Effect of Microwave Treatment on Current Flow Mechanisms in Au–TiB$_x$–Al–Ti–n$^+$–n–n$^+$–GaN–Al$_2$O$_3$ Ohmic Contacts


Abstract—The temperature dependences of the contact resistivity $\rho_c$ of Au–TiB$_x$–Al–Ti–n$^+$–n–n$^+$–GaN–Al$_2$O$_3$ ohmic contacts have been studied before and after microwave treatment followed by nine-month room-temperature sample storage. The temperature dependences of $\rho_c$ of initial samples were measured twice. The first measurement showed the temperature dependence typical of ohmic contacts; the repeated measurement in the temperature region above 270 K showed a decrease in $\rho_c$ caused by metallic conductivity. After microwave treatment, the metallic conductivity in the ohmic contact is not observed. This is presumably associated with local heating of metal Ga inclusions under microwave irradiation and the formation, due to high chemical activity of liquid gallium, of compounds of it with other metallization components. In this case, the temperature dependence of $\rho_c$ is controlled by ordinary charge transport mechanisms. After nine-month room-temperature storage, the temperature dependence of $\rho_c$ is described by the tunneling mechanism of charge transport.

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1. INTRODUCTION

Ohmic contacts to GaN epitaxial layers have been studied many times and their properties were summarized in a number of monographs and reviews [1–10]. Interest in this subject is mainly caused by difficult fabrication of low-resistance, heat-resistant, and area-reproducible ohmic contacts to GaN epitaxial structures grown on foreign substrates (Al$_2$O$_3$, SiC, Si, GaAs, etc.). Only on such substrates is it possible to obtain large-area GaN epitaxial layers applicable to modern industrial technologies of large-scale production of diodes and transistors. However, due to the mismatch of lattice parameters of GaN and substrate and the difference in their thermal expansion coefficients, GaN epitaxial layers contain a significant number of structural defects. In addition to dislocations, such films contain micro pores penetrating the entire film thickness, stacking faults, and impurity inclusions. All these defects predetermine the nonuniform distribution of the dopant concentration and majority carrier mobility in the film and, hence, the nonuniform distribution of the contact resistivity of ohmic contacts.

In conventional Si and GaAs microelectronics, the solution of the problem of the fabrication of low-resistance contacts with a small variance of the contact resistivity $\rho_c$ over the wafer area consists in correct selection of heat treatment conditions. However, in the case of GaN grown on foreign substrates, the formation of reliable ohmic contacts is a more complex physico technological problem, especially as concerns a decrease in $\rho_c$ and its reproducibility over the wafer [11–13]. The latter effect is caused by the fact that a number of compounds of the contact-forming metal with semiconductor components, which, as a rule, have different physicochemical properties, are formed in the near-contact region. For example, the mechanism of decreasing $\rho_c$ for the ordinary ohmic contact Al–Ti–n–GaN–Al$_2$O$_3$ upon rapid thermal annealing (RTA) at $T = 900^\circ$C is based on titanium nitride formation at the Ti–n–GaN interface. The TiN work function (3.7 eV) is lower than the Ti work function (~4.33 eV). Moreover, nitrogen vacancies behaving as donors are accumulated upon RTA in the near-contact region due to nitrogen drift from GaN. Both factors do cause a decrease in $\rho_c$. However, due to rapid Al oxidation and the formation of new complex phases in the Ti–Al–Ga–N system, the nonuniform distribution of $\rho_c$ over the area remains.

At the same time, in addition to thermal treatment, other methods for changing near-contact and surface properties of semiconductors are known [14]. One consists in microwave treatment of samples [15]. As noted in [14], the features of such treatment are processes occurring when microwaves are absorbed in the metallization skin layer (or a contact structure under...
study, including surface semiconductor layers), the short-term influence of which leads to structural-impurity ordering of the metal–semiconductor interface. Since the total thickness of the contact metallization upon exposure to centimeter-wavelength microwaves is on the order of the skin layer thickness, it seemed reasonable to study the effect of such treatment on changes in $\rho_c$, the temperature dependence of $\rho_c$ of ohmic contacts Au–TiB$_x$–Al–Ti–$n$-GaN–Al$_2$O$_3$, and charge transport mechanisms in them.

2. EXPERIMENTAL TECHNIQUE

The $n^+–n–n^+$-GaN/Al$_2$O$_3$ heteroepitaxial structure was grown on an Al$_2$O$_3$ substrate 400 µm thick by metalorganic chemical vapor deposition (MOCVD) at the Elma-Malachit Joint-Stock Co. (Zelenograd, Russia). The layer parameters are $n^+ ≈ 10^{18}$ cm$^{-3}$, $d_n^+ ≈ 0.8$ µm; $n ≈ 10^{17}$ cm$^{-3}$, $d_n ≈ 1.5$ µm; and the buffer layer $n^+ ≈ 10^{18}$ cm$^{-3}$, $d_n^+ ≈ 3$ µm. The dislocation density is $≥ 10^{8}$ cm$^{-2}$; ohmic contacts were fabricated by magnetron sputtering of sequentially sputtered layers Ti(50 nm)–Al(20 nm)–TiB$_x$(100 nm)–Au(200 nm). After deposition Ti–Al layers, the samples were subjected to RTA at $T = 900°C$ for 30 s in a nitrogen atmosphere. Then TiB$_x$ and Au films were deposited. The contact structures were formed by photolithography.

The contact resistivity $\rho_c$ was estimated from above using the radial transition line method (TLM) [16]. The total resistance $R$ between the internal and external contact areas is given by

$$ R = \frac{R_S}{2\pi} \ln \frac{r^*}{r} + \frac{R_S}{2\pi \alpha} \frac{L_0(\alpha r)}{I_0(\alpha r)}, $$

(1)

where $R_S$ is the semiconductor resistivity; $r$ and $r^*$ are the inner and outer radii of corresponding contact areas; $I_0(\alpha r)$ and $I_1(\alpha r)$ are the modified zeroth- and first-order Bessel functions, respectively; $\alpha = 1/L_T = (R_S/\rho_c)^{1/2}$ is the attenuation coefficient; and $L_T$ is the transport length.

Provided that $L_T ≫ r$, the approximation $I_0(\alpha r)/I_1(\alpha r) → 2/(\alpha r)$ is valid. If the ratio of inner and outer radii of contact areas is chosen constant, $\ln(r'/r) = C$ and the total resistance can be written as

$$ R = \frac{CR_S}{2\pi} + \frac{\rho_c}{\pi r^2}. $$

(2)

Thus, having plotted the dependence $R = f(1/(\pi r^2))$, we can determine $\rho_c$ from the line slope. However, if $L_T ≤ r$, the value obtained will correspond to the upper estimate of the contact resistivity.

In the case of thermionic emission as a dominant mechanism of charge transport, the contact resistivity in the metal–semiconductor contact is described by the dependence

$$ \rho_c = \frac{k}{qA^*} \exp \left(\frac{q\phi_b}{kT}\right), $$

(3)

where $k$ is the Boltzmann constant, $T$ is the temperature, $A^*$ is the modified Richardson constant for GaN, and $\phi_b$ is the barrier height at the metal–semiconductor interface. At the same time, the contact resistivity can be determined from (2) via the difference $\Delta R$ between measured resistivities of contacts with different outer and inner diameters, but with identical ratios $\ln(r'/r)$,

$$ \rho_c = \Delta R \pi \ln \left(\frac{r^*_2}{r_2^2} - \frac{r^*_1}{r_1^2}\right), $$

(4)

where $r_1$ and $r_2$ are the inner radii of contact pads.

Substituting (4) into (3) and taking the logarithm, we obtain

$$ \ln(\Delta R/T) = \ln \left(\frac{k(r^*_2 - r^*_1)}{\pi qA^* r^*_2 r^*_1} + \frac{q\phi_b}{kT}\right) = C + \frac{q\phi_b}{kT}. $$

(5)

Therefore, having plotted the dependence $\ln(\Delta R/T) = f(q/kT)$, we can determine the barrier height $\phi_b$ from the line slope. But if thermionic emission appears in a certain temperature range, we can determine $\phi_b$ from dependence (5) as well.

Microwave treatment was performed using magnetron radiation of frequency 2.45 GHz and specific power of 1.5 W/cm$^2$ for 1–1000 s. Samples were irradiated in air in free space. After microwave treatment for 1000 s, samples were stored at room temperature for nine months.

Before and after microwave treatment and nine-month storage, $\rho_c$ was measured in the range $T = 77–380 K$.

3. RESULTS AND DISCUSSION

Figure 1 shows (curves 1 and 2) the dependences $\ln(\Delta R/T) = f(q/kT)$ for the initial sample, measured twice in the temperature range of 77–380 K and curves 3–5 for samples irradiated for 60 and 1000 s and after microwave treatment for 1000 s in nine months. Figure 2 shows the dependences $\rho_c = f(T)$ for the same samples. We can see that a portion with a rather weak variation in $\rho_c$ can be distinguished in the dependences $\ln(\Delta R/T) = f(q/kT)$ and $\rho_c = f(T)$ for the initial sample (curves 1 in Figs. 1 and 2). It is characterized by the preferentially field mechanism of charge transport caused by the formation of a thin heavily doped $n$-type layer in the near-contact region due to RTA at $T = 900°C$. According to the published data [1–13, 17–24], the nature of this layer is associated with nitrogen vacancies.

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