Study of Ti/Si/Ti/Al/Ni/Au ohmic contact for AlGaN/GaN HEMT

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Abstract. This paper is dedicated to the experimental investigation of Ohmic contacts to the n+-doped region of AlGaN/GaN transistor heterostructure based on Ti/Si/Ti/Al/Ni/Au metallization. Effect of annealing temperature on the specific resistance of Ohmic contact was studied. Ohmic contact with the resistance of 3.4·10⁻⁶ Ω·cm² was formed by optimization of the annealing temperature and introduction of the additional doping silicon layer.

1. Introduction

Transistor devices on GaN-based heterostructures are widely used, both in the defense and civil industry. For example, as the main component of the microwave monolithic integrated circuits (RF MIC) millimeter and submillimeter bands for communication systems, radar, radio astronomy, radiometry, etc. [1]. Along with wide bandgap semiconductors based on GaN as a basis for the transistors, these materials have been applied in the optoelectronic industry as a base for the LED crystals.

Currently, in multilayer metallization contact microelectronics technologies are mostly used because of their best parameters (conductivity, adhesion to the surface morphology). For forming an ohmic contact to the n-type semiconductor is most often used by the multilayer contacts Ti/Al, the heat treatment in forming compounds with a low work function [2-3]. Standard metallization is a gallium nitride-based Ti/Al/Ni/Au.

The hypotheses on the mechanisms of formation of ohmic contact to the n-GaN-based Ti/Al metal system based on the appearance Ti₅N compound, which is a guide, begin to form during the deposition of titanium on the n-GaN surface and in the bulk of the titanium layer metallization during thermal annealing. Ti₅N formation temperature is in the range 200⁰ - 1000⁰ C, because of this titanium particles sprayed by various methods, can form a thin layer on the surface TiₓN.

In [4] indicated that the work function of Ti₅N is only 3.74 eV, which is on the theory corresponds to the formation of the Schottky ohmic contact to the n-GaN. The low specific contact resistance ohmic contact metal-GaN (to 10⁻⁶ - 10⁻⁷ Ω·cm² at high concentrations of carriers in a semiconductor) is associated with the formation of nitrogen vacancies due to the interaction with the semiconductor contact metallization. These nitrogen vacancies form a layer under the contact, playing the role of high-alloyed layer [5-6]. In literature, there are several options for plating systems, basic presented in Table 1.
Table 1. Ohmic contact to n-GaN

| Contact system | Layer thickness, nm | Annealing temperature, °C | Contact resistance, Ohm·mm | Source |
|----------------|---------------------|---------------------------|---------------------------|--------|
| Ti/Al/Ni/Au    | 30/200/40/10        | 800                       | 0,50                      | [7]    |
| Ti/Al/Ni/Au    | 20/220/55/45        | 870                       | 0,30                      | [8]    |
| Ti/Al/Mo/Au    | 15/60/35/50         | 850                       | 0,32                      | [9]    |
| Ti/Al/Ti/Au    | 15/60/35/50         | 750                       | 0,54                      | [10]   |
| Ta/Si/Ti/Al/Ni/Ta | 5/5/20/120/40/30 | 850                       | 0,27                      | [11]   |
| Ta/Ti/Al/Mo/Au | 10/30/90/40/25     | 850                       | 0,41                      | [12]   |
| Si/Ti/Al/Ni/Au | 3 nm Si             | 800                       | 0,23                      | [13]   |
|                | 6 nm Si             |                           | 0,26                      |        |

The thickness of metal system Ti / Al / Ni / Au is selected on the basis of experimental data. According to [14], on the one hand, should be sufficient for the titanium Ti₅N formation layer, and the other titanium layer should not interfere with the formation of an aluminum contact. Aluminium thickness also has a certain range of variation [15]. Aluminium should establish contact and prevent the diffusion of nickel and gold, as well as contribute to the occurrence of phase Al₃+xTi (x < 1). In general, it should be emphasized that during the annealing is a series of complex physical and chemical reactions and the products of which are still not fully understood.

2. Experimental method

We used AlGaN/GaN heterostructure. Ti/Al/Ni/Au (35/135/50/100 nm) multilayer metallization was deposited on it by a resistive evaporation method with the use of Kurt J. Lesker PVD 75 film deposition system. Annealing was performed using rapid thermal annealing system Modular RTP-600S at a constant temperature for 30 s. Ohmic contact measurements were carried out on test structure for transmission line method (TLM) [15]. To improve the accuracy of contact resistance measurements we also have used test structure [4]. Specific contact resistance was measured by the use of the Agilent B 1500 A semiconductor devices analyzer.

3. Results and discussion

To investigate substrate heterostructure AlGaN/GaN metallization system Ti/Al/Ni/Au. (35/135/50/100 nm) was deposited and studied in details in work [4]. Now we propose Si doping contact system Ti/Si/Ti/Al/Ni/Au.

To change the height of the Schottky barrier it is necessary to change the material, drawing a laborious study of intermetallic phases formed during heat treatment. Another approach may be an increase in carrier density, which helps to give forming an ohmic contact at lower annealing temperatures and reduce the width of the barrier, which also affects the specific contact resistance in the direction of its decrease.
When growing a semiconductor heterostructure contact layer dopant is added (in this case silicon with a concentration of $3 \cdot 10^{18} \text{ cm}^{-3}$ was used). To improve the art known concentration must be used, but time-consuming method of ion implantation. But there is another way to solve the problem - to introduce a system of dopant layers of metallization (between the heterostructure and metallization). This method makes sense since after annealing the mixing layers and silicon will still be required in the contact area and only. Also, this method is good because it is done in the same process area as the application of the metallization layers, that is, there is no need to make an extra process step.

The new system has the form metallization layers Ti/Si/Ti/Al/Ni/Au (5/6/30/135/50/100 nm) sublayer 5 nm titanium is required to provide greater adhesion to the semiconductor surface since layering occurred on the substrate without heating. The sample was treated at 800-1000 °C (Figure 2). Introduction silicon is possible to reduce specific contact resistance to $3.76 \cdot 10^{-7} \text{ Ohm} \cdot \text{cm}^2$, which is lower than resistance obtained in previous work without Si [16].

### Table 2. Specific contact resistance after annealing.

| Sample | Annealing temperature, °C | Concentration, cm$^{-3}$ | Specific contact resistance, $10^{-6}$ Ohm$ \cdot \text{cm}^2$ |
|--------|---------------------------|--------------------------|---------------------------------------------------------|
| 1      | 800                       | $7.50 \cdot 10^{19}$     | 19.9                                                     |
| 2      | 850                       | $1.00 \cdot 10^{20}$     | 6.18                                                     |
| 3      | 880                       | $1.20 \cdot 10^{20}$     | 1.6                                                      |
| 4      | 885                       | $1.75 \cdot 10^{20}$     | 3.2                                                      |
| 5      | 900                       | $4.00 \cdot 10^{20}$     | 0.38                                                     |
| 6      | 950                       | $8.50 \cdot 10^{19}$     | 18.5                                                     |
| 7      | 1000                      | $7.50 \cdot 10^{19}$     | 35                                                       |

![Figure 1. Contact resistance for Ti/Si/Ti/Al/Ni/Au](image)

As seen from Table 2 and Figure 1, the minimum resistivity for samples with metallization Ti/Si/Ti/Al/Ni/Au is $3.76 \cdot 10^{-7} \text{ Ohm} \cdot \text{cm}^2$ and achieved at a temperature of 900 °C. Therefore, to solve
this problem, a study was conducted of processes of forming an ohmic contact with the subsequent optimization of the contact system.

The sequential annealing can determine the stages of forming an ohmic contact, but you can’t explain the mechanism of formation of the contact and charge transport.

4. Conclusion

This study is about formation of an ohmic contact to the n-region AlGaN/GaN heterostructure during annealing the metallization system Ti/Si/Ti/Al/Ni/Au. To reduce contact resistance (resistivity and specific transition) we proposed to introduce dopant providing in the metallization during annealing increase the carrier concentration in the contact region. Optimum annealing time and temperature are respectively 900°C and 30 seconds. The specific transitional resistance is \(3.4 \times 10^6\) Ohm \(\times\) cm\(^2\). The obtained resistivity value is lower than those obtained by other authors [13] because of the introduction of dopant in the metallization system, which is caused by the difference process and the difference of layer thicknesses, forming a contact. Also presumably selected metallization system may be more stable due to the presence of the underlayer Ti, performing the role of an adhesive layer.

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