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Resistance formation mechanisms for contacts to *n*-GaN and *n*-AlN with high dislocation density

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We studied Au-Pd-Ti-Pd ohmic contacts made by thermal evaporation of metals in vacuum onto *n*-GaN (*n*-AlN) with high dislocation density heated to a temperature of 350 °C. Temperature dependence of ohmic contacts resistivity may be described by the mechanism of current flow through the metal shunts associated with dislocations, with allowance made for current limitation by diffusion supply of electrons to the contact.

1 Motivation

In recent years, there exists rather high interest in electrical properties of ohmic contacts in relation to the problems of development of high-power III–N-based devices [1-3]. In particular, a number of authors noted very complicated temperature dependences of contact resistivity, $\rho_c(T)$, in ohmic contacts to III–N compounds (among them GaN) that cannot be explained by the existing theoretical approaches [3, 4]. At the same time, the $\rho_c(T)$ dependences for AlN still remain practically unexplored. Here we propose a mechanism explaining the behavior of $\rho_c(T)$ curves in ohmic contacts to *n*-GaN and *n*-AlN films with high density of structural defects.

2 Specimens and measurement techniques

The *n*-GaN and *n*-AlN films were grown at the Ioffe Physico-Technical Institute of the Russian Academy of Sciences using chlorine vapor phase epitaxy and a standard setup with horizontal reactor [5]. The *n*-GaN layers (thickness of ~30 µm, free electron concentration $n > 10^{18}$ cm^{-3}) were grown on AlN template on sapphire. The high-resistance AlN layers (thickness of ~3.5 µm) were obtained on a heavily doped SiC substrate. The dislocation density in the films was 10^9 cm^{-2}. It was measured using an x-ray diffractometer Philips X'Pert – MRD. An ohmic contact was formed by deposition of Pd(30nm)-Ti(50nm)-Pd(70nm)-Au(100nm) in vacuum onto n-GaN(n-AlN) heated to a temperature of 350°C and subsequent rapid thermal annealing at $T = 900$ °C for 30 s. The components concentration depth profiles in the contacts were studied by Auger electron spectroscopy and were taken before and after annealing (Fig. 1, a-d). Morphological features of GaN and AlN film surfaces were studied using a Field Emission Auger Microprobe JAMP 9500F in the scanning electron microscopy mode (Fig. 2) and atomic force microscopy (AFM) (Fig. 3). The $\rho_c(T)$ curves were taken using the transmission line method in the 100-380 K temperature range [6].

3 Experimental results and discussion

One can see from Fig. 1 that the initial (before annealing) specimens had layered metallization structure (Fig. 1, a, c). After annealing the metallization components were intermixed with GaN (AlN) (Fig. 1, b, d); this is in agreement with the literature data [7]. In the initial *n*-GaN films, characteristic hexahedral defects along with dislocations were observed (Fig. 2), while pores were observed in the *n*-AlN films (Fig. 3).

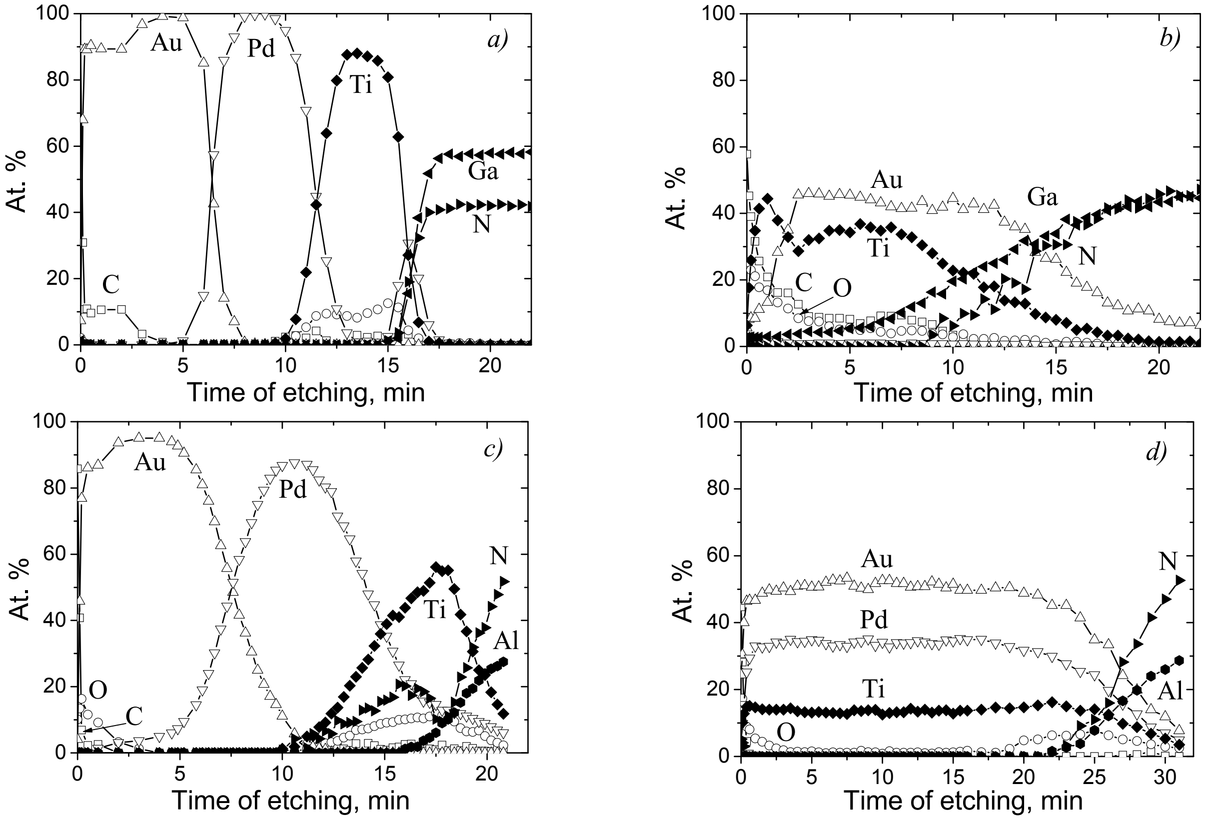

Figure 1 The components concentration depth profiles in the Au-Pd-Ti-Pd-*n*-GaN (a, b) and Au-Pd-Ti-Pd-*n*-AlN (c, d) contact metallizations taken before (a, c) and after thermal annealing at 900 °C for 30 s (b, d).

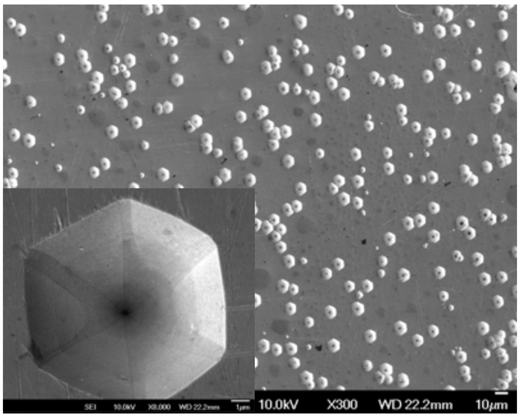

Figure 2 Surface morphology of GaN film with hexagonal defects.

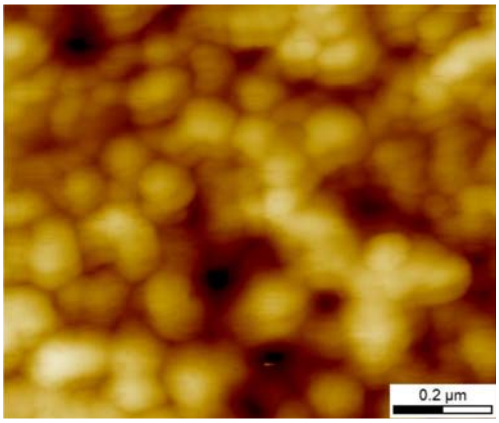

Figure 3 Surface morphology of AlN film.

Shown in Fig. 4 are the temperature dependences of ρ_c for annealed ohmic contacts (curve I for the Au-Pd-Ti-Pd-*n*-AlN contact, curve II for the Au-Pd-Ti-Pd-*n*-GaN contact). By comparing the $\rho_c(T)$ curves for ohmic contacts to *n*-AlN and *n*-GaN, one can see that at low temperatures (from 160 K up to 200 K for contacts to *n*-GaN and up to 250 K for contacts to *n*-AlN) the contact resistivity ρ_c goes down as temperature grows. At further increase of temperature up to 375 K, ρ_c varies but slightly. An essential distinction between the above dependences is that ρ_c value for ohmic contact to *n*-AlN is by three orders of magnitude higher than that to *n*-GaN. The reason for this is high resistance of the *n*-AlN film. Besides, for ohmic contact to *n*-GaN $\rho_c(T)$ practically does not depend on temperature at low temperatures (100-150 K) – see Fig. 4 (curve II).

To explain such effects, a novel concept for current flow at high dislocation density in semiconductor has been advanced in [8]. It involved current flow through the metal shunts associated with dislocations and current limitation by diffusion supply of electrons. In that case, an ohmic contact is a nanosystem involving metal shunts whose sizes are close to the atomic ones. The currents flowing between dislocations were neglected. This theory explained both power increase and decrease of ρ_c, depending on temperature variation. However, the $\rho_c(T)$ curves presented in Fig. 4 cannot be explained by either the known theories of current flow in ohmic contacts [4] or the model [8], because the decreasing part of the $\rho_c(T)$ curve obeys the exponential law.

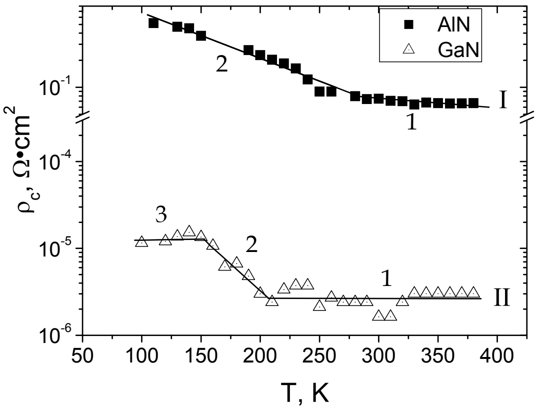

Figure 4 The $\rho_c(T)$ curves for ohmic contacts Au-Pd-Ti-Pd-*n*-AlN (full marks) and Au-Pd-Ti-Pd-*n*-GaN (open marks).

Let us start discussion of results from curve II (Fig. 4) showing temperature dependence of contact resistivity for ohmic contacts to GaN obtained on the Al_2O_3 substrate. One can see that there are three portions in that curve: 1. very weak dependence $\rho_c(T)$ in the 200-380 K temperature range; 2. exponential dependence $\rho_c(T)$ with activation energy of about 0.1 eV in the 160-200 K temperature range, and 3. the portion in which contact resistivity ρ_c does not depend on temperature (at $T < 160$ K). It should be noted that, in principle, the portion 1 may be described by the mechanism of current flow through the metal shunts associated with dislocations, with allowance made for current limitation by diffusion supply of electrons to the contact [8]. Increasing of ρ_c as temperature is going down (in the portion 2) is purely exponential. This cannot be explained by either power decrease of electron mobility due to scattering on dislocations or low-temperature electron freezing-out. In that case, silicon is shallow donor with ionization energy less than 20 meV, and this can result in $\rho_c(T)$ growth at temperatures below 50 K. Therefore, when trying to explain the portion 2, one should assume that this is related to effects of disordering in metal shunts conductivity at low temperatures. These effects lead to change of conductivity type (from metal-type to activation-type). Such a situation may occur if one takes into account that the metal shunt diameter is close to atomic sizes, so, in principle, a single defect can lead to activation-type conductivity at low temperatures [9].

The currents flowing through metal shunts associated with dislocations and those flowing between dislocations correspond to resistances connected in parallel. Therefore, saturation of the dependence $\rho_c(T)$ in the portion 3 at $T < 160$ K should be related to the current flowing between dislocations in the case of heavy doping near-contact region and, correspondingly, strong degeneration. It was shown in [8] that in this case contact resistance is determined by the mechanism of thermionic emission and practically does not depend on temperature. Indeed, the GaN structures under investigation had a thin heavily doped near-contact layer.

In the case of AlN contact (curve I in Fig. 4), the dependence $\rho_c(T)$ has the portions 1 and 2 only. Their presence is explained in the same way as in the case of GaN contact. No portion 3 exists in that case. Generally speaking, the saturation portion 3 may occur in the AlN contact at lower temperatures than in the GaN contact.

4 Conclusion

It is shown that current flowing through ohmic contacts to *n*-GaN (*n*-AlN) films with high dislocation density is determined mostly by metal shunts associated with dislocations. Explanation of exponential decrease of contact resistivity ρ_c with temperature T needs additional investigations.

The results obtained lead to considerable revision of the notion of physical mechanisms responsible for resistivity formation in ohmic contacts to *n*-GaN (*n*-AlN) films with high dislocation density.

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