Materials Science in Semiconductor Processing 29 (2015) 90–94

Contents lists available at ScienceDirect

Materials Science in Semiconductor Processing

journal homepage: www.elsevier.com/locate/mssp

Improvement of Ohmic contacts to *n*-type GaN using a Ti/Al multi-layered contact scheme

Liang Pang, Kyekyoon (Kevin) Kim *

Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, 1406 West Green Street, Urbana, IL 61801, USA

A R T I C L E I N F O

Available online 6 November 2013

Keywords:
AlGaN/GaN HEMT
Ohmic contacts
Ti/Al multi-layers
Al diffusion

A B S T R A C T

An improvement to the conventional Ti/Al/Ti/Au contact scheme has been developed to achieve better Ohmic contact properties to *n*-GaN using a Ti/Al multi-layered structure. Transmission electron microscopy demonstrates the formation of an AlGaN barrier layer at the metal–GaN interface of the conventional contact scheme, due to the in-diffusion of the excess Al during thermal annealing. X-ray photoelectron spectroscopy shows that the Al diffusion was significantly reduced via the new contact scheme, since the excess Al was tied up by the additional Ti layer. As a result, an order of magnitude smaller specific contact resistivity was realized. The surface morphology of the contact electrodes was also improved, as verified by scanning electron microscopy and atomic force microscopy. These results indicated that the Ti/Al multi-layered contact scheme is an improvement to the conventional counterpart in achieving lower contact resistance as well as higher reliability and uniformity of GaN-based devices.

1. Introduction

Recently, GaN has received much attention as a promising candidate material for high power, high frequency and high temperature electronics, due to its large critical breakdown field and saturation electron velocity [1–3]. However, because of the resistive nature of the wide band-gap material and the presence of native oxides between metals and GaN, it is difficult to form low-resistance Ohmic contacts. Efforts to fabricate low-resistance Ohmic contacts for *n*-type GaN have continued for decades and excellent results have been obtained using Ti/Al-based multiple metallizations, such as Ti/Al/Ti/Au, Ti/Al/Ni/Au, Ti/Al/Mo/Au, and Ti/Al/Pt/Au [4–7]. The success of this contact scheme mainly lies in the formation of low work-function TiN due to Ti in-diffusion during high temperature thermal annealing, which gives rise to donor-like N-vacancies on the GaN surface, therefore both thinning and lowering the barrier at the metal–GaN interface. Previous study showed that when no thermal annealing was conducted after metal deposition, Schottky contacts were formed instead of Ohmic contacts [8]. Besides Ti, other metals like Al also inter-diffuse through the metal stack during annealing. The formation of Ti–Al alloys is favorable to reduce the contact resistance due to their lower resistivity and work-function than that of Ti [9]. However, Al tends to diffuse all the way to the contact interface and form AlN. Unlike TiN, which is metallic in nature, the wide band-gap AlN may impede the current conduction and increase the contact resistance [10,11]. Nevertheless, little effort has been made to eliminate this barrier layer. In this study, the micro-structural properties of the interface between *n*-GaN and conventional Ti/Al/Ti/Au contact are investigated by transmission electron microscopy (TEM) and electron energy loss spectroscopy (EELS) to confirm the formation of Al-induced barrier layer. Then, a novel Ti/Al multi-layered structure is proposed to effectively eliminate this layer. The reduction of Al in-diffusion is confirmed by X-ray photoelectron spectroscopy (XPS), and

* Corresponding author. Tel.: +1 217 333 7162.
E-mail address: kevinkim@illinois.edu (K. (Kevin) Kim).

1369-8001/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mssp.2013.10.011

the improvement of the Ohmic contact properties is verified by a transmission line method (TLM). Furthermore, scanning electron microscopy (SEM) and atomic force microscopy (AFM) measurements show that the new contact scheme is able to produce metal contacts with better surface morphology, leading to better reliability and uniformity of GaN-based devices.

2. Experiment

Samples used in this study consisted of plasma-assisted molecular beam epitaxy (PAMBE)-grown 200 nm-thick *n*-GaN layer on a metal–organic chemical vapor deposition (MOCVD)-grown semi-insulating GaN template. The doping concentration and electron mobility measured at room temperature by a Hall-effect measurement system were $2.5\times10^{17}\ cm^{-3}$ and $360\ cm^2/V\ s$, respectively. The TLM patterns were defined by photolithography. The size of the metal pads was $200\ \mu m\times100\ \mu m$, and the gap spacings were 5, 10, 20, and 40 μm. Before the contact metal deposition, 30 s hydrogen chloride (HCl) treatment was performed to remove the native oxide from the GaN surface. Then Ohmic contact metals with different layers of Ti, Al and Au were deposited by electron-beam evaporation, followed by lift-off and metal-alloying via rapid thermal annealing (RTA) at 830 °C in N_2 ambient for 30 s. The RTA conditions were chosen based on previous reports [2,4,11]. Three metal stack structures were fabricated: sample A (the conventional contact scheme) with Ti/Al/Ti/Au (30/90/30/60 nm), sample B with Ti/Al/Ti/Al/Ti/Au (30/30/30/30/30/60 nm) and sample C with Ti/Al/Ti/Au (30/30/30/60 nm). The Ohmic contact resistance and specific contact resistivity were extracted from the current–voltage (*I–V*) characteristics measured by an Agilent 4155C semiconductor parameter analyzer. Micro-structural characteristics of the interface between the metals and GaN layer were closely examined using JEOL 2010 F (S)TEM and EELS line mapping. Metal diffusion after annealing was examined by Physical Electronics PHI 5400 XPS. The surface morphology was studied using a Hitachi S-4800 High Resolution SEM, Veeco Dimension 3100 AFM and optical microscope.

3. Results and discussion

EELS was obtained along with the TEM measurement for sample A at the contact interface [Fig. 1(a))]. Ti and N peaks were observed at different energies in the spectrum [Ti-L_3 ($E_{L_3}=456$ eV), N-K ($E_K=400$ eV)], indicating that the in-diffused Ti interfacially reacted with GaN to form TiN. Since the enthalpies of GaN and TiN are −110 kJ/mol and −336 kJ/mol, respectively, the formation of TiN is thermodynamically preferred [11]. As a result, N atoms out-diffused from GaN, and the donor-like N-vacancies produced a strongly *n*-type doped interfacial thin layer, which both thinned and lowered the energy barrier, therefore improving the Ohmic contacts. Meanwhile, the Al peak was also detected in this region, which means that Al was able to diffuse through the Ti barrier to form AlN composites in the *n*-GaN region. To further study this effect, a high-resolution (HR)TEM image was taken in the *n*-GaN region just below the TiN layer [Fig. 1(b)]. The atomic distance measurement shows that a layer with different atomic distance ($d_1=0.5056$ nm) than that of GaN ($d_2=0.5167$ nm) was formed between GaN and TiN. Assuming there is no potential AlGaN lattice distortion and using the simple linear relationship between d_{GaN} and d_{AlN}, the Al content was calculated to be 63.5%. The result suggests that for the conventional Ti/Al/Ti/Au contact scheme, the Al atoms can diffuse through the TiN layer during annealing and form an Al-rich AlGaN layer at the interface, which may block the current transport and increase the contact resistance due to its high potential barrier. Such a concern was also raised in previous study [10].

To prevent the formation of the barrier layer, the Al in-diffusion should be minimized. In order to achieve this, a new contact scheme that employs a Ti/Al multi-layered structure is proposed in sample B. Compared with the conventional contact scheme, a portion of the thick Al layer was replaced by an additional insertion of Ti. The rationale underlying this replacement is that the previous atomic ratio of Al to Ti was 1.59, but the thermodynamically stable phases at high annealing temperature over 800 °C were Ti_3Al and Ti_2Al [10]. This means that the thick Al layer cannot be fully consumed in forming the (Ti, Al) phases, so the excess Al may in-diffuse to the metal–GaN interface and form the AlGaN barrier layer. By inserting an additional Ti layer, the reaction extent between Ti and Al should be more; thus, the in-diffusion of Al may be reduced. However, one may raise the question – why not just make the original Al layer thinner? Therefore, sample C was deliberately made to prove that simply reducing the Al thickness is not feasible.

To examine the influence of Al in-diffusion on the Ohmic contact properties, the contact resistances of all three samples were measured using TLM. Fig. 2 shows the *I–V* characteristics for the metal pads with a gap spacing of 5 μm. The current transport resulting from the contacts in sample B ($I=39.35$ mA at $V=1$ V) was more facilitated than that of sample A ($I=26.43$ mA at $V=1$ V), indicating a lower barrier at the contact interface. On the other hand, sample C exhibited much lower current transport ($I=5.04$ mA at $V=1$ V), indicating poorer Ohmic contact properties. Although the Al in-diffusion should be minimized, simply reducing the Al thickness is not the right solution since the in-diffusion of the top Au layer would become a severe problem. In this case, Au was likely to penetrate through the whole metal stack and directly contact *n*-GaN, therefore degrading the Ohmic contacts due to its high work-function. The prevention of Au in-diffusion to semiconductors has been reported to be very important for achieving low Ohmic resistance [12,13]. Because of that, the adoption of Ti/Al multi-layered structure is more advantageous by preserving enough metal thickness and providing more Ti/Al to react with Au to form Al–Au–Ti ternary alloy phases, both of which help to prevent Au in-diffusion. The contact resistance and specific contact resistivity from an average of 10 contact patterns were extracted from the TLM data and are shown in Table 1. Compared with the specific contact resistivity of sample A ($5.69\times10^{-5}\ \Omega\ cm^2$), more than one order of magnitude smaller value was achieved for sample B ($4.52\times10^{-6}\ \Omega\ cm^2$). The contact resistance of the latter (0.52 Ω mm) is also less than one-third of that of the former (1.7 Ω mm), showing the efficacy of the new contact scheme for Ohmic contact enhancement. As expected, much higher contact resistance of 18 Ω mm and