Schottky-to-Ohmic behavior in annealed Ti/Si/Ti/Al/Ni/Au on AlGaN/GaN

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Abstract

Annealing of contact system Ti/Al/Ni/Au for the Ohmic contact formation to the AlGaN/GaN was performed. Method for determining the height of potential barrier in nonrectifying contact using voltage-capacitance characteristic was proposed. Temperature dependencies of the contact resistance for annealed Ti/Al/Ni/Au in temperature range 25÷175°C were obtained. Thermal field emission prevails in rectifying contact, whereas for nonrectifying contact field emission is typical. It is shown that the charge carriers’ concentration increase in four times influences on the transition from thermal field emission to field emission. The change of resistance under field emission agrees with the barrier height change. The resulting contact resistance for Ti/Si(6 nm)/Ti/Al/Ni/Au is equal to 0.2 Ω·mm.

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1. Introduction

Because of high electric conductivity, adherence and morphology, multilayer Ohmic contacts are often used in microelectronic applications. For Ohmic contact formation to n-type GaN semiconductor structure multilayer contacts based on Ti/Al (such as Ti/Al/Ni/Au) are often used. During the thermal treatment, they form compounds with low work functions by P. Luther (1997), N. Chaturvedi (2006), J. Burn (1997). Resistance of such contact annealed at temperature 800÷900°C is 0.2÷0.5 Ω·mm by X. Kong (2012), D. Deen (2010), D. Buttari (2002), V. Desmaris (2004).

The formation of conductive compound Ti₅N explains the formation of Ohmic contact to n-GaN, based on Ti/Al metal system by A. Durbha (1996). This compound is formed by the deposition of titanium on the n-GaN surface and it extends for layer of metallization during the annealing. Ti₅N compound is formed at temperature 200÷1000°C. Thus particles sprayed by various methods can form thick Ti₅N layer on the surface of semiconductor. Work function of Ti₅N is 3.74 eV and according to Schottky theory it corresponds to formation of Ohmic contact to n-GaN A. Durbha (1996). Resistance of metal-GaN Ohmic contact can

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reach 0.1÷1 μΩ·sm² at high charge carrier concentration in the semiconductor. This is due to the presence of nitrogen vacancies which are formed during the conductor interaction with contact metallization and produce high doped layer under contact by H. Morko (1994), M. Lin (1994), S. Prakashs (1999).

This paper is dedicated to experimental investigation of Ohmic contacts to n⁺-doped region of AlGaN/GaN transistor heterostructure based on Ti/Al/Ni/Au metallization. Effect of annealing temperature on the specific resistance of Ohmic contact was studied. Ohmic contact with resistance of 0.2 Ω·mm was formed by optimization of the annealing temperature and introduction of the additional doping silicon layer. Such resistance is considered acceptable for Ohmic contacts by X. Kong (2012) and V. Desmaris (2004).

2. Experimental details

We used AlGaN/GaN heterostructure. Ti/Al/Ni/Au (35/135/50/100 nm) multilayer metallization was deposited on it by resistive evaporation method with the use of Kurt J. Lesker PVD 75 film deposition system. Annealing was performed using rapid thermal annealing system Modular RTP-600S at a constant temperature for 30 s. Capacitance-voltage measurements were carried out on test structure for transmission line method (TLM) by G. Reeves (1982) at a frequency of 100 KHz. Specific contact resistance was measured by the use of the Agilent B 1500 A semiconductor devices analyzer.

To improve the accuracy of contact resistance measurements we also have used test structure by R. Zaharchenko (2014). Is allows considering the error introduced by parasitic resistance $R_p$ during the measurements which is the resistance of probes, connecting wires and probe contacts. A test structure diagram is shown in Fig. 1.

![Fig. 1. Test structure for the Ohmic contacts resistance measurements.](image)

Fig. 1 shows that the structure consists of two long lines of different configurations. Each line contains a number of semiconductor regions of equal length ($l_1$ and $l_2$ in left and right lines, respectively). Lines are connected in series with metallization of Ohmic contacts which have the same length in each branch. The topology was chosen so that the lengths of both lines were similar while the number of regions in each line is different. Thus the resistance of the right line $R_1$ is different from the resistance of the left line $R_2$ by the amount of Ohmic contact resistance $\rho_K$. As a result, we obtain the system of equations:

\[
\begin{align*}
R_1 &= 6\rho_K + R_{sh} \frac{3l_1}{w} + R_p \\
R_2 &= 8\rho_K + R_{sh} \frac{4l_2}{w} + R_p
\end{align*}
\]

where $R_{sh}$ is the resistance of semiconductor layer, $w$ is the width of contact. By subtracting one equation from the other we obtain the expression for the resistance of contact:

\[
R_0 = \frac{4l_2 R_1 - 3l_1 R_2 - R_p (4l_2 - 3l_1)}{24(l_2 - l_1)}
\]
Provided that $3 \cdot l_1 = 4 \cdot l_2$ the parasitic resistance $R_P$ can be eliminated from the expression (2). The use of test diagram allowed us to significantly improve the accuracy of determination of Ohmic contact resistance.

3. Results and discussion

To investigate the effect of annealing temperature on the properties of the contact 4 samples were prepared. They were annealed at various temperatures in the range 700°-1050°C. Obtained values of contact resistance are listed in Table 1. As can be seen from Table 1 contact resistance is not monotonic function of the annealing temperature. To explain obtained results the characteristics of Schottky barrier which is formed in the contact were determined. We chose the method of capacitance-voltage characteristics measurement to determine the height of the barrier $\varphi_B$. The total voltage $U$ applied to the contact is expressed through capacity according to formula by S. Sze (2007)

$$\varphi_B - U = \frac{kT}{q} = \frac{q\varepsilon_0 N_D S^2}{2C^2}$$

where $S$ is area of the contact, $q$ is elementary charge, $k$ is Boltzmann constant, $T$ is temperature, $N_D$ is charge-carrier concentration, $\varepsilon = 8.9$ is permittivity of Gallium nitride, $\varepsilon_0$ is vacuum permittivity. Capacitance-voltage characteristics were measurement for all samples in the voltage range 0÷10 V (the characteristic curve for the sample No 3 is shown in Fig. 2). In the first section of the capacitance-voltage characteristic ($\frac{\partial^2 C}{\partial U^2} > 0$) capacity of the first contact is charging. In the second section ($\frac{\partial^2 C}{\partial U^2} < 0$) the second capacitor is charging and capacity reaches the maximum. In this case in the first section first Ohmic contact plays a role of barrier and the second is Ohmic. Therefore to measure the Schottky barrier in the rectifying contact we should use the first section of the capacitance-voltage characteristic. Values of $\varphi_B$ were determined for all samples by comparing the measured capacitance-voltage characteristic with the theoretical curve (3). Obtained data are listed in Table 1.

Table 1. Resistance $\rho_k$, transition resistance $\rho_T$, charge carriers concentration $N_D$, Schottky barriers height $\varphi_B$ and width $L_0$ for contact samples, annealed at different temperatures $T$.

| Sample number | $T$, °C | $\rho_k$, $\Omega \cdot \text{sm}^2$ | $\rho_T$, $\Omega \cdot \text{mm}$ | $N_D$, $\text{sm}^{-3}$ | $\varphi_B$, eV | $L_0$, nm |
|---------------|--------|-------------------------------|---------------------------------|-----------------|---------|--------|
| 1 (Ti/Al/Ni/Au) | 700    | 1.05 $\cdot 10^{-2}$         | 1.75                              | 8.5 $\cdot 10^{18}$ | 0.93    | 10.35  |
| 2 (Ti/Al/Ni/Au) | 875    | 5.13 $\cdot 10^{-3}$         | 1.29                              | 4.4 $\cdot 10^{19}$ | 0.87    | 4.32   |
| 3 (Ti/Al/Ni/Au) | 950    | 1.64 $\cdot 10^{-3}$         | 0.57                              | 4.1 $\cdot 10^{19}$ | 0.69    | 4.08   |
| 4 (Ti/Al/Ni/Au) | 1050   | 3.77 $\cdot 10^{-3}$         | 2.18                              | 7.1 $\cdot 10^{19}$ | 1.04    | 3.79   |
| 5 (Ti/Si/Ti/Al/Ni/Au) | 850 | 9.95 $\cdot 10^{-3}$        | 0.20                              | 8.5 $\cdot 10^{19}$ | 0.99    | 3.39   |

Fig. 2. Capacitance-voltage characteristic of the sample No 3, measured at $T = 25°C$.

However the measured capacitance-voltage characteristic doesn’t allow calculating charge-carrier concentration $N_D$ with required accuracy. To determine the value of $N_D$ a contact resistance $\rho_k$ of samples as a function of the temperature in the range
25±175°C was measured. The value of $N_D$ is fitted to get the best agreement between experimentally obtained points and theoretical dependence $\rho_k(T)$. We use theoretical dependence for thermal field emission by F. Pandovani (1966)

$$\rho_k = \frac{kT}{qA} \frac{kT}{\sqrt{\pi(\varphi_0 + V_n)E_{00}}} \cdot \frac{\text{ch}(\frac{E_{00}}{kT})}{\sqrt{\pi(\varphi_0 + V_n)E_{00}}} \cdot \frac{\exp\left(\frac{(\varphi_0 + V_n - V_n)}{kT}\right)}{\exp\left(\frac{\varphi_0 + V_n - V_n}{kT}\right)}; E_0 = E_{00} = \frac{qh}{4\pi} \sqrt{\frac{N_D}{m^*}}$$

(4)

where $h$ is the Planck constant, $A = 27.9$ A/sm²·K² is Richardson constant (here in after all parameters are specified for Gallium nitride), $m^* = 0.23m_e$ is effective mass of electron, $V_n$ is the difference between the bottom of the conduction band and the Fermi level, $\text{ch}$ and $\text{cth}$ are hyperbolic cosine and hyperbolic cotangent, respectively. Also we use the expression for the field emission by F. Pandovani (1966)

$$\rho_k = \left(\frac{AT\pi q}{k \sin(\pi C_i kT)}\right) \frac{\exp\left(-\frac{\varphi_0}{E_{00}}\right)}{\exp\left(-\frac{\varphi_0}{E_{00}} - C_i V_n\right)}; C_i = \frac{1}{E_{00}} \ln\left(\frac{4\varphi_0}{V_n}\right)$$

(5)

Results are shown in Fig. 3. As can be seen from Fig. 3 thermal field emission mechanism of charge transfer is more typical for contact annealed at temperature 700°C while field emission mechanism is more typical for samples annealed at temperatures 875°C, 950°C and 1050°C. Therefore determination of carrier concentration $N_D$ was based on the best agreement between experimental data of curve (4) (for the first sample) and curve (5) (for three other samples). Contribution of the shunts to the total conductivity was not considered because in our experiment resistance decreases with the temperature. It means that the impact of shunts is negligible by T. Blank.
Then we calculated the width of the potential barrier $L_0$ using the formula by S. Sze (2007)

$$L_0 = \sqrt{\frac{2\varepsilon\varepsilon_0\Theta_b}{qN_D}}$$

All obtained values are summarized in Table 1. As expected the lowest resistance has been achieved at minimum of the barrier height while the process of contact formation accompanied by steady increase of charge-carrier concentration (see Table 1). Despite of differing trends in these parameters, the width of the barrier decrease with the resistance. Data listed in Fig. 3 allows concluding that the charge transfer mechanism changes at temperatures in the range 700-875°C from thermal field emission to field emission. This change is accompanied by almost twofold decrease of barrier width (58%) while the barrier height varies slightly (5.5%). This change of barrier is due to the sharp increase of carries concentration of about 4.5 times. Therefore the change in the transfer mechanism is affected by carrier concentration. On the other hand, the dependencies of barrier height and contact resistance on annealing temperature have similar trends. Thus additional formation of the contact occurs at temperatures over 875°C. This process is accompanied by significant decrease of the barrier (26%) while the increase of carrier concentration is not observed. This is also confirmed by the increase of contact resistance when annealing is performed at temperatures over 1000°C. The increase of resistance during degradation of the contact is caused by the increase of Schottky barrier.

To increase carrier concentration we prepared sample No 5 with additional silicon layer. We result in Ti/Si/Ti/Al/Ni/Au (5/60/30/135/50/100 nm) layer system. The titanium underlayer is required to provide adherence to the semiconductor surface because evaporation was performed without heating. The sample was annealed at temperature 850°C (see the last line in Table
1). The introduction of silicon allowed reducing the barrier width by 0.8 nm which reduced contact resistance to 0.2 $\Omega \cdot \text{mm}$ (see Table 1) by K. Vanukhin (2015). As can be seen from Table 1 the introduction of silicon led to the increase in carrier concentration in two times in comparison with the best sample without silicon without the decrease of barrier height.

4. Conclusion

Results presented show that carrier concentration and barrier height are independent and have equal contribution to the value of contact resistance: the change of the carrier concentration have predominant contribution in change of the charge transfer mechanism while during the field emission the change of resistance is mainly affected by the change of barrier height. Moreover, rectifying contact is characterized by thermal field emission while field emission is typical for the Ohmic contact.

Further decrease of resistance can be achieved by both reduction of Schottky barrier height or by increasing of carrier concentration. First approach requires the change of contact material and laborious investigation of intermetallic compounds phases. Thus the second approach based on the increase of charge carrier concentration seems to be more advantageous. In particular silicon doping has allowed us to create an Ohmic contact with resistance of $0.2 \Omega \cdot \text{mm}$ which is twice lower than the best result achieved without doping.

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References

[1] Luther P., Moloney, S., 1997, Investigation of the mechanism for Ohmic contact formation in Al and Ti/Al contacts to n-type GaN, Journal of Applied Physics 70, 57.
[2] Chaturvedi N., Zeimer U., Wurfl J., Trankle G., 2006, Mechanism of ohmic contact formation in AlGaN/GaN high electron mobility transistors, Semiconductor Science and Technology 21, 175.
[3] Burm J., Chu K., Schaff W., Eastman L., Khan M., Chen Q., Yang J., Shur M., 1997, 0.12-μm gate III-V nitride HFET’s with high contact resistances, IEEE Electron Device Letters 18, 141.
[4] Kong X., Wei K., Liu G., Liu X., 2012, Role of Ti/Al relative thickness in the formation mechanism of Ti/Al/Ni/Au Ohmic contacts to AlGaN/GaN heterostructures, Journal of Physics D: Applied Physics, 45, 265101.
[5] Deen D., Storm D., Katzer D., Meyer D., Biarni S., 2010, Dependence of ohmic contact resistance on barrier thickness of AlN/GaN HEMT structures, Solid-State Electronics 54, 613.
[6] Buttari D., Chini A., Meneghesso G., Zanoni E., Moran B., Heikman S., Zhang, N., Shen L., Coffie R., DenBaars S., Mishra U., 2002, Systematic characterization of Cl2 reactive ion etching for improved ohms in AlGaInGaN HEMTs, IEEE Electron Device Letters 23, 76.
[7] Desmaris V., Eriksson J., Rorsman N., Zirath H., 2004, Low-Resistance Si/Ti/Al/Ni/Au Multilayer Ohmic Contact to Undoped AlGaInGaN Heterostructures, Electrochemical and Solid-State Letters 7, G72.
[8] Durbha A., Pearton S., Abernathy C., Lee J., Holloway P., 1996, Microstructural stability of ohmic contacts to In,Ga,Al,N, Journal of Vacuum Science & Technology B 14, 2582.
[9] Morko H., Strike S., Gao G., Lin M., Svedlöf B., Burns M., 1994, Large-band-gap Si:C, AlGaN:V nitride, and II-VI ZnSe-based semiconductor device technologies Journal of Applied Physics 76, 1363.
[10] Nakamura S., Mukai T., Senoh M., 1994, Candelabra-class high-brightness InGaN/AlGaN double-heterostructure blue-light-emitting diodes, Applied Physics Letters 64, 1003.
[11] Prakasha S., Tan L., Ng K., Raman A., Chua S., Woe A., Lin S., Abstract of Int. Conf. on SiC and Rel. Mater. (Sheraton, 1999). P. 48.
[12] Reeves G., Harrison H., 1982, Obtaining the specific contact resistance from transmission line model measurements, IEEE Electron. Device Letters 3, 111.
[13] Zaharchenko R., Vanukhin K., Seidman L., Steblin S., Voronova A., Blinov P., Evseeva E., Minnebaev S., Scientific Session NRNU MEPhI-2014. Book of Abstracts (NRNU MEPhI, Moscow, 2014), Vol. 2. P. 87 (in Russian).
[14] Sze S., Ng K., Physics of Semiconductor Devices (Wiley, Hoboken, NJ, ed. 3, 2007).
[15] Pandovani F., Stratton R., 1966, Field and thermionic-field emission in Schottky barriers, Solid-State Electronics 9, 695.
[16] Blank T., Gol’dberg Yu., 2007, Mechanisms of Current Flowin Metal–Semiconductor Ohmic Contacts, Semiconductors 47, 1263.
[17] Vanukhin K., Zaharchenko R., Ryzhuk R., Shostachenko S., Scientific Session NRNU MEPhI-2015. Book of Abstracts (NRNU MEPhI, Moscow, 2015), Vol. 2. P. 136 (in Russian).