Solid-State Electronics 68 (2012) 85–89

Contents lists available at SciVerse ScienceDirect

Solid-State Electronics

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

Investigation of TiO_2 on AlGaAs prepared by liquid phase deposition and its application

Kuan-Wei Lee [a,*], Jung-Sheng Huang [a], Yu-Lin Lu [a], Fang-Ming Lee [b], Hsien-Cheng Lin [b], Tsu-Yi Wu [b], Yeong-Her Wang [b]

[a] Department of Electronic Engineering, I-Shou University, Kaohsiung 840, Taiwan
[b] Institute of Microelectronics, Department of Electrical Engineering, Advanced Optoelectronic Technology Center, National Cheng-Kung University, Tainan 701, Taiwan

ARTICLE INFO

Article history:
Received 7 June 2011
Received in revised form 26 September 2011
Accepted 17 October 2011
Available online 17 November 2011

The review of this paper was arranged by Prof. S. Cristoloveanu

Keywords:
TiO_2
AlGaAs
Liquid phase deposition (LPD)

ABSTRACT

The study explored titanium dioxide (TiO_2) on aluminum gallium arsenide (AlGaAs) prepared by liquid phase deposition (LPD) at 40 °C. The leakage current density was about 8.4×10^{-6} A/cm^2 at 1 MV/cm. The interface trap density (D_{it}) and the flat-band voltage shift (ΔV_{FB}) were 2.3×10^{12} cm^{-2} eV^{-1} and 1.2 V, respectively. After rapid thermal annealing (RTA) in the ambient N_2 at 350 °C for 1 min, the leakage current density, D_{it}, and ΔV_{FB} were improved to 2.4×10^{-6} A/cm^2 at 1 MV/cm, 7.3×10^{11} cm^{-2} eV^{-1}, and 1.0 V, respectively. Finally, the study demonstrates the application to the AlGaAs/InGaAs metal–oxide–semiconductor pseudomorphic high-electron-mobility transistor (MOS-PHEMT). The results indicate the potential of the proposed device with a LPD-TiO_2 gate oxide for power application.

1. Introduction

In recent years, AlGaAs/InGaAs pseudomorphic high-electron-mobility transistors (PHEMTs) with a low Al-content AlGaAs Schottky layer has shown promising features and good performance. However, Schottky-gate devices may still suffer from breakdown voltage and gate current leakage issues. Oxides are the common choice of materials grown on the AlGaAs Schottky layer for fabricating the metal–oxide–semiconductor pseudomorphic high-electron-mobility transistors (MOS-PHEMTs) with an enhanced gate voltage swing and a suppressed leakage current. In particular, using high-κ oxides as gate insulators is a very attractive approach.

Titanium dioxide (TiO_2) has a high dielectric constant, high refractive index, and an excellent transmittance in the visible and near infrared. It can be used in ceramics as a photocatalyst, in field-effect transistors as the gate insulator, and in solar cells as the optical coating. Many methods have been used to deposit TiO_2 films such as low pressure chemical vapor deposition (LPCVD) [1], plasma-enhanced chemical vapor deposition (PECVD) [2], electron beam evaporation (EBE) [3], sputtering [4], metalorganic chemical vapor deposition (MOCVD) [5], and liquid phase deposition (LPD) [6,7]. Compared with other methods, the LPD process has many advantages including simplicity, low cost, and low temperature. In addition, it does not require either anodic equipment or any additional energy source. Previous studies have demonstrated LPD-TiO_2 on InP [8], polysilicon [9], glass [10], and GaN [11]. However, no studies have reported LPD-TiO_2 on AlGaAs. This work characterizes the composition and electrical properties of LPD-TiO_2 with an ammonium hexafluorotitanate ($(NH_4)_2TiF_6$) aqueous solution serving as a liquid source, and a boric acid (H_3BO_3) aqueous solution controlling the deposition rate. Furthermore, the AlGaAs/InGaAs PHEMT using LPD-TiO_2 as gate oxide is also implemented.

2. Experimental

The AlGaAs wafer prepared by MOCVD, and consisting of a 20-nm-thick n$^+$-GaAs cap layer, a 1000-nm-thick $Al_{0.2}Ga_{0.8}As$ layer, a 100-nm-thick n$^+$-GaAs layer, and a n$^+$-GaAs substrate, was successively cleaned with acetone, methanol and DI water with ultrasonic vibration for 5 min. The GaAs capping layer was first removed by etching in $NH_4OH:H_2O_2:H_2O = 3:1:50$ mixed solution. The wafer was then immersed in the LPD-TiO_2 growth solution at a constant temperature, and TiO_2 films were grown on the AlGaAs for an appropriate period of time. The immersion time, deposition temperature, $(NH_4)_2TiF_6$ concentration, and H_3BO_3 concentration affect the LPD-TiO_2 quality. In this study, the optimal deposition conditions for TiO_2 on AlGaAs are 0.1 M $(NH_4)_2TiF_6$ and 0.3 M H_3BO_3 solutions at 40 °C, which were based on our previous

* Corresponding author.
E-mail address: kwlee@isu.edu.tw (K.-W. Lee).

0038-1101/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2011.10.005

work [11]. Finally, the samples were rinsed by DI water and blow dried with N_2.

The oxide thickness was measured by a "ULVAC ESM-1" ellipsometer using a visible laser as the incident beam, and this was confirmed by scanning electron microscopy (SEM). The surface morphologies of LPD-TiO_2 films were obtained using atomic force microscopy (AFM). X-ray photoelectron spectroscopy (XPS) was used to investigate the chemical bond of the oxide films by Ar ion sputtering with the take-off angle set to 45° relative to the surface normal. To investigate the electrical characteristics of LPD-TiO_2 on $Al_{0.2}Ga_{0.8}As$, a metal–oxide–semiconductor (MOS) capacitor was fabricated. Au and Au/Ge/Ni were used as the top and bottom electrodes of the MOS capacitor, respectively. The evaporated top electrode area was 1×10^{-4} cm^2. The current–voltage (*I*–*V*) characteristics were measured by HP4156B, and the high frequency (1 MHz) capacitance–voltage (*C*–*V*) was measured by HP4280A, respectively.

3. Results and discussion

The basic chemical reaction kinetics of LPD-TiO_2 is expressed by the following two equilibrium processes:

$$(NH_4)_2TiF_6 + 2H_2O \overset{\Delta H}{\leftrightarrow} 4HF + 2NH_4F + TiO_2 \downarrow \quad (1)$$

$$H_3BO_3 + 4HF \leftrightarrow BF_4^- + H_3O^+ + 2H_2O. \quad (2)$$

In Eq. (1), hydrofluoric acid (HF) is separated from $(NH_4)_2TiF_6$ by TiO_2 generation. The HF is then consumed by the H_3BO_3 and forms boron tetrafluoride ions (BF_4^-) as shown in Eq. (2). The addition of H_3BO_3 reduces the HF in Eq. (1) and it further shifts the equilibrium to the right. That is, the addition of H_3BO_3 shifts the equilibrium to the deposition of TiO_2 on the wafer. Fig. 1 shows the deposition rate and the refractive index of LPD-TiO_2 on AlGaAs. The deposition temperature is fixed at 40 °C, and the deposition time ranges from 1 to 3 h. The oxide deposition thickness increases nonlinearly with deposition time, and the deposition rate is about 90 nm/h for the first hour. After 2 h, the deposition rate decreases mainly due to the decrease in the concentration of H_3BO_3. The refractive index increases slightly after 3 h of oxidation, and the surface becomes a little rough. The as-grown refractive index (1.75–1.84) of LPD-TiO_2 on AlGaAs is comparable to 1.6 on InP [8] and 1.75 on glass [10] using a similar method.

After etching the capping layer, the AFM image (1 μm × 1 μm) of the AlGaAs surface is shown in Fig. 2a. The root mean square (rms) value of the AlGaAs surface is 1.3 nm. Fig. 2b shows the AFM image (1 μm × 1 μm) of the as-deposited LPD-TiO_2 surface

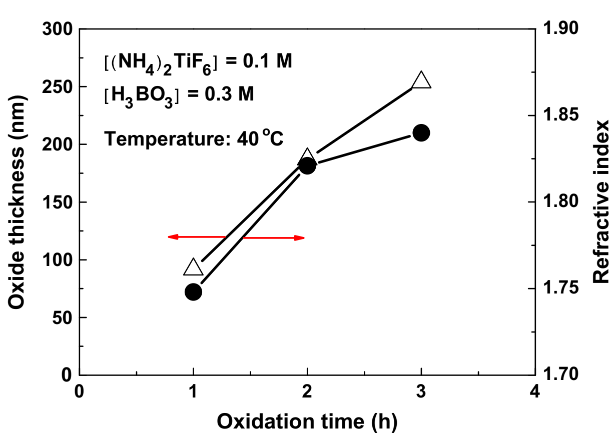

Fig. 1. Oxide thickness and refractive index versus deposition time.

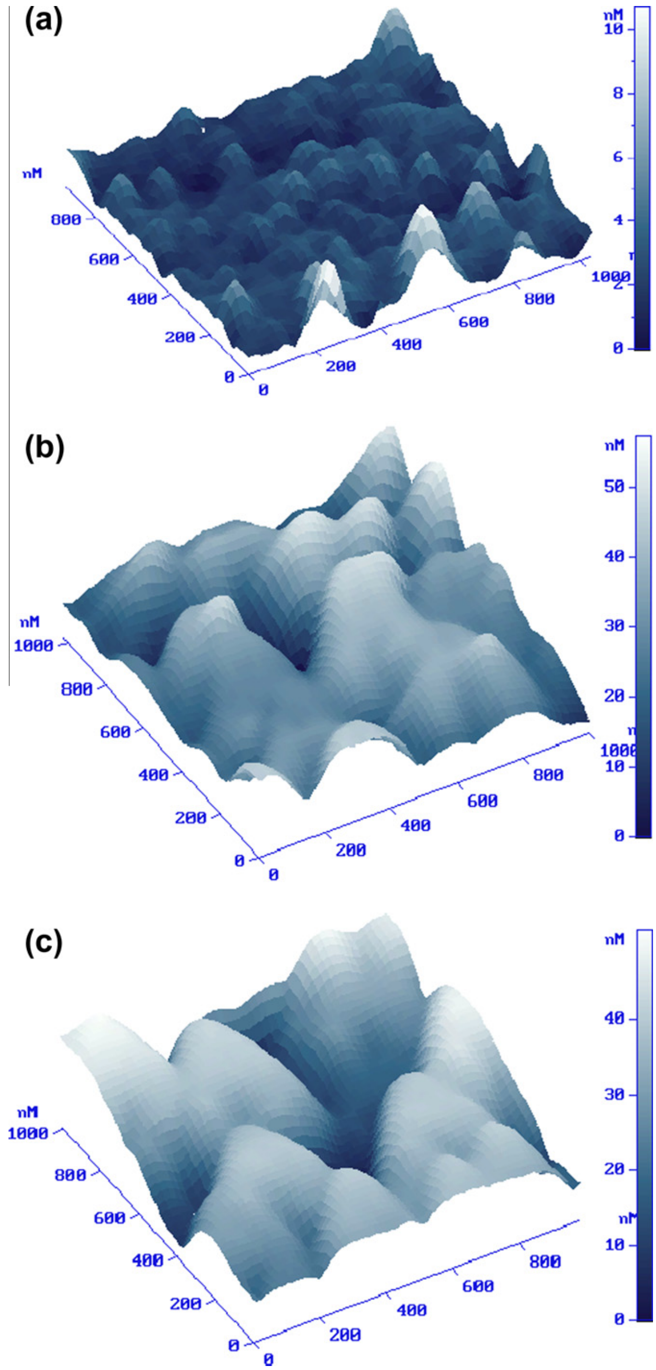

Fig. 2. AFM images of the surface of (a) AlGaAs before oxidation, (b) as-deposited LPD-TiO_2, and (c) LPD-TiO_2 with RTA treatment.

on the AlGaAs. The TiO_2 thickness is approximate 31 nm and the rms value is 8.7 nm for 20 min oxidation. Fig. 2c shows the AFM image (1 μm × 1 μm) of the LPD-TiO_2 surface on AlGaAs after rapid thermal annealing (RTA) in the ambient N_2 at 350 °C for 1 min. After RTA treatment, the TiO_2 thickness is approximate 30 nm and the rms value can be improved to 6.9 nm, which is an improvement of about 20.7%.

Fig. 3a and b shows the XPS spectrum of the Ti-2p and O-1s core levels by Ar ion sputtering for an etching rate of 48 nm/min. The main peak of the Ti-2p core level is at 458.5 eV. The peaks of the O-1s core levels are between 530.08 eV (Ti^{4+}) and 531.1 eV (Ti^{3+}) due to the wet etching before the LPD process. Before immersion