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Fabrication of ohmic contact based on platinum to p-type compositionally graded AlGaAs layers

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Abstract. Novel metallization scheme was proposed for ohmic contact formation to compositionally graded p-type AlGaAs. A metal multilayers of Ti/Pt/Au, Pt/Ti/Pt/Au and Pt/Ti/Ni/Au were deposited by thermal evaporation using electron gun and resistance heater. The contacts were sequentially annealed by rapid thermal annealing system in N₂ atmosphere at various temperatures (in the range from 350°C to 550°C). The duration of annealing step was 2 minutes. The as-deposited Pt/Ti/Pt/Au and Pt/Ti/Ni/Au multilayer metallizations had resistivities of \(1.4 \times 10^{-5} \, \Omega \cdot \text{cm}^2\) which have been gradually deteriorated after each subsequent annealing. The current-voltage characteristics of the ohmic contacts to compositionally graded p-type AlGaAs epitaxial layers were studied and discussed.

1. Introduction

AlGaAs/GaAs heterostructures are commonly applied for fabrication of semiconductor devices such as Heterojunction Bipolar Transistor, Monolithic Microwave Integrated Circuit [1], infrared light-emitting diode [2], laser diode [3], infrared photodetector [4] and solar cell [5].

Stable and low-resistance ohmic contacts are critical for performance and reliability of the devices. Their preparation and characterization require many technological efforts. Ohmic contacts with low specific resistance to p-type AlGaAs are essential for microwave and optical devices such as bipolar transistors, p-i-n diodes and diode lasers. The metallization should have smooth surface and good interface morphology, very low contact resistance, sharp edges and good thermal stability to meet the demand of the modern devices. One of the most important criteria for an ohmic contact is its thermal stability [6] which is usually assessed based on the test measurements performed at typical temperature for investigated material (400°C for GaAs) [7].

The fundamental steps in metallic contact fabrication are: the selection of proper metals, semiconductor surface cleaning, the subsequent deposition of each metallic layer and annealing of the contact. In our experiment the surface was chemically etched and rinsed before metal deposition in standard procedure [8]. Further, the Ti and Pt layers were deposited by electron beam and gold layers were evaporated from resistance heater. At the next step the annealing at various temperatures was performed. Afterwards the contacts were characterized using current-voltage (I-V) measurements. It is well known, that post-deposition contacts annealing is useful for stress reduction between the metallic layers and/or initiation of reaction between metal and semiconductor.

Typically, a heavy doped GaAs cap layer is applied to achieve a good ohmic contact to p-type AlGaAs layer. However, such a layer strongly degrades breakdown voltage of the device [9].
Therefore, in the present work, we focused on the development of low resistance ohmic contact based on platinum to p-type compositionally graded AlGaAs layer [10]. Application of GaAs cap layer was unavoidable because it prohibited the oxidation of AlGaAs layer oxidation and improved the properties of the metallic contact to semiconductor. Previous works indicated that the use of low doped GaAs cap layer did not fulfill requirements for good quality contact fabrication. Thus, the heavy doped GaAs cap layers, with thickness of 20 nm, have to be applied.

2. Experimental details

A cross-sectional diagrams of the AlGaAs/GaAs structure is shown in figure 1. The structures were grown by metalorganic vapor phase epitaxy (MOVPE) method.

| Layer                        | Composition    | Doping Density  | Thickness |
|------------------------------|----------------|-----------------|-----------|
| Cap layer                    | p++ GaAs       | $N_a = 3 \times 10^{18} \div 3 \times 10^{19} \text{ cm}^{-3}$ | 0.02 µm   |
| Compositionally graded layer | Al$_x$Ga$_{1-x}$As | $N_a = 3 \times 10^{18} \text{ cm}^{-3}$ | 0.5 µm    |
| Nucleation layer             | p-GaAs         | $N_a = 3 \times 10^{18} \text{ cm}^{-3}$ | 0.01 µm   |
| Buffer layer                 | SI GaAs        | $N_a = 3 \times 10^{18} \text{ cm}^{-3}$ | 0.22 µm   |
| Semi-insulating substrate    |                |                 |           |

Figure 1. Cross-sections scheme of semiconductor structure with compositionally graded layer

The $p$-type GaAs layer of 20 nm thick was applied as a cap layer to prevent oxidation of aluminum. The cap layer protected the active layer by inhibition of point defects generation at the subsurface of AlGaAs. It results in the improvement of electrical characteristics of the device [11].

The transfer length method (TLM), originally proposed by Shockley [12, 13] was used to determine the specific-contact resistivity. Deposited metallization were examined by TLM technique for which mesas were etched using $H_3PO_4:H_2O_2:H_2O$ (1:1:40). Next, rectangular pads (80×90 µm) were patterned by lift-off method on these electrically isolated mesas. Further, the Ti/Pt/Au (5/30/150 nm), Pt/Ti/Pt/Au (5/5/30/150 nm) and Pt/Ti/Ni/Au (5/30/150 nm) multilayer contacts were evaporated on the mesas. Prior to metal deposition, the native oxide was removed by etching of the samples in $HCl:H_2O$ (1:1) solution for 30 seconds, followed by a deionized water rinsing and drying in $N_2$ flow. The metallic contact was deposited in sequence on the substrate under a vacuum conditions with a base pressure lower than $10^{-6}$ mbar. Metals stack and layers thicknesses of the multilayer metallizations of ohmic contact were selected on the basis of our previous study. Electron-beam evaporation was used to deposit titanium, nickel and platinum, while gold was deposited by thermal evaporation. The influence of annealing process of the contact on the properties of investigated metallization stacks was evaluated. Rapid thermal annealing of the samples was preformed in an nitrogen ambient. The temperature of the annealing was changed in the range from 350 to 410°C. The duration of annealing step was 2 minutes. On-wafer current-voltage measurements were performed at room temperature.

The titanium layer in multilayer metallization was introduced to improve the adhesion of ohmic contact while the gold layer allowed us to reduce the contact resistance. The nickel layer in Pt/Ti/Ni/Au multilayer metallization was inserted to check the role of second platinum layer in Pt/Ti/Pt/Au multilayer metallization.

3. Results

The current-voltage characteristics for the as-deposited and annealed contacts were measured (Fig. 2-4) between ohmic pads with the spacing of 10 µm. The optical microscope images of multilayer metallizations Ti/Pt/Au, Pt/Ti/Pt/Au and Pt/Ti/Ni/Au, annealed at 400°C, 500°C and 550°C are shown.
in Fig. 5-6, respectively. The as deposited Ti/Pt/Au contact was not linear (table 1). Annealing of that contact at 350ºC assures its linearity (Fig. 2).

Table 1. Specific resistances of the contacts: as-deposited and after annealing in various temperatures.

| Temperature of the annealing (ºC) | Specific resistance (Ω·cm²) |
|-----------------------------------|-----------------------------|
| Ti/Pt/Au metalization             | Pt/Ti/Pt/Au metalization    | Pt/Ti/Ni/Au metalization |
| As-deposited                      | Nonlinear $I$-$V$ characteristics | 1.4·10⁻⁵      | 1.4·10⁻⁵ |
| 350                               | 2.8·10⁻⁵                   | 2.2·10⁻⁵       | Nonlinear $I$-$V$ characteristics |
| 400                               | 2.8·10⁻⁵                   | 3·10⁻⁵         |
| 425                               | 2.8·10⁻⁵                   | 3.6·10⁻⁵       |
| 450                               | 3.2·10⁻⁵                   | 4.8·10⁻⁵       |
| 475                               | 6.4·10⁻⁵                   | Nonlinear $I$-$V$ characteristics |
| 500                               | Nonlinear $I$-$V$ characteristics |
| 550                               | Nonlinear $I$-$V$ characteristics |

Figure 2. Current-voltage characteristics of Ti(5 nm)/Pt(30 nm)/Au(150 nm) contact as-deposited and after annealing at various temperatures (350ºC ÷ 550ºC)

Figure 3. Current-voltage characteristics of Pt(5 nm)/Ti(5 nm)/Pt(30 nm)/Au(150 nm) contact as-deposited and after annealing at various temperatures (350ºC ÷ 550ºC)
As-deposited Pt/Ti/Pt/Au and Pt/Ti/Ni/Au multilayer metallizations were ohmics (Fig. 3 and 4), with specific resistance of $1.4 \cdot 10^{-5} \Omega \cdot \text{cm}^2$ (Table 1). The role of platinum layer deposited on the semiconductor surface in the Pt/Ti/Pt/Au and Pt/Ti/Ni/Au system was found to be essential in obtaining better electrical properties of the metallic contact compared to non-annealed Ti/Pt/Au contact. During annealing the Pt layer diffused into the titanium layer in Ti/Pt/Au metallization and formed the ohmic contact with specific contact resistance of $2.8 \cdot 10^{-5} \Omega \cdot \text{cm}^2$ (Table 1).

Figure 4. Current-voltage characteristics of Pt(5 nm)/Ti(5 nm)/Ni(30 nm)/Au (150 nm) contact as-deposited and after annealing at various temperatures (350ºC ÷ 550ºC)

Figure 5. Optical images of the surface of Ti(5 nm)/Pt(30 nm)/Au(150 nm) metallization on $p$-type compositionally graded layer after annealing at: 400ºC (a), 500ºC (b) and 550ºC (c) for 2 minutes

Figure 6. Optical images of the surface of Pt(5 nm)/Ti(5 nm)/Pt(30 nm)/Au(150 nm) metallization on $p$-type compositionally graded layer after annealing at: 400ºC (a), 500ºC (b) and 550ºC (c) for 2 minutes

The surface of Pt/Ti/Pt/Au contact after annealing at 500ºC was still smooth (Fig. 6(c)) compared to Ti/Pt/Au contact, annealed at the same temperature (Fig. 5(c)). It meant, that annealing at this temperature started to degrade the Ti/Pt/Au and Pt/Ti/Pt/Au ohmic contacts multilayer structure. Also, the specific contact resistivity increased steadily with the increase of annealing temperature above 450ºC (table 1), what corresponded with escape of arsine from GaAs. Further increase of the annealing temperature above 500ºC caused the nonlinearity of $I-V$ characteristics in each contact.
The role of the second Pt layer in the Pt/Ti/Pt/Au system was also investigated. It was observed that platinum played also essential role in obtaining better electrical performance of the contact in comparison with Pt/Ti/Ni/Au contact. In this case, platinum in Pt/Ti/Pt/Au and nickel in Pt/Ti/Ni/Au multilayers, operated as a barriers for diffusion of Au layer. The as-deposited Pt/Ti/Ni/Au multilayer contact to compositionally graded p-type AlGaAs had ohmic character. The annealing of this contact, above 350ºC, dramatically deteriorated its electrical parameters – the current-voltage characteristics were not linear (Fig. 4). Pt and Ti layers in Pt/Ti/Ni/Au multilayer metallization had the thickness of 5 nm. This is the reason of dramatic deterioration of Pt/Ti/Ni/Au contact characteristics. During the annealing step, the Ni layer diffused into the Pt/Ti bilayer in Pt/Ti/Pt/Au metallization and decreased the electrical parameters (Table 1) of the contacts.

Additionally, the optical image of the Pt/Ti/Ni/Au metallization (Fig. 7), annealed above 400ºC, showed that Au has been soluted in Ni stop diffusion layer. In general, higher-melting-point metals exhibit lower-bulk diffusivities [14] what explained well the superiority of Pt for the application as diffusion barrier in comparison to Ni.

4. Conclusions
We have investigated the electrical properties of Ti/Pt/Au, Pt/Ti/Pt/Au and Pt/Ti/Ni/Au ohmic contacts to p-type compositionally graded AlGaAs layers by current-voltage (I-V) measurement performed at the function of annealing temperature ranging from 350ºC to 550ºC. A specific contact resistivities as low as 1.4·10^{-5} \( \Omega \text{cm}^2 \) have been obtained for ohmic contacts Pt/Ti/Pt/Au and Pt/Ti/Ni/Au without annealing. The specific contact resistivity of 1.4·10^{-5} \( \Omega \text{cm}^2 \) of Pt/Ti/Pt/Au contact remained constant up to 400ºC, next, decreased steadily to 4.8·10^{-5} \( \Omega \text{cm}^2 \) with the increase of annealing temperature to 475ºC. Further growth of annealing temperature resulted in nonlinear I-V characteristics of the contact. The role of the second Pt stop diffusion layer in the Pt/Ti/Pt/Au system was also investigated. It was found that its presence was essential in obtaining better electrical performance in comparison with the Pt/Ti/Ni/Au contacts containing the Ni stop diffusion layer. The specific contact resistivity of 1.4·10^{-5} \( \Omega \text{cm}^2 \) of Pt/Ti/Ni/Au contact was constant up to 400ºC, increase of the annealing temperature dramatically deteriorated the electrical parameters of the contact – the current-voltage characteristics became nonlinear (Fig. 4).

The improvement of the electrical properties of Ti/Pt/Au contacts after annealing was observed, compared to as-deposited ones. The Ti/Pt/Au contacts were found to be relatively stable during annealing up to 500ºC but as-deposited contacts were nonlinear. At an elevated temperature the Pt diffused into the Ti layer what assured the formation of the ohmic contact to compositionally graded p-type AlGaAs layer.

Results indicated that Ti/Pt/Au and Pt/Ti/Pt/Au contacts are suitable for the high temperature applications. Using elaborated multilayer metallization, photodetectors with compositionally graded active area were fabricated by utilizing standard photolithography and lift-off processes of metallization. Examined ohmic contacts have also excellent adhesion to the compositionally graded AlGaAs layer.
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