Formation of ohmic contacts to $n(p)$-gan and measurement of their contact resistivity

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Abstract. We propose multilayer ohmic contacts to $n$- and $p$-GaN layers, with titanium boride as diffusion barrier. It is shown that the optimal method of contact resistivity measurement is the transmission line method (TLM) with circular contact geometry. The Ti–Al–TiB$_x$–Au contact metallization to $n$-GaN retains its layer structure after thermal annealing at temperatures up to 900 °C. The contact resistivity $\rho_c$ is $(6.69\pm 1.67)\times 10^{-5}$ Ω·cm$^2$. For the Au–TiB$_x$–Ni–$p$-GaN contact structure, the contact resistivity is $(1\pm 0.15)\times 10^{-3}$ Ω·cm$^2$.

Keywords: ohmic contact, gallium nitride, contact resistivity, transmission line method.

1. Introduction

In recent years, the lighting engineering dealing with production of light-emitting diodes (LEDs) for various purposes has been developing intensely. Having higher light efficiency and longer service life, LEDs rather actively displace other illuminators such as incandescent and luminescent lamps [1, 2]. The process has become more evident after appearance of highly efficient LEDs based on the III group nitrides that made it possible to develop blue LEDs and, closing the RGB range, obtain white light using concurrently red, green and blue LEDs. Such three-color cells are of importance for developing of LED monitors.

It is known that one cannot realize such properties of gallium nitride (that is the most advanced material of the III group nitrides) as high value of avalanche breakdown field and thermal stability without highly reliable ohmic contacts. The reason is that application of LEDs for illumination requires increase of power of the present-day diodes. In this case, LED heating in both the base region and contacts will lead to device degradation. Therefore, search for contact metallization systems to gallium nitride LEDS that would be high-tech, thermally stable and compatible with technological processes for microwave devices makes a topical problem.

Another (no less important) problem in development of investigations of contact metallization to GaN is making of low-resistance thermally stable contacts to $p$-GaN. The existing experimental data on the resistivity $\rho_c$ for contacts to $p$-GaN indicate wide spread of $\rho_c$ values depending on the level of doping with acceptor impurity and crystallographic orientation of GaN surface as well as on the work function $\phi_m$ of the material of contact-forming layer. The latter can be formed with multicomponent compounds with high $\phi_m$ value [3-8].

Reduction of resistivity $\rho_c$ of contact to $p$-GaN can be achieved (along with choosing the appropriate value of $\phi_m$) by doping the near-surface layer with an acceptor impurity that provides tunnel current transport in the ohmic contact. The theoretical studies of $\rho_c$ for contact to $p$-GaN showed [8] that, in the case of a tunnel contact and with allowance made for tunneling of light and heavy holes, $\rho_c$ value depends on the crystallographic orientation of GaN. The calculated $\rho_c$ value of about $2\times 10^4$ Ω·cm$^2$ corresponds to concentration of noncompensated acceptors $\sim 10^{19}$ cm$^{-3}$ for GaN [0001] and $5\times 10^{18}$ cm$^{-3}$ for GaN [1010], respectively.
At the same time, it turned out that, along with the well-known mechanisms of current transport in ohmic contacts to n-GaN grown on sapphire, metallic conductance is observed in such contacts over a wide temperature range. The reason is high density of structural defects in GaN. Increase of \( \rho_c \) as temperature grows (and contributes to device structure heating) is undesirable not only for LEDs but for other types of GaN-based electronic devices as well. Thus, formation of metal–GaN interface with preset parameters as well as making of buffer layers (diffusion barriers) between the upper metallization layer and contact-forming layer that impede mass transfer of contact components are topical from the viewpoint of production of highly reliable thermally stable ohmic contacts to \((n/p)\)-GaN epitaxial layers grown on foreign substrates.

Therefore, one should use multilayer contact metallizations (made of refractory metals and their compounds) serving as diffusion barriers. In this connection, borides and nitrides of refractory metals seem most promising [9–11]. Choice of procedures and estimation of \( \rho_c \) measurement errors are of great importance too. In this work, we studied efficiency of TiB as diffusion barrier in ohmic contacts to GaN using the transmission line method (TLM) to measure \( \rho_c \).

2. Methods of contact resistance measurement

Contact resistivity is one of the main parameters that characterize both an ohmic contact and processes of heat release in it. The principal difficulty in measurement of contact resistance is its determination from the measured resistance \( R \). The latter can be represented as a sum of resistances of the contacts \( (R_c) \), semiconductor \( (R_s) \), probes and lead-ins \( (R_p) \) and the resistance provoked by current spreading \( (R_I) \) [12]:

\[
R = R_c + R_s + R_T + R_p. \quad (1)
\]

It was shown in [13] that the biggest error in determination of contact resistivity is characteristic of the method with vertical geometry of test structure (the Cox–Strack method) [14–16]. In this method, the minimal relative error of \( \rho_c \) measurement (at \( \rho_c/\rho_s = 0.01 \) cm, where \( \rho_c \) is the semiconductor resistivity) is as high as 90% if one uses lithography with accuracy of 2.5 \( \mu \)m [13]. Therefore, it is reasonable to apply the Cox–Strack method [14] only if one has to measure the parameters of contacts to bulk material and in the case \( \rho_c \geq \rho_s \). The minimal value of error is ensured by the method of interface probing [17] and Kelvin method [16, 18, 19]. At \( \rho_c/\rho_s = 0.01 \) cm, the relative error of \( \rho_c \) measurement is 25% and 15%, respectively, if one uses lithography with accuracy of 2.5 \( \mu \)m [13]. When using the probing method, the lithography should ensure one to deposit sufficiently small external terminals, while application of the Kelvin method for measurement of low resistances requires contacts smaller than 1 \( \mu \)m×1 \( \mu \)m [19].

The most convenient and sufficiently accurate methods are those TLM versions [20–27] that make it possible to measure low contact resistances, and the lithography used meets the requirements to making test structures for measurements. TLM has many modifications that differ in geometry and \( \rho_c \) calculation technique. One should set off the versions of TLM with linear and circular contact geometry.

The necessary condition for resistance measurement by TLM with linear geometry of contact pads is absence of edge surface spreading of current. To this end, each group of contacts has to be separated from the rest part of semiconductor plate. This requires application of additional technological process. Contrary to this, use of structures with circular geometry of contact pads makes it possible to avoid edge spreading of current without additional treatment [25, 26].

In the TLM with circular geometry, the resistance between contact pads is determined with the following expression [25]:

\[
R = \frac{R_{SH}}{2\pi} \ln \frac{r_2}{r_1} + \frac{R_{SH}}{2\pi} \frac{1}{\alpha_1(\alpha_i)} \quad (2)
\]

Here \( r_1 \) (\( r_2 \)) is the inner (outer) radius of the corresponding contact pad, \( I_0(\alpha_i) \) and \( I_1(\alpha_i) \) the modified Bessel functions of the zeroth and first order, respectively, \( \alpha = 1/L_T \) the damping coefficient, \( L_T = \sqrt{\rho_c t/\rho_s} \) transfer length, \( t \) thickness of the semiconductor epitaxial layer.

If \( L_T >> r_1 \) and \( \ln(r_2/r_1) = C \), then the approximation \( I_0(\alpha_i)/I_1(\alpha_i) \rightarrow 2/\alpha_i \) is valid, and the resistance measured is determined as [25]:

\[
R = \frac{CR_{SH}}{2\pi} \frac{1}{\pi r_1^2}. \quad (3)
\]

Thus, by plotting the dependence \( R = f(1/\pi r_1^2) \), one can calculate \( \rho_c \) from the slope of the straight line. If \( L_T \leq r_1 \), then the value obtained in the above way will give the upper estimate for contact resistivity [25].

One should note that, to determine contact resistivity accurately, the difference between the outer and inner radii of contact pad has to be minimal. In that case, the contribution from semiconductor resistance to the total resistance becomes smaller [21]. The relative error of contact resistivity measurement can be determined from the following expression [13]:

\[
\frac{\Delta \rho_c}{\rho_c} = \frac{2}{r} \frac{\Delta r}{R} + \frac{\Delta \rho_s}{\rho_s} + \frac{C}{2 t} \left( \frac{\Delta R}{R} \frac{\Delta R}{t} \right), \quad (4)
\]

where \( \Delta t \) is inaccuracy of the grown epitaxial layer thickness, \( \Delta r \) inaccuracy of lithography when depositing contacts. The results of calculation of the dependence \( f(r) = \Delta \rho_c/\rho_c \) are shown in Fig. 1. At best, if \( \rho_c/\rho_s = 0.01 \) cm\(^2\), the relative inaccuracy of \( \rho_c \) measurement is 28%.
If one uses TLM with linear geometry of contact pads and $\rho_x/\rho_0 = 0.01 \text{ cm}$ and $\rho_x = 10^4 \Omega \text{ cm}$, the relative inaccuracy of $\rho_c$ measurement is 16% [13]. This value is below that obtained in the case of TLM with circular geometry. However, as $\rho_c$ increases to $10^2 \Omega \text{ cm}$, the relative inaccuracy in the case of TLM with linear geometry grows to 50%, contrary to the case of TLM with circular geometry in which the error does not depend on the value of semiconductor resistivity.

3. Formation of contact systems

To measure resistivity of ohmic contacts to $n$- and $p$-GaN, we chose TLM with circular geometry of contact pads. We made a test pattern with circular geometry of contacts (Fig. 2) and test TLM structures to measure $\rho_c$.

The GaN epitaxial structures were MOCVD-grown on the sapphire (0001) substrates 400 $\mu$m thick. The LED structures were made at the Close Corporation “Svetlana-Optoelektronika”, Saint-Petersburg, Russia. A low-temperature nucleating layer, $n$-GaN layer (3.5 $\mu$m), active area with five InGaN/GaN quantum wells, $p$-AlGaN current-limiting layer (20 nm) and $p$-GaN layer (0.1 $\mu$m) with dopant concentration $> 2 \times 10^{17}$ $\text{cm}^{-3}$ were grown successively on the sapphire substrate. The $n^−$-$n^+$-$n^−$-$\text{Ga}$-$\text{Al}_2\text{O}_3$ epitaxial structures were grown at the Close Corporation “Elma-Malakhit”, Zelenograd, Russia. The layer parameters were as follows: $n^− \approx 10^{18} \text{ cm}^{-3}$, $d_{\text{w}} \approx 0.8 \mu$m; $n \approx 10^{17} \text{ cm}^{-3}$, $d_n \approx 3 \mu$m; buffer layer: $n^+ \approx 10^{18} \text{ cm}^{-3}$, $d_{\text{w}} \approx 3 \mu$m.

The dislocation density in structures of both types was over $10^8 \text{ cm}^{-2}$. The successive Ti–Al–Ti$\text{B}_x$–Au (Ni–Ti$\text{B}_x$–Au) metallization layers to form ohmic contact to $n^+$-GaN ($p$-GaN) were deposited with magnetron sputtering in the argon atmosphere onto the gallium nitride surface subjected to photon cleaning. After sputtering the Ti–Al (Ni) layer to $n$-GaN ($p$-GaN), the samples were subjected to rapid thermal annealing (RTA) at $T = 900° \text{ C}$ in the nitrogen atmosphere for 30 s. Then the Ti$\text{B}_x$ and Au layers were deposited. As a result, the ohmic contacts Au–Ti$\text{B}_x$–Al–Ti–$n$-GaN and Au–Ti$\text{B}_x$–Ni–$p$-GaN were formed.

The contact resistivity was studied for the Au–Ti$\text{B}_x$–Al–Ti–$n$-GaN contact structures before and after RTA at $T = 700° \text{ C}$, $870° \text{ C}$ and $900° \text{ C}$ for 60 s and Au–Ti$\text{B}_x$–Ni–$p$-GaN contact structures before and after RTA at $700° \text{ C}$ for 60 s. We used the developed plant for measurement of parameters of ohmic contacts to semiconductors (Fig. 3), as well as Auger electron spectroscopy with ion etching by an argon beam (energy of 1 keV) to determine concentration depth profiles of metallization components.
4. Structure of contacts before and after RTA

It was shown in [29] that the contacts with TiBₓ antidiffusion layer (barrier) demonstrate better thermal stability than those with more widespread metallization with Ti and Al as diffusion barrier. As in [29], our analysis of the concentration depth profiles for components of the Ti–Al–TiBₓ–Au contacts to n-GaN taken before and after RTA at $T = 700 \, ^\circ\text{C}$ in the nitrogen atmosphere for 60 s showed that no interactions between phases in the contact metallization. Some changes in the layer structure of such contact were observed after RTA at a temperature of 900 °C only. One should also note considerable oxygen concentration in the TiBₓ layer. Therefore, one may assume presence of titanium oxyboride instead of single-phase of TiBₓ in it. This may be the reason for contact metallization structural failure in the course of RTA at a temperature of 900 °C.

It was noted in a number of works [3-5, 30-32] that formation of ohmic contact to n-GaN with contact-forming layers of Al–Ti occurs owing to appearance at RTA of TiN composition whose work function is 3.87 eV, i.e., below that of pure Ti (3.95 eV). In this case, nitrogen vacancies are produced in the GaN near-surface layer because of N atoms coming to the titanium film. These vacancies are produced in the GaN near-surface layer in the course of RTA at a temperature of 900 °C only. One should also note considerable oxygen concentration in the TiBₓ layer. Therefore, one may assume presence of titanium oxyboride instead of single-phase of TiBₓ in it. This may be the reason for contact metallization structural failure in the course of RTA at a temperature of 900 °C.

Fig. 4. The total resistance of Au–TiBₓ–Al–Ti–n-GaN contacts as function of $\frac{1}{\pi r^2}$.

5. Electrophysical properties of ohmic contacts


The $I$–$V$ curves of Ti–Al–TiBₓ–Au contacts to the n⁺-n⁻-n⁺-GaN structure taken in the 90–380 K temperature range turned out to be linear over the whole this range. The contact resistivity at room temperature was $(6.69\pm1.67)\times10^{-5}$ Ω·cm² (Fig. 4). The semiconductor resistivity estimated from the dependence $R(1/\pi r^2)$ was $\approx10^{-5}$ Ω·cm².

The current through the Au–TiBₓ–Al–Ti–n⁺-n⁻-n⁺-GaN contact structure is determined by the semiconductor resistance because structure conductance increases as temperature grows up to 150 K. Further temperature increase led to decrease of conductance. This fact correlates with the temperature dependence of electron mobility in GaN considered in [33].

The contact resistivity measurements in the 225–380 K temperature range showed that there are two regions of $\rho_c$ variation. In the 225–335 K temperature range, $\rho_c$ practically does not depend on temperature. This is characteristic of the tunnel mechanism of current transport in the contact. In the 335–380 K temperature range, $\rho_c$ decreases exponentially with temperature and is linear in the coordinates $\ln(\rho_c T) = f(1/T)$. This is characteristic of the thermionic mechanism of current transport. The potential barrier height $\phi_B$ determined from the dependence $\ln(\rho_c T) = f(q/kT)$ in the 335–380 K temperature range was 0.16 eV.

In the 225–335 K temperature range, the tunnel mechanism via dislocations of current transport is characteristic of the contact structure. The dislocation density in some samples was $\approx10^8$ cm⁻². The current transport mechanism via dislocations was observed in [34] for gallium nitride Schottky barrier diodes. In that case, the dislocation density in GaN was $\approx10^8$–$10^{10}$ cm⁻². Such mechanism was advanced earlier to describe the temperature dependence of saturation current in the GaP-based surface-barrier diodes [35].

For the best gallium nitride epitaxial structures with Au–TiBₓ–Al–Ti–n-GaN ohmic contacts, the contact resistivity was $\approx10^{-6}$ Ω·cm². After repeated RTA of the Au–TiBₓ–Al–Ti–n-GaN contacts at $T = 700$ °C and $T = 870$ °C, the current transport mechanism and ohmic contact parameters did not change considerably. This indicates their thermal resistance.


The $I$–$V$ curves of the Au–TiBₓ–Ni–p-GaN contact structure subjected to RTA at $T = 700$ °C for 60 s were linear. The contact resistivity was $\approx10^3$ Ω·cm². This is much higher than that of the ohmic contacts to n-GaN; the $\rho_c$ value estimated from the cutoff in the $R(1/\pi r^2)$ curve is $\approx10^2$ Ω·cm. This value is in agreement with the data of other authors who studied ohmic contacts formed in the course of thermal annealing (at $T = 700$ °C) of a gilded nickel film (Au–Ni) deposited onto the surface of p-GaN with $p \approx$
parameters, we applied this method for study of the developed plant for measurement of ohmic contact of the Ga phases that reduce the barrier at the interface between acceptors [7] also favors reduction of vacancies in the near-contact region that serve as acceptors [7] also favors reduction of vacancies in the near-contact region that serve as acceptors.

When comparing our data on $\rho_c$ value with those of other authors [6, 7], one may assume that in our case, with TiB$_2$ diffusion barrier, the contact-forming layer (after RTA at $T = 700 \, ^\circ C$) is formed by the GaNi$_3$ and Ga$_2$Ni$_2$ intermetallic phases, since the TiB$_2$ layer prevents from penetration of Au atoms to the interface between Ni and GaP. However, this should be confirmed with x-ray diffraction studies. In this case, one should not exclude also additional (positive) influence of Ga vacancies in the p-GaN near-contact region on decrease of $\rho_c$. The repeated RTA ($700 \, ^\circ C$, 60 s) did not change $\rho_c$ value for the Au–TiB$_2$–Ni–p-GaN ohmic contact. This fact indicates completeness of metallurgical reactions in the near-contact region and at the metal–GaN interface in the course of the first RTA.

The fact that $\rho_c$ values are higher than those in the ohmic contact to n-GaN is determined by the features of doping of p-GaN, e.g., owing to impurities passivation by hydrogen atoms in the course of MOCVD-growth and doping of GaN with uncontrollable donor impurities [37]. The complication results also from absence of metals with work function over 7.5 eV. Therefore, to make low-barrier ohmic contacts to p-GaN, one should either use contact-forming compounds with high work function values or form a heavily doped narrow-gap near-surface layer in GaN [3-5, 30].

6. Conclusion

A comparison between the methods of measurement of contact resistivity of ohmic contacts to n(p)-GaN showed that TLM with circular contact geometry is optimal. Using the developed plant for measurement of ohmic contact parameters, we applied this method for study of electrophysical properties of ohmic contacts to n- and p-GaN. The contacts were multilayer Au–TiB$_2$–Al–Ti–n-GaN structures (that remained thermally stable after RTA at temperatures up to 900 °C [29]) and Au–TiB$_2$–Ni–p-GaN structures (that remained thermally stable after RTA at temperatures up to 700 °C). The $I–V$ curves of the Ti–Al–TiB$_x$–Au contacts to the n-n-GaN structure were linear in the 90–380 K temperature range; the contact resistivity $\rho_c$ at room temperature was $(6.69\pm1.67)\times10^{-5} \, \Omega \cdot \text{cm}^2$. For the Au–TiB$_x$–Ni–p-GaN contact structure, $\rho_c = (1\pm0.15)\times10^{-3} \, \Omega \cdot \text{cm}^2$, and the contact $I–V$ curves were.

Thus, the experimental results obtained by us indicate high thermal stability of ohmic contacts, with titanium boride as diffusion barrier, to n- and p-GaN layers.

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References


