Temperature influence on process of Ti/Al/Ni/Au contact formation to heterostructure AlGaN/GaN

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Temperature influence on process of Ti/Al/Ni/Au contact formation to heterostructure AlGaN/GaN.

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Abstract. This paper is dedicated to the experimental investigation of Ohmic contacts to the n+-doped region of the AlGaN/GaN transistor heterostructure based on Ti/Al/Ni/Au metallization. The Al-Ti-N system has been assessed on the basis of available thermodynamic descriptions for binary subsystems. The effect of annealing temperature on the specific resistance of Ohmic contact was studied.

1. Introduction

GaN-based transistor devices are widely used in defense and civil industries. This includes the use of the main component of the microwave monolithic integrated circuits (RF MIC) millimeter and submillimeter bands for communication systems, radar, radio astronomy, radiometry, etc. [1]. These materials have been applied moreover in the optoelectronic industry as the basis for LED crystals along with the use of wide bandgap GaN-based semiconductors as the basis of the transistors.

Multilayer metallization is mostly used in contact microelectronics technologies because of their better parameters (conductivity, adhesion to the surface, morphology). The multilayer contacts of Ti/Al that form compounds with a low work function are often used to form an ohmic contact to the n-type semiconductor [2-4]. For standard metallization is used gallium nitride-based Ti/Al/Ni/Au.

The hypothesis of the mechanisms of Ti/Al-based ohmic contact formation to the n-GaN is based on the appearance of the Ti_xN compound, which is a conductor. It begins to form during the deposition of titanium on the n-GaN surface and in the bulk of the titanium layer metallization during thermal annealing. Ti_xN formation temperature is in the range 200÷1000°C; because of this, titanium particles sprayed by various methods can form a thin layer of Ti_xN on the surface.

2. Al-Ti-N compounds

The analysis of the features of solid-state interaction processes in Al/Ti/GaN contacts during annealing on their parameters [5] showed that the contact is transformed into a structure consisting of phases that are the products of solid-phase interaction of titanium and aluminum. The presence of nitrides, intermetallics and ternary phases along with free titanium and aluminum makes it difficult to analyze the stability of Al/Ti/GaN contacts, requiring the detection of patterns of solid-phase reactions between contacting materials and changing the phase composition of these structures in the temperature range of contact formation and their operation.

In the ternary Al-Ti-N system, the following compounds can be formed: nitrides (AlN, TiN), aluminides (AlTi, Al_3Ti, $AlTi_3$, Al_3Ti_2, Al_2Ti). To analyze the stability of the two phases in the ternary system, it is necessary to take into account all possible chemical reactions. The phases do not interact with each other, i.e. they are thermodynamically stable, if in the considered temperature range for all the reactions ΔG> 0 and a connecting line can be made between these phases in ternary phase diagram.

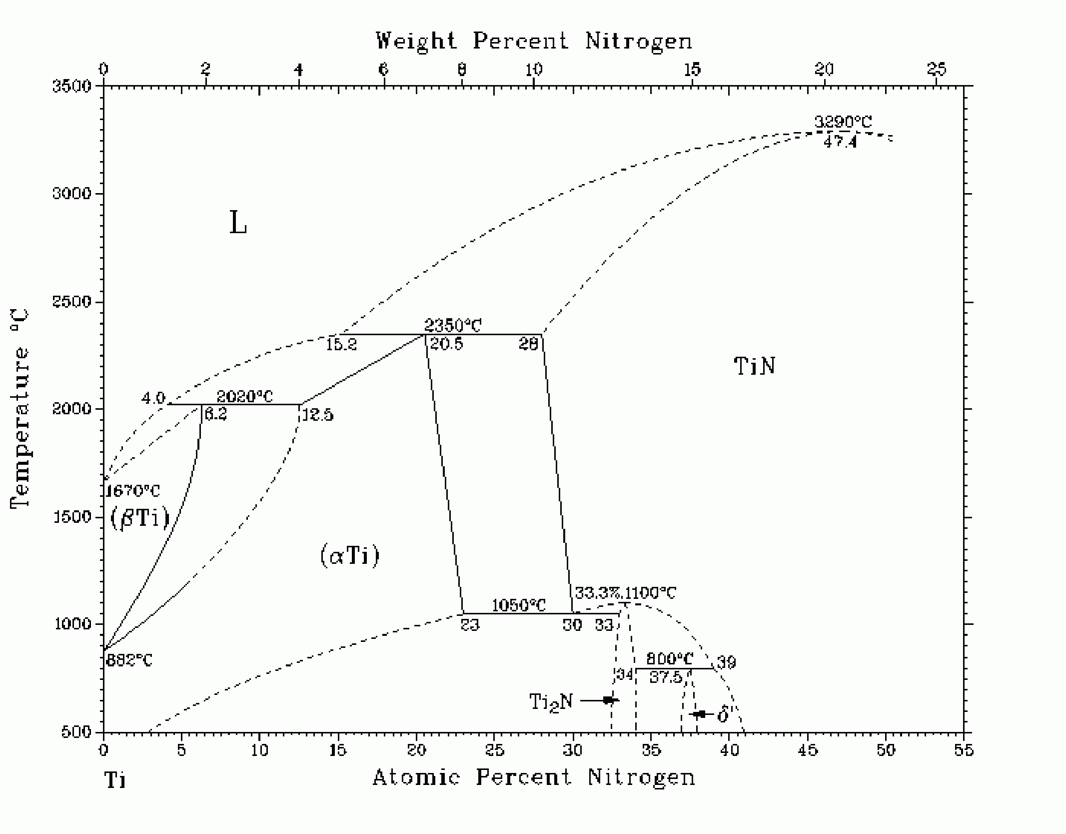

Figure 1. Titanium-Nitrogen phase diagram

According to the phase diagram (Figure 1) and [6, 7], at temperatures below 882°C, titanium has an α-Ti modification with a hexagonal close-packed lattice, at temperatures above 882°C – β-Ti with a cubic body-centered lattice. Because of this, it is necessary to consider separately the temperature ranges below and above 882°C for some compounds.

To analyze the stability of two phases in a ternary system, it is necessary to record all possible chemical interactions of these phases and calculate the temperature dependence of the change in the free Gibbs energy for each reaction. The phases do not interact with each other, i.e. are thermodynamically stable, if in the considered temperature range for all the reactions ΔG> 0, while on the ternary phase diagram, it is possible to draw a connecting line between these phases.

For example, in order to analyze the stability of titanium, aluminum, and nitrogen, it is necessary to write down the reaction equations for their interaction (Table 1).

Table 1. Gibbs free energy for reactions at different temperatures *T*.

Reaction	ΔG, KJ/(g·atom)				
	800°C	850°C	900°C	950°C	1000°C
1. Ti+N=TiN	-237	-231	-226	-222	-217
2. Al+Ti=AlTi	404	307	-64	-63	-62
3. 3Al+Ti=Al_3Ti	254	302	-128	-126	-124
4. 3Ti+Al=$AlTi_3$	-810	-889	-98	-98	-98
5. 2Ti+3Al=Al_3Ti_2	1649	1861	-117	-117	-116
6. Al+N=AlN	-206	-200	-194	-188	-183
7. Ti+2Al=Al_2Ti	121	141	-10	-0.8	-1.7

Thus, we can say that the most favorable temperature conditions for the formation of the better ohmic contacts are those up to 882°C, since free titanium goes to form a large number of different aluminides above this temperature. This reduces the possibility of the formation of titanium nitrides, which are necessary to obtain nitrogen vacancies, due to which the contact resistance decreases.

3. Experiment

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 the Kurt J. Lesker PVD 75 film deposition system. Annealing was performed using the rapid thermal annealing system Modular RTP-600S at a constant temperature for 30 s. Ohmic contact measurements were carried out on test structure for the transmission line method (TLM) [8]. To improve the accuracy of contact resistance measurements, we also used test structure [9]. Specific contact resistance was measured by the use of the Agilent B 1500 A semiconductor devices analyzer.

4. Results and Discussion

To investigate the effect of the annealing temperature on the properties of the contact, 8 samples were prepared. They were annealed at various temperatures in the range of 800-1000°C. The obtained values for the contact resistance are listed in Table 2. To explain the 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 φ_B. The total voltage U applied to the contact is expressed through capacity according to formula [10]

$$\varphi_B - U - \frac{kT}{q} = \frac{q\varepsilon\varepsilon_0 N_D S^2}{2C^2} \tag{1}$$

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, ε_0 is vacuum permittivity. Capacitance-voltage characteristics were measured for all samples in the voltage range of 0-10 V. In the first section of the capacitance-voltage characteristic ($\partial^2C/\partial U^2 > 0$), capacity of the first contact is charging. In the second section ($\partial^2C/\partial U^2 < 0$), the second capacitor is charging and capacity reaches the maximum. In this case, in the first section, the first Ohmic contact plays the role of a barrier and the second is Ohmic. Therefore, to measure the Shottky barrier in the rectifying contact, we should use the first section of the capacitance-voltage characteristic. Values of φ_B were determined for all samples by comparing the measured capacitance-voltage characteristic with the theoretical curve (3). Obtained data are listed in Table 2.

Table 2. Resistance ρ_k, transition resistance ρ_T, Schottky barriers height φ_B for contact samples, annealed at different temperatures *T*.

Sample number	*T*, °C	ρ_T, Ω·mm	φ_B, eV
1	-	-	1.21
2	800	0.35	1.04
3	850	0.32	0.918
4	880	0.07	0.903
5	885	0.28	0.95
6	900	0.67	1.05
7	950	0.77	1.08
8	1000	1.88	1.47

5. Conclusions

The formation of Ohmic contacts to the n+-doped region of AlGaN/GaN heterostructure based on Ti/Al/Ni/Au metallization through annealing was studied. The optimum temperature and annealing time are 880°C and 30 seconds, respectively. The specific resistance of the contact is 0.07 Ω·mm. The obtained resistivity values are lower than those obtained by other authors [11].

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References

[1] Luther P and Mohney S E 1997 *Appl. Phys. Lett.* **70** 57
[2] Kong X 2012 *J. Phys. D: Appl. Phys.* **45** 1
[3] Durbha, Pearton S J, Abernaty C R, Lee J W and Holloway P H 1996 *J. Vac. Sci. Tech B* **14** 2582
[4] Morkoc H, Strike S, Gao G B, Lin M E, Sverdlov B and Burns M 1994 *J. Appl. Phys* **76** 1363
[5] Kireyev V A 1975 *Methods of Practical Calculations in Thermodynamics of Chemical Reactions (in Russian)* (Moscow: Chemistry) p 536
[6] Samsonov G V and Vinitskiy I M 1976 *Refractory compounds (in Russian)* (Moscow: Metallurgy) p 560
[7] Hultgren R R 1963 *Selected values of thermodynamic properties of metals and alloys* (New York: Wiley–Interscience) p 963
[8] Reeves G and Harrison H B 1982 *IEEE Electr. Device Lett.* **3** 111
[9] Shostachenko S 2015 *Physics Procedia* **72** 419
[10] Sze S M and Kwok Ng K 2007 *Physics of Semiconductor Devices* (NJ, Hoboken: Wiley-Interscience) ed. 3 p 832
[11] Blank T and Gol'dberg Yu 2007 *Semiconductors* **47** 1263