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Modification of the sheet resistance under Ti/Al/Ni/Au Ohmic contacts on AlGaN/GaN heterostructures

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A B S T R A C T

This paper reports on the modification of the sheet resistance under Ti/Al/Ni/Au Ohmic contacts on AlGaN/GaN heterostructures, studied by means of Transmission Line Model (TLM) structures, morphological and structural analyses, as well as computer simulations. In particular, the contacts exhibited an Ohmic behaviour after annealing at 800 °C, with a specific contact resistance $\rho_C = (2.4 \pm 0.2) \times 10^{-5}\,\Omega\,cm^2$, which was associated to morphological and structural changes of both the metal layer and the interface. Interestingly, TLM analyses gave a value of the sheet resistance under the contact ($R_{SK} = 26.1 \pm 5.0\,\Omega/\square$) significantly lower than that measured outside the metal pads ($R_{SH} = 535.5 \pm 12.1\,\Omega/\square$).

The structural changes observed near the metal/AlGaN interface can be responsible for this electrical modification deduced by TLM analyses. As a matter of fact, two-dimensional TCAD simulation confirmed that the sheet resistance under the contact and the two-dimensional current distribution are affected by the electrical properties of the alloyed metal/semiconductor interface.

1. Introduction

In the last two decades, the wide band gap semiconductor Gallium Nitride (GaN) has become increasingly important, due to the possible applications in optoelectronics, high-power and high-frequency devices, and sensors [1–3]. In particular, owing to the outstanding physical and electronic properties, such as a wide band gap (3.4 eV), a high critical field (3.3 MV/cm) [4] and a high electron saturation velocity (3×10^7 cm/s) [5], GaN and its related ternary alloys $Al_xGa_{1-x}N$, are considered among the best candidates to replace the Silicon-based devices in next generation of high efficiency power conversion systems [6,7].

One of the unique features of GaN-based materials is the possibility to grow AlGaN/GaN heterostructures, which can be used for the fabrication of high electron mobility transistors (HEMTs), taking advantage of the formation of a two dimensional electron gas (2DEG) generated at the AlGaN/GaN interface by the spontaneous and piezoelectric polarization charges [8].

Ohmic contacts are very important bricks for the fabrication of power devices. In particular, in the case of GaN-based HEMTs, good source-drain Ohmic contacts are required to minimize the device on-resistance and, hence, the overall conduction losses. In this context, while enormous efforts have been done in the last decades in the study of Ohmic contacts formation to GaN materials [9], the full comprehension of the carrier transport mechanisms at metal/AlGaN/GaN interfaces remains object of intensive scientific debate.

Generally, Ti- based multilayers are used to obtain Ohmic contacts to GaN-materials [10,11], where Ti/Al/Ni/Au stacks are among the most common solutions [12,13]. However, in such complex schemes, there are several parameters that influence the contact properties, like the Ti/Al ratio [14,15], the Ti thickness [16], the presence of defects on AlGaN surface [17], etc. In order to achieve an Ohmic behaviour [9] on Ti/Al/Ni/Au stacks, thermal annealing processes, typically in the temperature range of 800–900 °C, are needed. These processes can lead to significant structural modifications of the region under the contact, including the formation of different phases or even the appearance of metal protrusions at the interface [18–20].

The method which is commonly used to evaluate the specific contact resistance (ρ_C) in Ohmic contacts is the Transmission Line Model (TLM) [21,22]. Besides the contact properties, this method also allows

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to determine the sheet resistance of the semiconductor (R_{SH}), from the linear correlation between the total resistance (R_T) and the TLM pads distance (d) [22]. However, this model is based on the assumption that the sheet resistance of the semiconductor outside the contacts, R_{SH} (Ω/□), is identical to the value assumed under the contacts, R_{SK} (Ω/□) [23]. Hence, since the 2DEG is extremely sensitive to the surface conditions, in the presence of thermal induced reactions occurring at the interface between the Ti/Al-based stacks and the AlGaN, this general assumption of the TLM cannot be valid, and the sheet resistance under the contact can be modified with respect to its value outside the contact ($R_{SK} \neq R_{SH}$). As a matter of fact, modification of the electrical properties of n-type GaN below the contacts has been already deduced by temperature dependent electrical measurements in Ohmic contacts [24].

To take into account this possibility and to determine the value of the sheet resistance under the contact R_{SK}, the standard TLM method can be corrected, performing an additional measurement of the so called *end contact resistance* (R_E), defined as the resistance due to the voltage drop at the end of the contact [22,25]. More details on the definition of R_E are reported in Section 3.2.

Many studies, in the last decades, reported on the modification of the sheet resistance under the Ohmic contacts on different semiconductors materials, e.g., silicon (Si), silicon carbide (SiC) or gallium arsenide (GaAs) [23,26–28]. Typically, in these works lower values of R_{SK} with respect to R_{SH} have been determined, whereas only in few cases the value of R_{SK} was found to be higher than R_{SH}. As an example, Si/Co contacts on SiC gave R_{SK} values of about one order of magnitude lower than R_{SH}, which has been related to the alloying with the substrate due to the silicidation process of the Si/Co stack during thermal annealing [26]. Similar results and analogous interpretation has been reported for Al/Sb metallization on Si substrates [23]. More extensive works have been reported in the case of Ohmic contacts on GaAs materials, where values of R_{SK} either lower or higher than R_{SH} have been measured, depending on the processing conditions. In particular, AuGe/Ni/Au contacts on GaAs substrates resulted into a R_{SK} lower than R_{SH}, ascribed to saturation of Ge doping under the contact during annealing. On the other hand, a R_{SK} higher than R_{SH} was related to the absorption, during annealing, of part of the GaAs surface into the contact, thus leaving a thinner and more resistive interfacial layer [27]. Similar behaviour has been reported for Pt metallization on GaAs, where the increase of R_{SK} has been attributed to the formation of alloyed phases (e.g., PtAs, PtGa), resulting in a reduction of the GaAs layer thickness [28]. Recently, Hajlasz et al. [29] reported on the determination of the sheet resistance under Ti/Al Ohmic contacts on AlGaN/GaN heterostructures. In particular, the lower value of R_{SK} (236.9 Ω/□) with respect to R_{SH} (505.8 Ω/□) was explained by the extraction of nitrogen atoms from the semiconductor due to the formation of an interfacial TiN layer. Indeed, the reaction occurred at the metal-semiconductor interface lead to the formation of N-vacancies, which act as donors and contribute to the reduction of the sheet resistance under the contact. The authors' conclusion was that a similar effect should occur also in other alloyed contacts, involving the formation of TiN [29].

The modification of the semiconductor sheet resistance under Ohmic contacts remains still a debated topic. In particular, the topic deserves additional investigation in the case of GaN-based systems, for which only very limited literature data are still available.

In this paper, the behaviour of Ti/Al/Ni/Au Ohmic contacts on AlGaN/GaN heterostructures has been studied, correlating the electrical measurements to morphological and structural analyses of the contact and interfaces. In particular, a sheet resistance under the contact significantly lower than its counterpart outside the contact has been determined by electrical measurements. The results were attributed to the interface structural modification occurred upon thermal annealing and supported by technology computer aided design (TCAD) simulation.

2. Experimental

The experiments have been carried out using AlGaN/GaN heterostructures grown on 6-in. Si wafers. The AlGaN layer had a thickness of 16 nm and an Al concentration of 26%, which were determined by Transmission Electron Microscopy (TEM) and photoluminescence measurements, respectively. The sheet carrier density of the 2DEG was 7.45×10^{12} cm^{-2}, as determined by Hall measurements.

The metal contacts have been obtained by sputtering a Ti/Al/Ni/Au multilayer with the following metal thickness values: Ti = 15 nm, Al = 200 nm, Ni = 50 nm, Au = 50 nm. For the electrical characterization of the contacts, linear TLM (L-TLM) patterns have been defined by using standard photolithography and lift-off of the metals. The TLM patterns consisted in rectangular pads of length L = 100 μm and width W = 200 μm. The distance d between adjacent TLM pads varied between 20 and 100 μm. The lateral isolation of the TLM patterns was obtained by a plasma etch. In order to obtain Ohmic characteristics, the contacts were subjected to Rapid Thermal Annealing (RTA) in Ar for 60 s in a Jipelec JetFirst furnace at a temperature of 800 °C. The current voltage (I–V) measurements were carried out on several TLM patterns using four point probe configuration in order to eliminate the probe resistance contribution. The measurements were performed on a Karl Suss Microtec probe station equipped with a HP 4156B parameter analyzer. Unpatterned ("blanket") Ti/Al/Ni/Au samples were used for the structural and morphological analyses.

The structural characterization of the layers was carried out by X-ray diffraction (XRD) in grazing incidence mode (0.5°) using a Smartlab Rigaku diffractometer, equipped with a rotating anode of Cu Kα radiation operating at 45 kV and 200 mA. High resolution Transmission Electron Microscopy (TEM) in cross section was performed using a 200 kV JEOL 2010 F microscope, equipped with Energy Filtered Transmission Electron Microscopy (EFTEM). The morphological analysis of the contacts surface was carried out by Atomic Force Microscopy (AFM), using a Veeco Dimension 3100 microscope.

Two-dimensional TCAD simulations have been carried out by means of the ATLAS device simulation tool by SILVACO, in order to visualize the potential distribution under the contact in TLM structures [30].

3. Results and discussion

3.1. Electrical properties of the contacts

Initially, the electrical properties of the Ti/Al/Ni/Au contacts have been evaluated using the standard TLM method [22]. Accordingly, rectangular planar contacts (length L, width W) have been fabricated at different distances d one to each other. Then, the total resistance R_T is determined from I-V measurements performed between two adjacent contacts and is plotted as a function of the pad distance d.

In the standard TLM formulation, under the assumption that the sheet resistance under the contact R_{SK} (Ω/□) and the sheet resistance outside the contact R_{SH} (Ω/□) are identical, the total resistance R_T can be expressed as:

$$R_T = 2R_C + \frac{R_{SH}}{W}d \quad (1)$$

with

$$R_C = \frac{\sqrt{R_{SH}\rho_C}}{W}\coth(L/L_T) \quad (2)$$

and

$$L_T = \sqrt{\rho_C/R_{SH}} \quad (3)$$

In the above expressions, R_C is the contact resistance (expressed in Ω) and L_T is the transfer length that can be imagined as that distance over which most of the current transfers from the semiconductor to the

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