ISSN 1063-7826, Semiconductors, 2006, Vol. 40, No. 10, pp. 1173–1177. © Pleiades Publishing, Inc., 2006.
Original Russian Text © T.V. Blank, Yu.A. Gol'dberg, O.V. Konstantinov, V.G. Nikitin, E.A. Posse, 2006, published in Fizika i Tekhnika Poluprovodnikov, 2006, Vol. 40, No. 10, pp. 1204–1208.

SEMICONDUCTOR STRUCTURES, INTERFACES, AND SURFACES

The Mechanism of Current Flow in an Alloyed In–GaN Ohmic Contact

T. V. Blank^, Yu. A. Gol'dberg, O. V. Konstantinov, V. G. Nikitin, and E. A. Posse

Ioffe Physicotechnical Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia

^e-mail: tblank@mail.ioffe.ru

Submitted February 1, 2006; accepted for publication February 17, 2006

Abstract—The resistance of alloyed In–GaN ohmic contact is studied experimentally. In the temperature range 180–320 K, the resistance per unit area increases with temperature, which is typical of metallic conduction and disagrees with current flow mechanisms associated with thermionic, field-effect, or thermal field emission. It is assumed that In–GaN ohmic contact is formed by conducting shunts arising due to precipitation of In atoms on dislocations. As determined from the temperature dependence of the contact resistance, the number of shunts per unit contact area is ~(10^7–10^8) cm^{-2}, which is close to the dislocation density of 10^8 cm^{-2} measured in the initial material.

PACS numbers: 73.40.Cg, 73.40.Ns

DOI: 10.1134/S1063782606100095

1. ANALYSIS OF PUBLISHED DATA

Several theories of current transport in an ohmic metal–semiconductor contact dependent on the carrier density in the semiconductor and temperature have been developed [1–4].

According to the thermionic emission theory, the specific (per unit area) resistance R_c of an ohmic contact decreases with a rise in temperature T, and exponentially increases with the height of the metal–semiconductor barrier, φ_B:

$$R_c \propto \exp\frac{q\varphi_B}{kT}, \qquad (1)$$

where k is the Boltzmann constant and q is the elementary charge. The thermionic emission theory is valid at high temperatures, when $kT \gg qE_{00}$, where E_{00} is the Padovani–Stratton parameter

$$E_{00} = \frac{\hbar}{2}\sqrt{\frac{N}{\varepsilon_s m^*}}. \qquad (2)$$

Here N is the concentration of uncompensated impurity in the semiconductor; ε_s, the dielectric constant of the semiconductor; and m^*, the electron effective mass in the semiconductor.

According to the field-emission theory ($kT \ll qE_{00}$), R_c is virtually independent of T, but it increases with φ_B and decreases with the rise of the concentration of uncompensated impurity in the semiconductor, N:

$$R_c \propto \exp\frac{\varphi_B}{E_{00}}. \qquad (3)$$

According to the thermal field emission theory ($kT \approx qE_{00}$), R_c must increase with φ_B and slightly decrease with the rise of temperature T:

$$R_c \propto \exp\frac{\varphi_B}{E_{00}\coth(qE_{00}/kT)}. \qquad (4)$$

These theories were confirmed experimentally for ohmic contacts with semiconductors characterized by high density of surface states and pinned Fermi level at the semiconductor surface: the thermionic emission theory, for contacts on p-GaAs ($p = 5 \times 10^{18}$–1×10^{19} cm^{-3}) [5], p-InP [6], p-InGaAs ($p = 5 \times 10^{18}$ cm^{-3}) [7]; and the field emission theory, for contacts on p-GaAs ($p = 4 \times 10^{20}$ cm^{-3}) [8] and n-ZnO ($n = 1 \times 10^{18}$–1×10^{20} cm^{-3}) [9].

In recent years, progress in ultraviolet electronics has drawn much attention to semiconducting nitrides GaN, AlN, and related solid solutions. In contrast to arsenides and phosphides, the density of surface states in these materials is not high, and the position of the Fermi level on the surface may vary widely, dependent on the electron work function of the contacting metal [10, 11]. At the direct contact of these n-type semiconductors with metal, an ohmic contact must be formed if the electron work function of the metal, Φ_m, is less than the electron affinity of the semiconductor, χ_s (χ_s = 4.1 eV for GaN and 0.6 eV for AlN [12]). Therefore, metals forming compounds with low work function in the course of thermal treatment are chosen to produce an ohmic contact with n-GaN. For example, in [4], ohmic contacts to n-GaN ($n = 1.5 \times 10^{18}$ cm^{-3}) were produced by alloying of Si/Ti, because heating of Si/Ti

Table 1. The published data on the mechanism of current flow in ohmic contacts to GaN

Contact	Concentration, n, p, cm^{-3}	R_c dependence on temperature	R_c dependence on concentration	Current flow mechanism	Ref.
Ti/Ag–n-GaN	$(1.5–1.7) \times 10^{18}$		Decreases $\propto 1/\sqrt{n}$	Tunneling	[16]
Ti/Ag/Ni/Au–n-GaN	$(4–30) \times 10^{17}$		Decreases $\propto 1/\sqrt{n}$	Tunneling	[17]
Ti/Au/Pd/Au–n-GaN	$6 \times 10^{17}–10^{20}$	Increasing	Decreases	Tunneling	[18]
Pt–n-GaN	2×10^{17}	Decreases $\propto \exp(T^{-1/4})$		Thermionic emssion at $T \geq 200$ K; tunneling at $T \leq 200$ K	[19]
Si/Ti–n-GaN		Decreases $\propto \exp(1/T)$		Thermionic emssion	[4]
n-GaN (theory)			Superlinear decrease; sublinear decrease	Tunneling	[20]
Pt–n-GaN	$(1.8–10) \times 10^{17}$	Decreases $\propto \exp(1/T)$		Thermionic emssion	[21]
Pd/Pt/Au–p-GaN	$(2–22) \times 10^{17}$	Decreases $\propto \exp(T^{-1/4})$		Hopping conductivity	[22]

yields titanium silicide, which is characterized by an electron work function smaller than the GaN electron affinity ($\Phi_m \approx 3.7$ eV for Ti_5Si_3).

The low resistivity of contact (below 10^{-6}–10^{-7} Ω cm^2) at high carrier density in a semiconductor [13–15] is usually attributed to the formation of oxygen vacancies via the interaction of GaN with the material of contact, e.g., Ti. These vacancies form a distorted layer under the contact, which plays the role of a heavily doped layer. The formation of ohmic contacts to n-AlN presents severe problems owing to the low electron affinity of this semiconductor.

Some published data [4, 16–22] concerning the mechanism of current flow through an ohmic contact to GaN are listed in Table 1. In the case of heavily doped GaN, the resistance of an ohmic contact, R_c, decreased as the density of majority carriers increased, which gave reason to consider field emission (tunneling) as the principal mechanism of current flow [16–18, 20]; in the case of GaN of medium doping, the contact resistance R_c decreased with the rise of temperature T, which gave reason to consider thermionic emission as the principal mechanism of current flow [4, 19, 21]. In [22], the contact resistance R_c decreased with the rise of temperature T, but the dependence $R_c(T)$ was very weak, and the authors supposed hopping conduction via deep levels to be the principal mechanism of current flow.

Thus, resistance of the known ohmic contacts either decreased as the temperature increased, or did not change. The increasing of resistance with temperature in the range 50–300°C was observed only in [18]; the authors suggested that, as temperature increases, some distortions are formed in the GaN surface layer, which can raise the height of the metal–semiconductor barrier.

It is necessary to note that all these studies were performed with thin-film metal contacts, in which the semiconductor (GaN) does not noticeably dissolve even at high annealing temperatures.

In our earlier study [23], we assumed that an alloyed ohmic In contact to GaP can be formed by metallic shunts threading the space charge layer. In the present study, we investigate the mechanism of current flow in an ohmic contact formed by alloying of In into n-GaN with a low electron density in the initial material. At the formation of this contact, the GaN layer of ~1 μm in thickness is dissolved in the contacting metal (In).

The electron work function of In, $\Phi_m \approx 4$ eV, nearly equals the electron affinity of GaN, and bringing indium in direct contact with a cleaned surface of GaN does not form an ohmic contact; it appears only after annealing of the In–GaN system.

2. EXPERIMENTAL

The initial material was single-crystal GaN deposited by MOCVD onto 0.4-mm-thick sapphire substrates. The thickness of [0001] GaN layers was 4 μm. The electron concentration in the layer was 5×10^{16} cm^{-3}, the mobility at 300 K was ~500 cm^2/(V s).

The dislocation density P_d in GaN crystals, as determined by chemical etching method, was 10^8 cm^{-2}. It is noteworthy that the dislocation density in commercial crystals is 10^8–10^{10} cm^{-2}; in particular, in [24] the value of P_d determined by chemical etching of GaN in H_3PO_4 and KOH melt was 10^9 cm^{-2}.

An array of In contacts was alloyed into GaN wafers at 600°C in a flow of pure hydrogen. The contact area was ~10^{-4} cm^2 and the total length of the wafer was 2 cm.

After alloying and cooling to room temperature, current–voltage (I–V) characteristics were measured at temperatures 77–420 K between the first and all the other contacts. The temperature in the thermostat was maintained constant with an accuracy of 1 K.

All the structures demonstrated linear I–V characteristics (Fig. 1). To separate the resistance of an ohmic contact R_c from the bulk resistance R_{bulk} of the semiconductor, the dependence of the measured resistance R_{meas} on the distance d between the contacts was determined. Since the depth of In alloying is close to the GaN layer thickness and the substrate is virtually insulating, the spreading resistance and the inhomogeneity of current flow across the wafer must not introduce a large error into the determined resistance of contacts. Therefore,

$$R_{meas} = 2R_c + R_{bulk} = 2R_c + \frac{\rho d}{S} = 2R_c + \frac{d}{qn\mu_n S}, \quad (5)$$

where ρ is the bulk resistivity of the semiconductor; S, the contact area; and μ_n, the mobility. For the case of ohmic contacts, the dependence of R_{meas} on d must be linear (Fig. 1). The intercept of this line with the ordinate axis must correspond to doubled contact resistance, and its slope must correspond to the bulk resistivity of the semiconductor, $\rho = 1/qn\mu_n$.

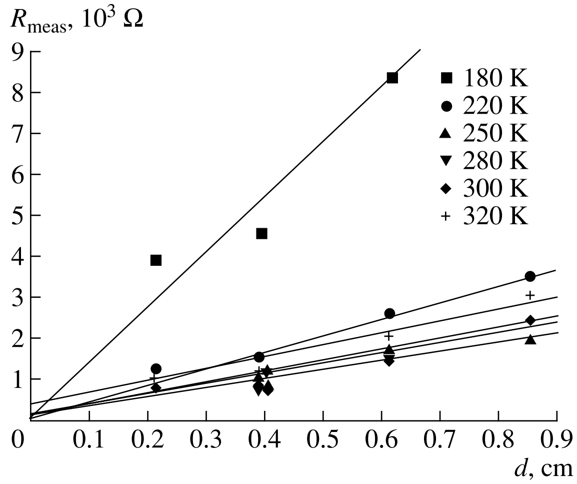

Fig. 1. The measured resistance R_{meas} of In–GaN–In structure with two ohmic contacts vs. the distance d between contacts for different temperatures.

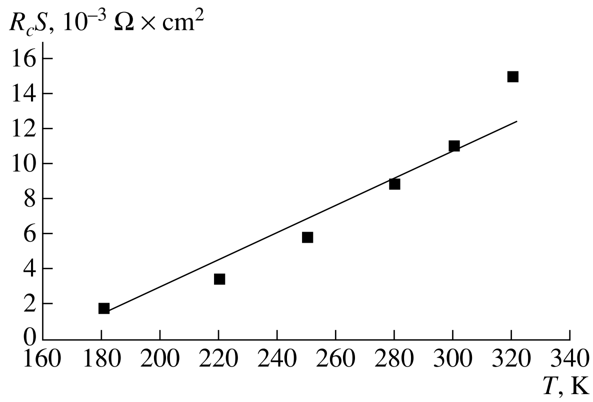

Fig. 2. Temperature dependence of the resistance per unit area for an In–GaN ohmic contact in the range 180–320 K.

3. THE MECHANISM OF CURRENT FLOW IN AN ALLOYED In–GaN OHMIC CONTACT

The resistance R_{meas} was measured for all the wafers with ohmic contacts. The results are as follows:

(i) at low temperatures, T = 77–180 K, the resistance R_{meas} strongly decreased as temperature increased; the bulk resistivity ρ of the semiconductor also strongly decreased, which can be attributed to freeze-out of the impurities;

(ii) at T = 180–320 K, R_{meas} slightly decreased as temperature increased; ρ also slightly decreased;

(iii) at T = 320–400 K, R_{meas} sharply increased with temperature.

The specific (per unit area) resistance of contact, R_cS, increased in the temperature range 180–400 K (Fig. 2, Table 2), in contradiction with the basic theories of current flow in the ohmic contact: thermionic, field-effect, and thermal field emission. According to these models, R_cS must either decrease or remain constant as temperature increases. The resistance increasing with temperature is typical of metals; therefore, we assumed that, similar to the case of alloyed In contact to GaP, the formation of ohmic contact is related to metallic shunts constituted by In atoms precipitated on imperfections, e.g., along the dislocations threading the space charge layer. In this case, the ohmic contact between the boundaries of shunts and the semiconductor bulk can arise owing to concentration of the electric field at the contact points.

As temperature increases from 180 to 320 K, the bulk resistivity ρ first decreases, reaches its minimum at ~250 K, and then slowly increases. This behavior can be attributed to variation in mobility in the initial material: according to [25], the electron mobility in n-GaN ($n \approx 10^{17}$ cm^{-3}) increases with temperature, reaches its peak at $T \approx 200$ K, and then decreases.

Table 2. Parameters of ohmic contacts

T, K	R_cS, 10^{-3} Ω cm^2	ρ, Ω cm	ρ_{In}, 10^{-6} Ω cm	R_{shunt}, 10^5 Ω	K, 10^7 shunts
180	1.8	1.35	4.7	1.2	7
220	3.4	0.4	6.4	1.7	5
250	5.8	0.225	5.8	2.1	4
280	8.8	0.247	8.8	2.3	3
300	11	0.27	11	2.6	2.5
320	19	0.3	19	3	2

Note: R_cS is the resistance of In–n-GaN ohmic contact per unit area; ρ, the bulk resistivity of GaN; ρ_{In}, the resistivity of In; and R_{shunt}, the resistance of ohmic contact calculated assuming that there are K shunts per unit area.

In the same temperature range, 180–320 K, the contact resistance R_c increased nearly by an order of magnitude. Assuming that the contact is formed by metallic shunts, we can estimate the number of shunts per unit area, N. Let the radius of a shunt be close to the atomic radius of In, 0.16 nm; then the cross-sectional area is $\sim 8 \times 10^{-16}$ cm^2. Let the shunt length be about the width of the space-charge layer, W. To determine W, it is necessary to know the height of the Schottky barrier φ_B between In and n-GaN. These data are not available in the literature, but the height of the Schottky barrier for Ti–n-GaN was determined in [26] as $q\varphi_B = 0.59$ eV. Since the electron work function of Ti, 3.83–4.33 eV, is close to that of In, 3.97 eV, we calculate the width of the space-charge layer W for $q\varphi_B = 0.6$ eV. At zero bias, $W = \sqrt{(2\varepsilon_s\varepsilon_0/qN_d)(V_d - kT/q)} \approx 10^{-5}$ cm (here $\varepsilon_s = 9.7$ is the dielectric constant of GaN; $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m, the permittivity of free space; $N_d = 5 \times 10^{16}$ cm^{-3}, the concentration of uncompensated donors; and $V_d \approx 0.5$ V, the diffusion potential).

The calculated data are listed in Table 2. As can be seen from Table 2, the number of shunts does not strongly vary with temperature. The calculated contact resistance per unit area coincides with the experimental one if we assume that 1 cm^2 of the contact area contains 10^7–10^8 metallic shunts. This value is close to the density of dislocations, $\sim 10^8$ cm^{-2}, in the GaN crystals under study. Therefore, we may assume that an alloyed ohmic In–GaN contact is formed by metallic shunts, which are In atoms precipitated on dislocations in the semiconductor.

This mechanism of current flow through ohmic contacts to GaN was not considered in literature, though the presence of shunts was suggested in the study of the reverse current flow in Ni–n-GaN Schottky diodes [27, 28]. Indium shunts in GaN p–n structures have been observed directly: as mentioned in [29], In diffuses along dislocations during thermal annealing of GaN LEDs with contact made of In–Sn oxide.

4. AN OHMIC CONTACT TO HIGH-RESISTIVITY AlN

To confirm our assumption on the formation of an ohmic contact, we have fabricated an alloyed ohmic In contact to semi-insulating n-AlN. The electron affinity of n-AlN is very low (0.6 eV [12]) and the Fermi level is virtually not pinned at its surface. Therefore, the formation of an ohmic contact to n-AlN, especially to that of high resistivity, is difficult. A high-resistance Schottky barrier is formed upon direct deposition of metallic films onto the AlN surface.

The studied AlN with the resistivity of $\sim 10^6$ Ω cm was deposited onto a sapphire substrate by MOCVD. Ohmic contacts were formed by alloying In at 650°C in a hydrogen atmosphere. The I–V characteristic of the alloyed contact was linear, though the contact resistance was close to that of the semiconductor bulk.

5. CONCLUSIONS

Studies of temperature dependence of the resistance of alloyed In–n-GaN ohmic contacts have shown that the contact resistance per unit area increases with temperature in the range 180–320 K, which is typical of metallic conduction. This dependence is inconsistent with thermionic or field emission theories.

We assume that In–n-GaN ohmic contact is formed by metallic shunts composed of In atoms precipitated on dislocations. The number of shunts per 1 cm^2 area of contact is 10^7–10^8, close to the measured density of dislocations, 10^8 cm^{-2}, in the initial GaN.

REFERENCES

1. E. H. Rhoderick, *Metal–Semiconductor Contacts* (Clarendon, Oxford, 1978; Radio i Svyaz', Moscow, 1982).
2. A. Y. C. Yu, Solid-State Electron. **13**, 239 (1970).
3. F. Ren, C. B. Vartuli, S. J. Pearton, et al., J. Vac. Sci. Technol. A **15**, 802 (1997).
4. Dae-Woo Kim and Hong Koo Baik, Appl. Phys. Lett. **77**, 1011 (2000).
5. A. Katz, S. Nakahara, W. Savin, and B. E. Weir, J. Appl. Phys. **68**, 4133 (1990).
6. T. Clausen and O. Leistiko, Appl. Phys. Lett. **62**, 1108 (1993).
7. S. N. G. Chu, A. Katz, T. Boone, et al., J. Appl. Phys. **67**, 3754 (1990).
8. H. Shimawaki, N. Furuhata, and K. Honjo, J. Appl. Phys. **69**, 7939 (1991).
9. K. Ip, Y. W. Heo, K. H. Baik, et al., Appl. Phys. Lett. **84**, 544 (2004).
10. L. L. Smith, R. F. Davis, M. J. Kim, et al., J. Mater. Res. **11**, 2257 (1996).
11. L. F. Lester, J. M. Brown, J. C. Ramer, et al., Appl. Phys. Lett. **69**, 2737 (1996).
12. *Properties Advanced Semiconductor Materials*, Ed. by M. E. Levinshtein, S. L. Rumyantsev, and M. S. Shur (Wiley, New York, 2001).
13. H. Morkoc, S. Strike, G. B. Gao, et al., J. Appl. Phys. **76**, 1363 (1994).
14. M. E. Lin, Z. Ma, F. Y. Huang, et al., Appl. Phys. Lett. **64**, 1003 (1994).
15. S. Prakashs, L. S. Tan, K. M. Ng, et al., in *Abstracts of International Conference on SiC and Related Materials* (Sheraton, 1999), p. 48.
16. J. D. Guo, C. I. Lin, M. S. Feng, et al., Appl. Phys. Lett. **68**, 235 (1996).
17. Z. Fan, S. N. Mohammad, W. Kim, et al., Appl. Phys. Lett. **68**, 1672 (1996).

18. Changzhi Lu, Hongnai Chen, Xiaoliang Lv, et al., J. Appl. Phys. **91**, 9218 (2002).
19. K. Suzue, S. N. Mohammad, Z. F. Fan, et al., J. Appl. Phys. **80**, 4467 (1996).
20. S. N. Mohammad, J. Appl. Phys. **95**, 7940 (2004).
21. J.-S. Jang and T.-Y. Seong, Appl. Phys. Lett. **76**, 2743 (2000).
22. Joon Seop Kwak, Ok-Hyun Nam, and Yongjo Park, J. Appl. Phys. **95**, 5917 (2004).
23. T. V. Blank, Yu. A. Gol'dberg, O. V. Konstantinov, et al., Pis'ma Zh. Tekh. Fiz. **30** (19), 17 (2004) [Tech. Phys. Lett. **30**, 806 (2004)].
24. P. Visconti, K. M. Jones, M. A. Reshchikov, et al., Appl. Phys. Lett. **77**, 3532 (2000).
25. W. Götz, N. M. Johnson, C. Chen, et al., Appl. Phys. Lett. **68**, 3144 (1996).
26. J. D. Guo, M. S. Feng, R. J. Guo, et al., Appl. Phys. Lett. **67**, 2657 (1995).
27. E. J. Miller, D. M. Schaadt, E. T. Yu, et al., J. Appl. Phys. **94**, 7611 (2003).
28. E. J. Miller, E. T. Yu, P. Waltereit, and J. S. Speck, Appl. Phys. Lett. **84**, 535 (2004).
29. Chin-Yuan Hsu, Wen-How Lan, and Yew Chung Sermon Wu, Jpn. J. Appl. Phys., Part 1 **44**, 7424 (2005).

Translated by D. Mashovets