Microelectronic Engineering 151 (2016) 60–63

Contents lists available at ScienceDirect

Microelectronic Engineering

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

Interfacial AlN formation of Si/Ti/Al/Cu Ohmic contact for AlGaN/GaN high-electron-mobility transistors

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ARTICLE INFO

Article history:
Received 20 July 2015
Received in revised form 3 December 2015
Accepted 9 December 2015
Available online 17 December 2015

Keywords:
Power transistors
Au-free Ohmic contact
AlGaN/GaN heterostructure

ABSTRACT

We report on the electrical and microstructural analysis on Si/Ti/Al/Cu Ohmic contact for AlGaN/GaN high-electron-mobility transistors grown on Si (111) substrate. With optimized Si and Ti thickness in Si/Ti/Al/Cu Ohmic metallization, a minimum Ohmic contact resistance of 0.44 Ω mm and specific contact resistance of 3×10^{-6} Ω-cm^2 with smooth surface morphology were achieved. Significant change in electrical performance and morphology showed high dependence of Ti and Si thickness on the multilayer metal scheme. Importantly, refractory behavior was shown in low annealing temperature, though uniform and continuous TiSi$_x$ with low work function was formed on AlGaN. However, Ohmic behavior was shown in high annealing temperature, because thin AlN surrounding TiN promotes further N vacancies in GaN than the conventional Ti/Al-based Ohmic contact does. An outer Cu layer has low resistivity and the interfacial Si layer forms TiSi$_x$, which works as only a barrier to prevent Cu in-diffusion, not to transport current. As a result, we revealed that Ohmic contact mechanism in Si/Ti/Al/Cu is governed mainly by field emission near the Fermi level or themionic-field emission. Microstructural study on metal/semiconductor interface region was conducted by using transmission electron microscopy (TEM).

1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) with a two-dimensional electron gas (2-DEG) channel have demonstrated promise for high frequency and power applications. To enhance the performance of AlGaN/GaN HEMTs, source and drain electrodes should have a low contact resistance (R$_c$), high thermal stability, and smooth surface morphology [1]. The mechanism for ohmic contacts on AlGaN/GaN heterostructure contains the interfacial reaction between Ti/Al bilayer and semiconductor. Ti and Al atoms form nitride alloys in the AlGaN/GaN layers, which are low work function metal lowering the Schottky barrier height and prompting electron tunneling by N-deficient n-type doping [2,3]. So far, many studies have addressed Ti/Al-based metallization for low specific contact resistance (ρ$_c$) [4,5]. Recently, Yu-Sheng et al. studied Ti/Al/Ti/Ni/Au metallization with low R$_c$ of 0.28 Ω mm with improved surface morphology(rms 27.6 nm) [6]. Selvanathan et al. [7] and Mohammed et al. [8] reported the formation of excellent Ohmic contacts to AlGaN/GaN HEMTs using high refractory Mo as a barrier layer in Ti/Al-based metallization. However, the high refractory metal before Au deposition has been reported to not act as an effective barrier layer for preventing Au diffusion into the GaN [9]. In addition, conventional Ti/Al-based metallization contains Au, which hinders the fabrication of complementary metal oxide semiconductors (CMOS) in AlGaN/GaN HEMTs, since Au acts as a deep level contaminant in Si [10]. Some studies on Si, which is a n-type dopant, in GaN assert that when Si is employed in the Ti/Al-based contact metallization, it enhances Ohmic performance in AlGaN/GaN HEMTs [11–15]. Youn et al. [11] have reported that the formation of an Al–Ti–Si–N intermetallic layer and in-diffusion of Si into GaN improved Ohmic performance. On the other hand, Desmaris et al. [12] reported that the interfacial silicide layer had an unfavorable effect on Ohmic contact formation because of the trade-off between the increase in the surface doping level and the formation of a thick Al–Ti–Si–N interfacial layer. For the more detailed study in micro-structure of Si incorporated metallization, transmission electron microscopy (TEM) was conducted by Mohammed et al. [13], who concluded that silicide with a low work-function may be more favorable than TiN formation-induced N-vacancy creation in improving Ohmic performance. We have recently demonstrated a Au-free Ohmic contact with Ti/Al-based metallization by incorporating Si and Cu into the scheme [16]. Results indicated that Ohmic contact formation in Si/Ti/Al/Cu metallization depends on the interfacial TiSi$_x$ alloy, which prevents Cu from diffusing into GaN. While non-uniform TiN alloys were formed in GaN, it was enough for electron tunneling to reduce R$_c$ by using a highly conductive Cu cap layer.

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http://dx.doi.org/10.1016/j.mee.2015.12.005
0167-9317/

In this paper, we present an electrical and physical analysis of Si/Ti/Al/Cu metallization using varying Si and Ti thickness. The Si/Ti- based metallization system was well-optimized to obtain better contact resistance and smooth surface morphology. Furthermore, we compared results between the Si/Ti/Al/Cu metallization after annealing at low and high temperature. Although $TiSi_x$ alloy with low work-function was formed uniformly on AlGaN surface at low temperature annealing, Ohmic behavior was not observed, on the contrary to the sample with high temperature annealing. The detailed structural studies revealed that Si/Ti/Al/Cu metallization after annealing at high temperature formed interfacial AlN layers, which enabled a low specific contact resistance with heavy n-type doping in GaN.

2. Experiments

An undoped $Al_xGa_{1-x}N$ ($x = 0.25$)/GaN heterostructure was grown on a 6-in. Si substrate using metal organic chemical vapor deposition. The AlGaN/GaN layers were then cleaned with HCl:DI water (1:1) to remove the native surface oxide. The specific contact resistivities were measured using a circular-transmission line method (C-TLM). The nominal radius of the inner dot of the C-TLM was 200 μm with interspaces of 2, 3, 4, 5, 8, 10, 12, 16, 20, and 30 μm. The exact feature sizes were examined by scanning electron microscopy. Ohmic metals of Si/Ti/Al/Cu (d_{si}/d_{Ti}/60/50 nm) were deposited using an electron-beam evaporator with a background pressure of low 10^{-6} Torr with varying Si and Ti thicknesses. Following the metal lift-off processes, the wafers were annealed at 650 °C and 870 °C for 60 s in N_2 ambient using rapid thermal annealing. Electrical analysis was performed using the four-point probe technique on an Agilent B1505A curve tracer. Extensive physical analysis was performed using energy dispersive X-ray spectroscopy (EDS), high angle annular dark-field (HAADF) scanning transmission electron microscopy (STEM), and high resolution transmission electron microscopy (HRTEM).

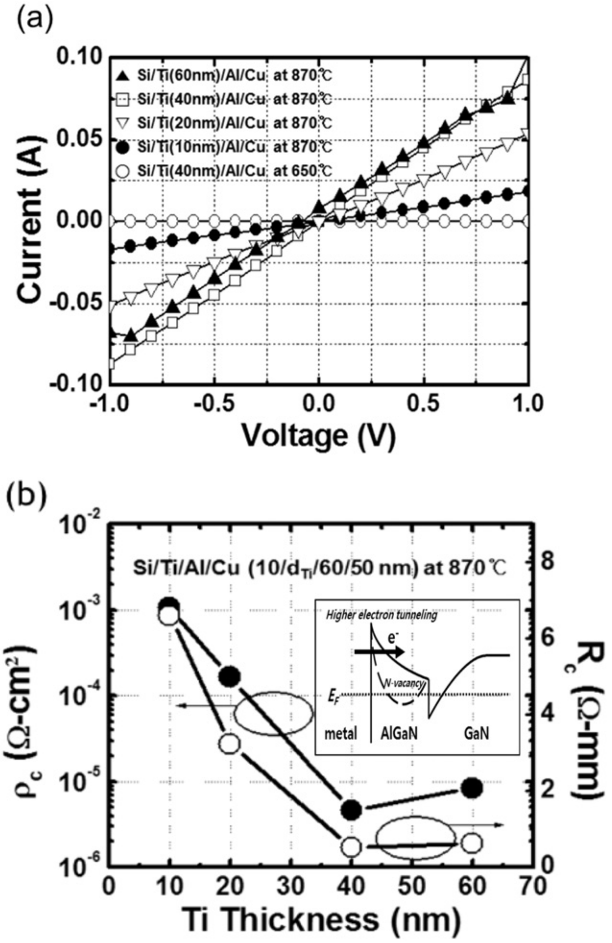

Fig. 1. (a) Comparison of current–voltage characteristics with two annealing temperatures for Si/Ti/Al/Cu (10/40/60/50 nm) (□: 870 °C, ○: 650 °C), and with four different Ti thickness at 870 °C (▲: 60 nm, ▽: 20 nm, ●: 10 nm). (b) Specific contact resistance and contact resistance of Si/Ti/Al/Cu ($10/d_{Ti}/60/50$ nm) after annealing at 870 °C as a function of Ti thickness (●: ρ_c, ○: R_c). The inset of (b) shows band diagram of MS interface at an optimal Ti thickness, which shows higher electron tunneling through N vacancy at AlGaN surface.

3. Results and discussion

Current–voltage (I–V) curves of the Si/Ti/Al/Cu metallization were measured between two electrodes separated by 10 μm as a function of Ti thickness (d_{Ti}) at various annealing temperatures in Fig. 1. The I–V curves showed rectifying characteristics at 650 °C; Ohmic characteristics were observed at 870 °C with various Ti thicknesses while maintaining other metals' thicknesses. The current increased as the Ti thickness (d_{Ti}) increased up to 40 nm and then decreased at 60 nm. The minimum contact resistance of 0.44 Ω-mm with a specific contact resistivity of 3×10^{-6} Ω-cm^2 was obtained with Si/Ti/Al/Cu (10/40/60/50 nm) metallization at 870 °C. This demonstrates that a certain amount of Ti is required in a multilayer metal scheme since it forms TiN and $TiSi_x$ alloys simultaneously for Ohmic contacts. It is assumed that enough Ti thickness has a favorable reaction between other metals but too much Ti amount leads to degradation of resistance due to increase of metal thickness. The surface morphology was improved as Si thickness (d_{si}) increased while maintaining other metals' thicknesses. The smoothest surface was found at 10 nm of Si, as shown in the optical microscope images in Fig. 2. Results suggest that incorporating Si was important for better surface morphology and uniformity, as well as for enabling high reproducibility and high edge acuity for scaled transistors. Above results show that the electrical performance noticeably depends on the Ti thickness while Si plays an important role in surface morphology. To examine the microstructural changes in the metallization on AlGaN/GaN HEMTs, HAADF-STEM and HRTEM analysis was undertaken.

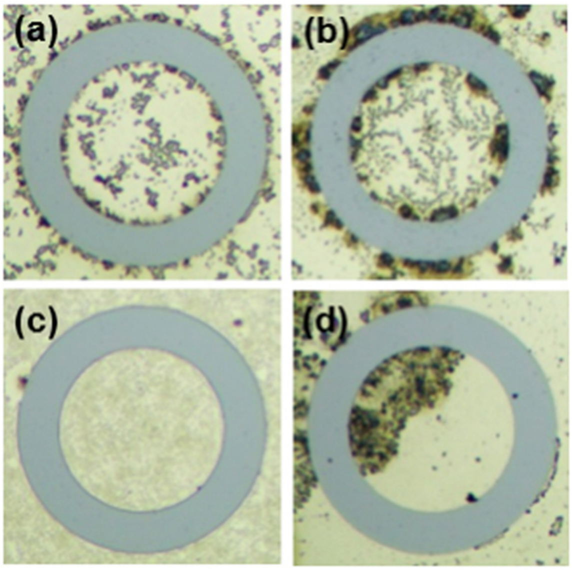

Fig. 2. Optical microscope image of a Si/Ti/Al/Cu Ohmic contact after annealing at 870 °C with 4 different Si thicknesses of 1, 3, 10, and 20 nm for a, b, c, and d, respectively.

Fig. 3 shows as-deposited Si/Ti/Al/Cu (10/40/60/50 nm) metallization in a cross-sectional HADDF-STEM image. It is confirmed that each metal layer evaporated in accordance with the metal scheme. Without annealing, no elements intermixed and no phase change occurred in the metal and semiconductor region. The outer Cu layer was deposited with a rough morphology because the deposition rate varied easily