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Liquid-phase-deposited high dielectric zirconium oxide for metal-oxide-semiconductor high electron mobility transistors

Chih-Chun Hu [a], Chu-An Chiu [a], Chien-Hua Yu [a], Jian-Xuan Xu [a], Tsu-Yi Wu [a], Po-Wen Sze [b], Chang-Luen Wu [c], Yeong-Her Wang [a, *]

[a] *Institute of Microelectronics, Department of Electrical Engineering, Advanced Optoelectronic Technology Center, National Cheng-Kung University, Tainan 701, Taiwan*
[b] *Department of Electrical Engineering, Kao Yuan University of Technology, Kaohsiung 821, Taiwan*
[c] *Transcom Inc., Tainan 741, Taiwan*

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ABSTRACT

AlGaN/GaN metal-oxide-semiconductor high electron mobility transistor (MOSHEMT) with a liquid phase deposited (LPD) ZrO_2 thin film as gate insulator was fabricated. Compared with the conventional HEMT, the maximum drain current increases from 492 to 627 mA/mm, and leakage current is four orders magnitude lower. The gate swing voltage and off-state breakdown were also improved while applying ZrO_2 oxide layer.

1. Introduction

III-nitride semiconductor materials have been investigated as high promising semiconductor materials for high power/high frequency devices [1–4]. However, Schottky gate in GaN-based HEMTs may suffer from higher gate leakage and lower breakdown voltage, which limit the device performance. MOS gate structures using a thin insulator film between the gate electrode and the semiconductor could suppress these problems. High-*k* materials such as TiO_2, and Al_2O_3 have been widely used as gate dielectrics [5–8]. These materials are able to maintain the capacitance density of thin SiO_2 films while providing low leakage current. Among these materials, ZrO_2 has great potential due to its high dielectric constant, and larger energy bandgap. On the other hand, as compared to other insulator deposition methods, the Liquid-phase-deposited (LPD) process provides a low-cost and low-complex method to form oxide layers at room temperature [5–8], which can prevent the defects from high temperature processes. In this paper, applications of the AlGaN/GaN MOSHEMT with LPD-ZrO_2 thin film have been investigated.

2. Device and fabrication

The cross-sectional view of the fabricated device is shown in Fig. 1. The AlGaN/GaN HEMT structure was prepared by an MOCVD system on a silicon substrate. The structure is composed of a 3.3 μm buffer layer, a 1.5 μm undoped GaN channel layer, a 30-nm undoped $Al_{0.26}Ga_{0.74}N$ barrier layer, and a 2-nm undoped GaN cap layer. The measured Hall mobility and sheet carrier concentration were 1373 $cm^2/V\,s$ and $1.06 \times 10^{13}\ cm^{-2}$, respectively. The device isolation was accomplished by an inductively coupled plasma reactive ion etching system down to the buffer layer. Ti/Al/Ni/Au was deposited as the source/drain ohmic contacts by an electron beam evaporation system, and followed by annealing at 850 °C in N_2 environment. Next, the LPD solution was prepared as follows: The 0.1 M zirconium sulfate ($Zr(SO_4)_2 \cdot 4H_2O$, Alfa Aesor) of 25 ml and 0.3 M ammonium persulfate ($(NH_4)_2S_2O_8$, Riedel-de Haen) of 25 ml were mixed and stirred 5 min for the deposition solution of ZrO_2 films. The sample was then immersed into the solution to

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* Corresponding author. Fax: +886 6 2080598.
E-mail address: yhw@ee.ncku.edu.tw (Y.-H. Wang).

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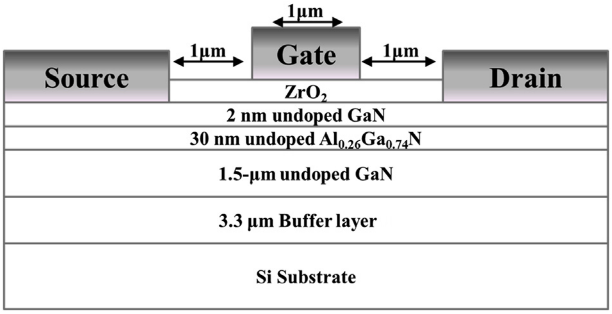

Fig. 1. Cross-sectional schematic of the AlGaN/GaN MOSHEMT.

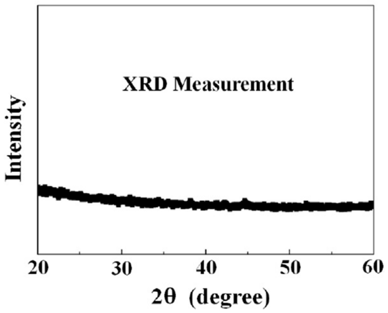

Fig. 3. XRD analysis of the deposited ZrO_2 film on n-GaN.

deposit ZrO_2 films at 30 °C. The concentration of $(ZrSO_4)_2$ and $(NH_4)_2S_2O_8$ were maintained at 0.05 M and 0.15 M. The ohmic contact characteristics did not degrade after the sample was immersed into the LPD solution. Finally, the Ni/Au gate electrode was formed by sputtering. The conventional HEMT without using LPD technique was fabricated on the same wafer with the same process.

3. Results and discussion

The growth rate of ZrO_2 film is shown in Fig. 2. The deposited rate was really stable which was easy to control the deposited ZrO_2 thickness and reproduce the process. Fig. 3 shows the X-ray diffraction (XRD) analysis of the ZrO_2 film on n-GaN. The XRD patterns show no peak which indicate that the LPD ZrO_2 film is amorphous. Fig. 4 presents the 2D and 3D AFM images of as-deposited ZrO_2 films for 10 nm, 20 nm, and 30 nm. The corresponding RMS value is 4.33 nm, 3.68 nm and 6.26 nm, respectively.

Fig. 5 shows the X-ray photoelectron spectroscopy (XPS) spectra of the ZrO_2 film. The binding energies of Zr $3d_{5/2}$ and Zr $3d_{3/2}$ are observed at 183.06 and 185.46 eV, with a separation of 2.4 eV between the peaks which is a typical characteristic of the Zr^{2+} in ZrO_2 film. The O 1s spectra can be divided into two peaks, including O_2- from ZrO_2 films and the hydroxyl groups resulting from the chemisorbed water [9].

The capacitance–voltage (C–V) measurements of HEMT and MOSHEMT at 1 MHz are shown in Fig. 6. A small hysteresis can still be observed. The relative dielectric constant of the oxide films can be obtained by calculating the following equation:

$$1/C_{HEMT} + 1/C_{ox} = 1/C_{MOSHEMT} \tag{1}$$

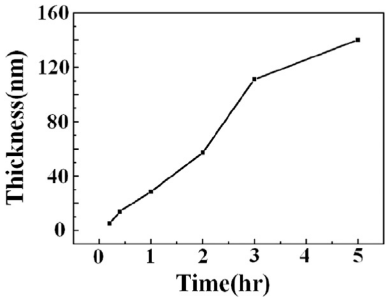

Fig. 2. The growth rate of the deposited ZrO_2 film.

and

$$C_{ox} = \frac{\varepsilon_r \varepsilon_0 A}{t_{ox}} \tag{2}$$

The calculated interface state density was found to be $4.78 \times 10^{12}\ cm^{-2}\ eV^{-1}$ [10]. The dielectric constant of the ZrO_2 film is about 20.43.

Fig. 7 shows the I_{DS}–V_{DS} characteristics of the conventional HEMT and the MOSHEMT. The maximum drain current of the conventional HEMT is 492 mA/mm while the maximum drain current of MOSHEMT with 10 nm and 20 nm ZrO_2 film are 627 mA/mm and 600 mA/mm, respectively. The larger drain current in the MOSHEMT may be partly attributed to the reduced

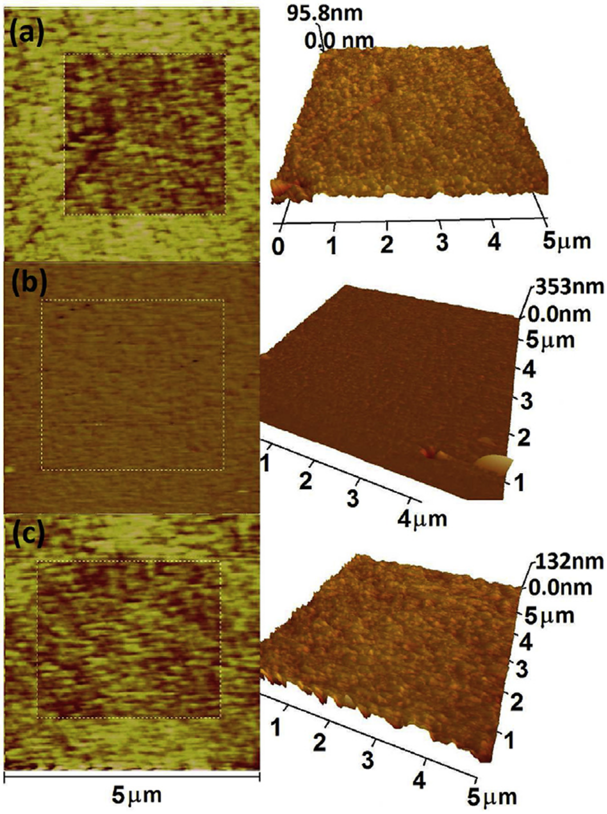

Fig. 4. 2D and 3D AFM images of as-deposited ZrO_2 films (a) 10 nm, (b) 20 nm, and (c) 30 nm. The corresponding RMS value is 4.33 nm, 3.68 nm and 6.26 nm, respectively.