layers on the RTA temperatures and duration, respectively, which indicate an appearance of ohmic contact at T_{an} above 700 °C and a minimum specific contact resistivity below 10^{-3} Ohm·cm^2 in the layers annealed at a temperature of 900 °C for 60 seconds. A further increase in the temperature did not lead to a significant decrease in the contact resistance, but the surface morphology of the contact pads deteriorated (see Fig. 2, *c*). The optimal RTA duration of 60 s was chosen due to enormous inhomogeneity of the contact resistance over the sample surface at shorter durations of RTA and its increase at longer durations, as shown in Fig. 2, *d*).

In addition, we compared the obtained results with the contact characteristics for the GaN:Si layer with $n > 10^{18}$ cm^3 and the same contacts annealed at the optimal RTA regimes (t_{an} = 60 sec and T_{RTA} = 900 °C). The binary layers showed significantly lower values of r_c = 0.1 Ohm×mm and $\rho_c = 5\cdot10^{-6}$ Ohm·cm^2.

These results are consistent with the general view on the formation of ohmic contacts in AlGaN layers with a high aluminum content, where this process is hindered by lower electron affinity of ternary alloys compared to work function of titanium, while this problem is completely absent in binary GaN. Moreover, the appearance of an ohmic contact, according to the literature data [4,5], is associated with the diffusion of nitrogen atoms from AlGaN into Ti layer. The contact

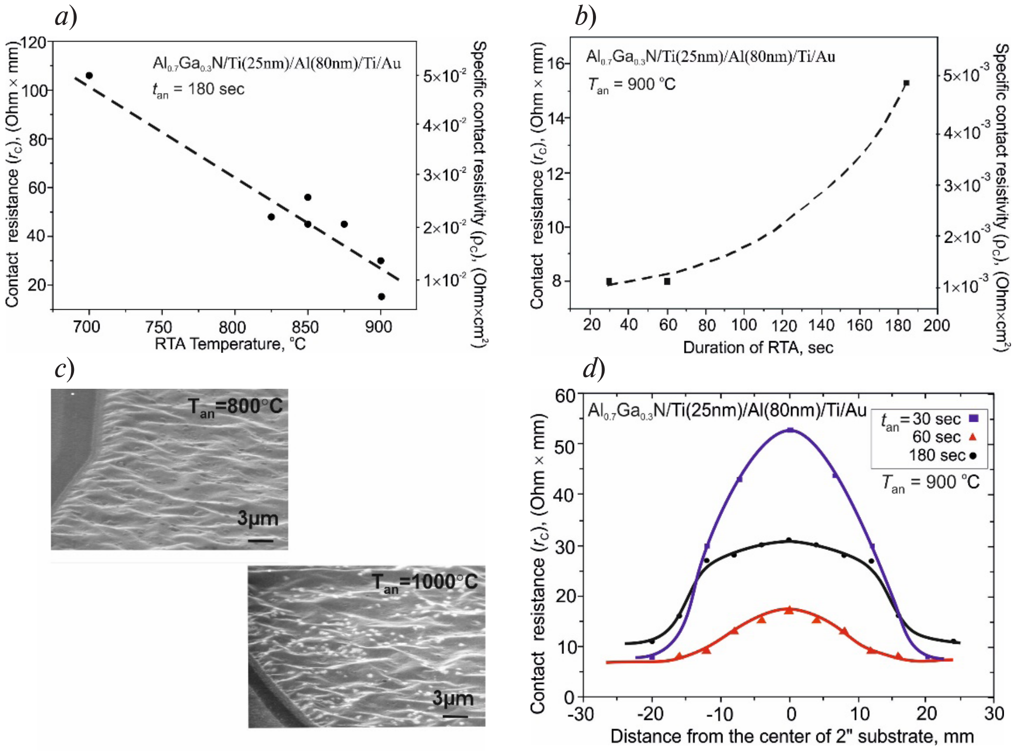

Fig. 2. Dependences of the contact resistance (r_c, Ohm·mm) and specific contact resistivity (ρ_c, Ohm·cm^2) on RTA temperature (*a*) and duration of RTA at 900 °C (*b*). SEM images of the contact surface (*c*). Distributions of contact resistances over the areas of the two-inch substrates (*d*). The dots are the experimental results, the lines are the approximations

improvement is associated with the appearance of nitrogen vacancies near the metal interface. These vacancies create donor states, pinning the Fermi level and thus creating a tunnel junction, which reduces the contact resistance. The described diffusion is able due to the higher enthalpy of formation of TiN compared to GaN (−265.5 and −110.9 kJ/mol, respectively), but it must be considered that the higher enthalpy of formation of AlN (−318.8 kJ/mol) restricts the extraction of N from AlGaN layers compared to GaN ones. These values explain the fact that even under optimal conditions for RTA of the Ti/Al/Ti/Au contact stacks, the difference between contact resistances of the $Al_{0.7}Ga_{0.3}N$:Si and GaN:Si layers exceeds three orders, and further process optimization is required.

Next, we investigated $Al_{0.7}Ga_{0.3}N$:Si layers doped using a low Si-cell temperature of 1240 °C, which resulted in an electron concentration lower than 10^{17} cm^{-3}. Figure 3, *a* shows the strong dependences of r_c and ρ_c on the Al thickness in the Ti(25 nm)/Al/Ti/Au contact stacks deposited on these layers. They demonstrate a decrease in contact resistance by more than 5 times with an increase in Al thickness from the standard value of 80 nm to 240 nm with Ti/Al thickness ratios of 2.5 and 10, respectively.

On the other hand, too strong interaction of Ti with AlGaN at high T_{an} can result in local transformation of the AlGaN ternary alloy into the highly defected Al + Ti + N phase, increasing the contact resistance. Therefore, a way must be found to decrease the high reactivity of Ti, and its reaction with the upper Al in the metallization stack can play this role. Indeed, Al in metallization schemes can alloy with Ti layer below, leading to reducing its reactivity. This mechanism explains the influence Al thickness on contact resistance in $Al_{0.7}Ga_{0.3}N$:Si/Ti/Al/Ti/Au contacts with a relatively low electron concentration below 10^{17} cm^{-3}.

The proposed model is confirmed by comparative measurements of the temperature dependences of the contact resistances of heavily (> 10^{18} cm^{-3}) and lightly (< 10^{17} cm^{-3}) Si-doped $Al_{0.7}Ga_{0.3}N$ layers with the same Ti(20 nm)/Al(250 nm)/Ti/Au contacts. Fig. 3, *b*) shows that only the latter layer shows a clear temperature dependence in the T_{an} = 900–1000 °C range, while its counterpart doesn't reveal such dependence.

It should be noted that $Al_xGa_{1-x}N$:Si layers with $x > 0.7$ used in sub-250 nm UVC- LED and

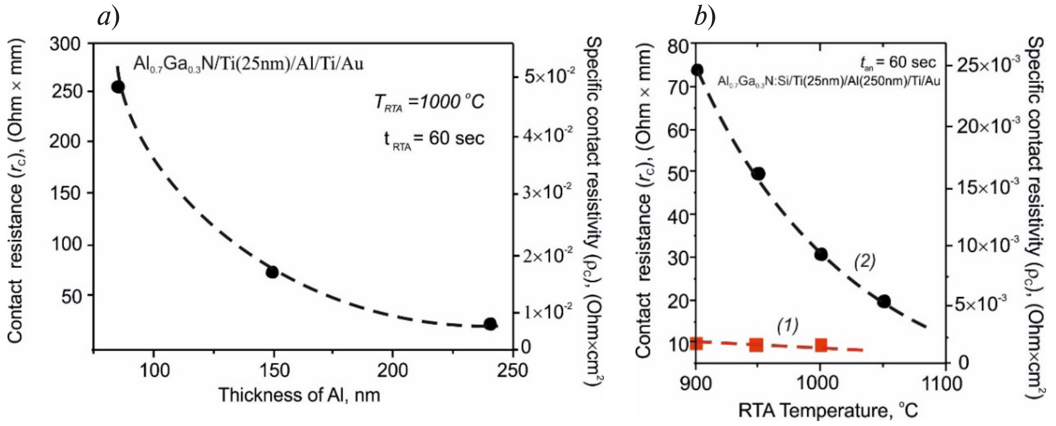

Fig. 3. Dependence of contact and specific resistance on the thickness of the aluminum (*a*). Dependence of $Al_{0.7}Ga_{0.3}N$ contact and specific resistance on the RTA temperature for: *1* – $n > 10^{18}$ cm^{-3}; *2* – $n < 10^{17}$ cm^{-3} (*b*)

photodetectors usually have an electron concentration below 10^{17} cm^{-3} due to high activation energy of Si-dopant in such layers. Therefore, the results obtained in this work for lightly doped AlGaN layers will be useful for designing of these devices.

Conclusion

The technologies of the forming Ti/Al/Ti/Au ohmic contacts to $Al_{0.7}Ga_{0.3}N$:Si layers with electron concentration from below 10^{17} cm^{-3} to higher than 10^{18} cm^{-3} have been optimized. The best results were obtained for Ti(25 nm)/Al(80 nm)/Ti/Au contacts annealed by RTA at a temperature of 900 °C for 60 sec. These conditions provided minimum values of a contact resistance of 8 Ohm·mm and a specific contact resistivity of 9×10^{-4} Ohm·cm^2 with a reasonable uniformity over a 2-inch substrate. It has been established that increasing the RTA temperature up to 1000 °C and Al thickness in metallization stack up to 250 nm improve contact characteristics in lightly doped $Al_{0.7}Ga_{0.3}N$:Si layers.

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REFERENCES

1. **Razeghi M.,** Short-wavelength solar-blind detectors-status, prospects, and markets Proceedings of the IEEE, 90 (2002), 1006–1014.

2. **Rehm R., Driad R., Kirste L., Leone S., Passow T., Rutz F., Watschke L., Zibold A.,** Toward AlGaN Focal Plane Arrays for Solar Blind Ultraviolet Detection Phys. Status Solidi A, 1900769 (2019) 1–6.

3. **Tut T., Biyikli N., Kimukin I., Kartaloglu T., Aytur O., Unlu M.S., Ozbay E.,** High bandwidth-efficiency solar-blind AlGaN Schottky photodiodes with low dark current Solid-State Electronics, 49 (2005) 117–122.

4. **Liang Y.-H., Towe E.,** Progress in efficient doping of high aluminum-containing group III-nitrides. Appl. Phys. Rev. 5 (2018) 011107.

5. **Van Daelea, Van Tendeloo G., Ruythooren W., Derluyn J., Leys M.R., Germain M.,** The role of Al on Ohmic contact formation on n-type GaN and AlGaN/GaN Appl. Phys. Lett 87 (2005) 061905.

6. **Iucolano F., Greco G., Roccaforte F.,** Correlation between microstructure and temperature dependent electrical behavior of annealed Ti/Al/Ni/Au Ohmic contacts to AlGaN/GaN heterostructures. Appl. Phys. Lett. 103 (2013) 201604.

7. **Nebauer E., Osterle W., Hilsenbeck J., Wurfl J., Klein A.,** XTEM and TFXRD investigations of ohmic Ti/Al/Ti/Au/WSiN contacts on AlGaN/GaN HFET layer systems. Semicond. Sci. and Technol. 17 (2002) 249–254.

8. **Motayed A., Bathe R., Wood M.C., Diouf O.S., Vispute R.D., Mohammad S.N.,** Electrical, thermal, and microstructural characteristics of Ti/Al/Ti/Au multilayer Ohmic contacts to *n*-type GaN. J. Appl. Phys. 93 (2003) 1087–1094.

9. **Nechaev D.V., Koshelev O.A., Ratnikov V.V., Brunkov P.N., Myasoedov A.V., Sitnikova A.A., Ivanov S.V., Jmerik V.N.,** Effect of stoichiometric conditions and growth mode on threading dislocations filtering in AlN/*c*-Al_2O_3 templates grown by PA MBE. Superlattices and Microstructures 138 (2020) 106368.

10. **Nechaev D.V., Brunkov P.N., Troshkov S.I., Jmerik V.N., Ivanov S.V.,** Pulsed growth techniques in plasma-assisted molecular beam epitaxy of $Al_xGa_{1-x}N$ layers with medium Al content ($x = 0.4-0.6$) J. Crystal. Growth 425 (2015) 9.

11. **Reeves G.K., Harrison H.B.,** Obtaining the specific contact resistance from transmission line model measurements. IEEE Electr. Dev. Leter. 3 (1982) 111–113.

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