Journal of Ceramic Processing Research. Vol. 11, No. 6, pp. 665~668 (2010)

J O U R N A L O F
Ceramic Processing Research

The impact of lanthanum hafnium oxide as a gate insulator on the performance of zinc oxide thin film transistors

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Recently, the quality of the oxide-TFT gate insulator is given the utmost consideration strongly affecting device performance. In this study, preliminary experiments were carried out using a multi-component of lanthanum hafnium oxide (LHO) as a gate insulator. First, we investigated the electrical properties of LHO thin films deposited by ECR-ALD. Also, we report the fabrication and characteristics of ZnO-TFT with a LHO thin film as a high-k gate insulator. The deposition conditions of the gate insulator were optimized for leakage current, breakdown field and high device performance. ZnO-TFTs with high-k LHO gate insulator exhibited an excellent performance. The field effect channel mobility, turn on voltage, on/off current, and subthreshold swing were obtained as 2.77 cm^2/Vs, –0.4 V, 10^7, and 0.35 V/decade, respectively. We examined the characteristics of a device consisting of LHO compared to SiO_2, La_2O_3, and HfO_2. This multi-component high-k LHO thin film is favorable for success in the development of oxide-TFTs.

Key words: zinc oxide, oxide thin film transistor, high-k gate insulator, lanthanum hafnium oxide.

Introduction

In recent studies, transparent TFTs (TTFTs) have been investigated by application of ZnO based oxide semiconducting materials such as i-ZnO, ZnSnO, ZnInO, and ZnInGaO as alternatives to a-Si : H films [1-3]. However, ZnO based TFTs have a number of problems such as a high turn-on voltage and low stability. It was reported that many of the ZnO based TFTs have larger threshold and turn-on voltages compared to a-Si TFTs [4, 5]. In order to reduce the turn-on voltage of the ZnO based TFTs, the coupling should be increased by a gate voltage to the ZnO channel layer. This can be accomplished by using gate dielectrics with a higher relative permittivity and by decreasing the thickness of the gate dielectrics [6]. Also, when the ZnO channel layer is deposited on the high-k dielectrics layer, unlike the integration of a non-oxide high-k gate dielectric, channel layer/high-k dielectric interfaces are expected to have good characteristics without deleterious chemical interactions. Optimal gate dielectrics should be amorphous and smooth with having a large breakdown field (> ~4 MV/cm), a low leakage current density (< ~10 NA/cm^2 at 1 MV/cm), and a large relative dielectric constant (> ~10). Most oxide-TFTs involve the use of binary oxide gate insulators, such as SiO_2 [7], Al_2O_3 [8], HfO_2 [8], or Y_2O_3 [9]. Although binary oxides will undoubtedly be used for gate insulators, we suggested that binary oxides are not optimal gate dielectrics for oxide-TFTs. Wilk et al. and Robertson reported that binary oxides often have a tendency to crystallize, even at low process temperatures [10, 11]. A binary oxide with a high dielectric constant typically has a smaller band gap related to the breakdown field. In contrast, a binary oxide with wide a band gap typically has a smaller dielectric constant. Therefore, it is very important to know that a binary oxide involves a trade-off between breakdown field and dielectric constant.

In this study, the characteristics of ZnO based TFTs using amorphous lanthanum hafnium oxide (LHO) high-k dielectrics were investigated. LHO high-k dielectrics were deposited by ECR-ALD. ZnO and ITO thin films were deposited as a channel layer and electrodes by DC magnetron sputtering, respectively. Thin film transistor structures consisted of ZnO and LHO thin films deposited on n-Si substrate. The performance and device characteristics of the ZnO-based TFTs were investigated with an HP4145B semiconductor parameter analyzer. We examined the characteristics of a device consisting of a LHO and compared them to other binary oxides for potential high-k dielectrics in future TFT devices.

Experiments

The p-Si substrates were ultrasonically cleaned in acetone and methanol and rinsed in de-ionized water for 10 minutes each. High-k dielectric LHO films were deposited on n-Si substrates by ECR-ALD with $La(iPrCp)_3$, and TEMAHf as the lanthanum, and hafnium precursors, respectively. O_2 plasma was used as an oxygen source. The ECR plasma power was 500 W and the deposition temperature was varied from 150 °C to 350 °C. To deposit nano-composite LHO films, the total cycle consists of two steps in order to

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deposit La_2O_3 and HfO_2 film, separately. And then, intrinsic ZnO channel layers were prepared on LHO/p-Si substrate using DC magnetron sputtering. The target used in this study was sintered stoichometric ZnO (99.999% purity) ceramic. The substrate temperature was about 100 °C and the plasma discharge power density was 0.5 W/cm^2.

After ZnO thin film deposition, the structural, electrical, and chemi-physical properties were characterized using various analytical tools. More details on the characteristics of ZnO thin films are demonstrated in a previous paper [12]. To investigate the electrical properties of LHO films, the Au/dielectrics/Si MOSCAP structure was prepared using the lift off method. The C-V and leakage current were measured using an Agilent B1500A.

We fabricated a ZnO-TFT device with a conventional bottom gate structure (Fig. 1). The entire device was fabricated on n-Si substrates with high-k LHO thin films of 100 nm as the gate insulator. Indium tin oxide (ITO) thin films were used for the source and drain electrodes and were deposited by DC magnetron sputtering at room temperature. All electrical characterizations of ZnO TFTs were carried out with the semiconductor parameter analyzer (HP 4145B, Agilent Technologies) at room temperature in a dark environment.

Results and Discussions

Electrical properties of lanthanum hafnium oxide thin films

We investigated the electrical properties of the lanthanum hafnium oxide (LHO) thin films deposited by ECR-ALD. Fig. 2 shows the high-frequency C-V curves of MOCAPs with high-k dielectrics such as La_2O_3, HfO_2, and LHO thin films. C-V measurements were conducted at a frequency of 1 MHz. There was no hysteresis found in the MOSCAP with LHO thin films. The ideal V_{FB} (flat-band voltage) value, on the assumption that there is no fixed oxide charge for the Au/LHO/Si structure, is calculated to be +0.1 V as a difference of work function values between metal and semiconductor. However, we obtained a negative V_{FB} value of the LHO thin films through the CVC program. This result suggests that the LHO thin films contain negative fixed charges. Negative fixed charge assist in obtaining a positive turn-on voltage for an n-channel device, which is highly recommended since it causes an enhancement mode operation of the TFT devices.

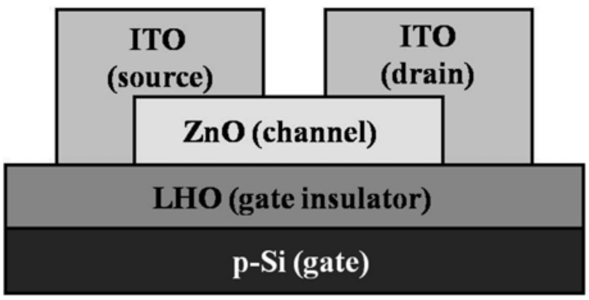

Fig. 1. Cross-sectional diagram of the ZnO-TFT with a LHO high-k gate insulator structure.

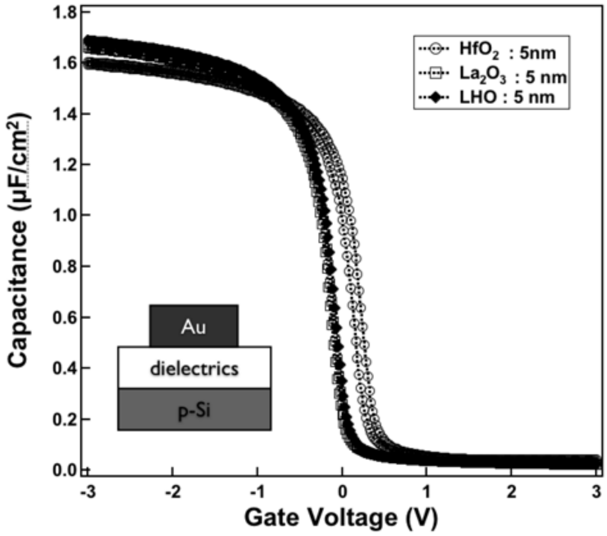

Fig. 2. High-frequency C-V characteristics of the La_2O_3, HfO_2, and LHO MOSCAPs.

Fig. 3 shows the relationship between EOT and physical oxide thickness with compared to other oxide films such as HfO_2 and La_2O_3. The EOT values were extracted using the C-V simulation program developed at NCSU and calculated by the following equation:

$$EOT_{total} = \frac{\kappa_{SiO_2}}{\kappa_{OX}} t_{OX} \quad (1)$$

where t_{OX} and κ_{OX} are the physical oxide thickness and the dielectric constant of the high-k oxide thin films, i.e., La_2O_3, HfO_2, and LHO, respectively. The dielectric constants of high-k oxide films were obtained: La_2O_3 ~11, HfO_2 ~12, and LHO ~16. These experimental results in

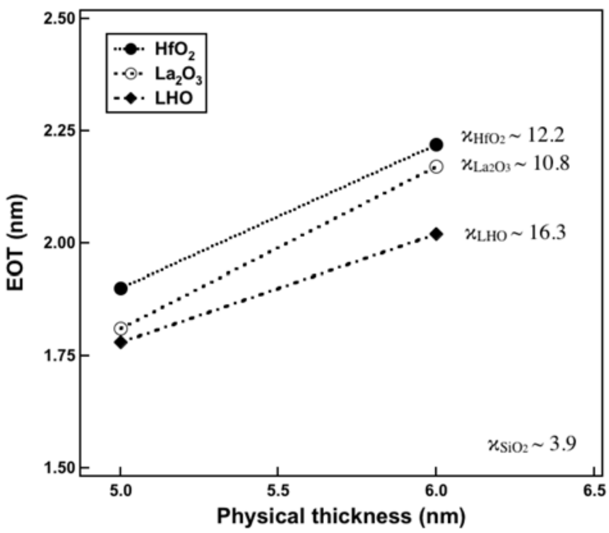

Fig. 3. Variation in EOT as a function of physical oxide thickness of the La_2O_3, HfO_2, and LHO thin films.

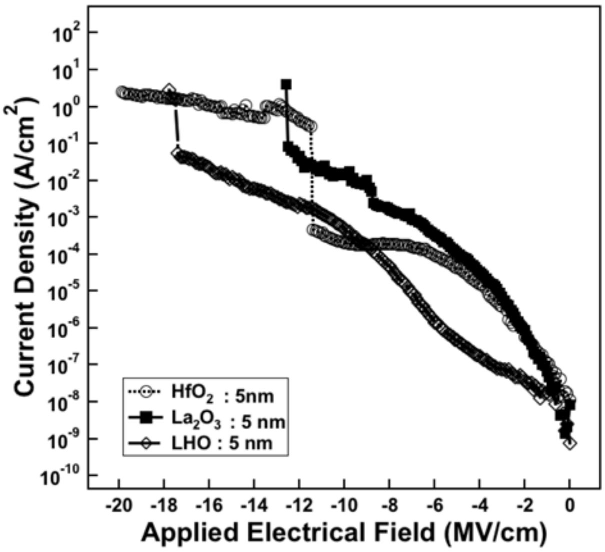

Fig. 4. Leakage current density characteristics of the La_2O_3, HfO_2, and LHO MOSCAPs.

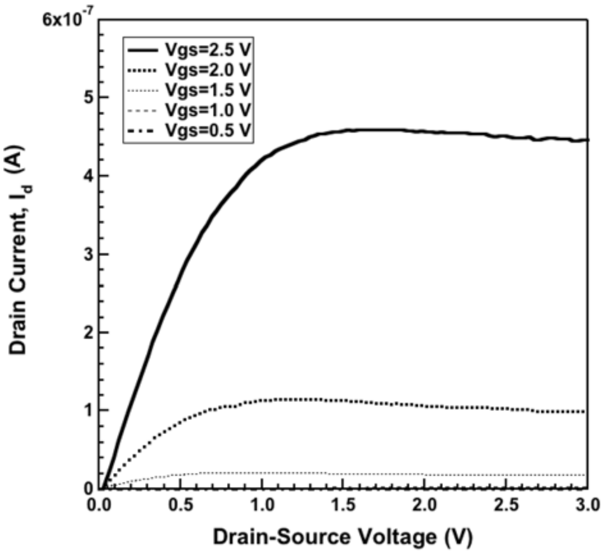

Fig. 5. Typical output characteristics of a ZnO-TFT with LHO high-k gate insulator.

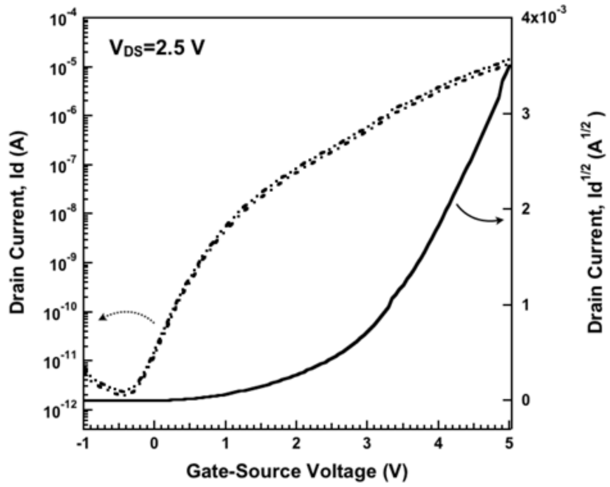

Fig. 6. Typical transfer characteristics of a ZnO-TFT with LHO high-k gate insulator.

which the dielectric constants of La_2O_3 and HfO_2 are lower than other reports, is due to the La-silicate and Hf-silicate formation during the deposition process. As contrasted with previous cases, the LHO thin film showed a higher dielectric constant which is similar to the reported value of ~18 for a-LHO films [13].

Fig. 4 shows the leakage current density as a function of the applied electrical field. The leakage current density of a LHO thin film has the lowest value of 3.8×10^{-8} A/cm^2 at −1 V among high-k oxides films and the breakdown field was 12.6, 11.5, and 17.5 MV/cm for the La_2O_3, HfO_2, and LHO thin films, respectively. Although the leakage current density of LHO thin film is insufficient to the standard condition of 10 nA/cm^2 at 1 MV/cm, we believe it is possible to materialize the LHO thin films as gate insulators, due to the higher dielectric constant, low leakage current density, and large breakdown field, with a consideration of increasing the LHO thickness.

Characteristics of ZnO thin film transistor with LHO gate insulator

The performance and device characteristics of the ZnO-TFT with LHO gate insulator was investigated with the HP4145B semiconductor parameter analyzer. The device was tested by measuring the drain current (I_D) as the drain-source voltage (V_{DS}) was swept from 0 to 3 V with a gate-source voltage (V_{GS}) that ranged in −0.5 V steps from 2.5 to 0.5 V in a dark environment. It can be seen from Fig. 5 that the fabricated device operated in the enhancement mode and showed hard saturation. The enhancement mode operation is more favorable to the depletion mode due to the reduction of power consumption of TFT devices. The channel conductance of a ZnO-TFT with LHO gate insulator increased dramatically before the saturation point of I_D with increasing V_{DS}. While a small contact resistance was observed in the output curve at a low drain voltage, but ohmic contacts between source/drain electrodes and the ZnO active channel layer were well formed.

Fig. 6 shows the transfer characteristics (I_D-V_{GS}) of a ZnO-TFT having the device structure shown in Fig. 1. A series of measurements were conducted when the gate-source voltage was swept from −1 to 5 V at a fixed drain-source bias of 2.5 V. The source and drain electrodes are patterned by the lift-off method, and the channel width and length were 200 μm and 20 μm, respectively. The transfer characteristics indicate that the ZnO-TFT with a LHO gate insulator operates in the enhancement mode and as a typical n-channel field effect transistor with an excellent performance. The field effect mobility, saturation mobility, and turn-on voltage were estimated to be approximately 2.8 cm^2/Vs, 3.6 cm^2/Vs, and −0.4 V, respectively. The obtained device characteristics were similar to or better than that of other ZnO-TFTs. Moreover, there is nearly no hysteresis in transfer curves within a range of

Table 1. Transistor parameters of ZnO-TFT with various gate insulators such as SiO_2, La_2O_3, HfO_2, and LHO thin films

Gate insulator (ZnO-TFT)	μFE (cm^2/Vs)	μSAT (cm^2/Vs)	V_{ON} (V)	I_{ON}/I_{OFF}	S (S/decade)
SiO_2	1.65	0.86	-18	10^5	8.0
La_2O_3	0.71	0.61	-0.8	10^5	1.2
HfO_2[15]	5.32	-	2.8 (V_{TH})	10^3	> 3.0
LHO	2.77	3.55	-0.4	10^7	0.35

V_{GS} from -1 to 3 V. This result indicates that the LHO gate insulator exhibited good interfacial characteristics, i.e., low defect density, with the ZnO active channel layer. An important transistor parameter for a TFT application is the on-to-off current ratio (I_{ON}/I_{OFF}). In this study, the I_{ON}/I_{OFF} was obtained 10^7 and more, and the off current was measured around 10^{-12} A. Furthermore, the subthreshold swing value (S) was obtained as 0.35 V/decade, this result permits a fast switching of TFT device. These characteristics are little different from or better than the pervious reported ZnO-TFT with high-k gate insulator [14, 15].

Table 1 also summarizes the characteristics of ZnO-TFTs with various gate insulators such as field effect mobility, saturation mobility, turn-on voltage, on-to-off current ratio, and subthreshold swing value. From Table 1, it can be seen that the performance of the ZnO-TFT with a LHO gate insulator stands in different levels compared to other devices. It can be concluded that the TFT gate insulator solution recommended here is to employ a multi-component combination of the oxides of La and Hf. This multi-component high-k gate insulator has advantages to be highly successful in the development of the next generation of displays, i.e., AMLCD and AMOLED, used as switching and/or driving TFTs.

Conclusions

From the experimental results, the following conclusions can be drawn. We investigated the electrical properties of LHO thin films by C-V and I-V measurements. The leakage current density and breakdown field of LHO thin films were obtained with excellent values better than La_2O_3 and HfO_2 thin films. The dielectric constant of LHO as $16.3\varepsilon_0$ is higher than La_2O_3 and HfO_2. The transistor parameters of the ZnO-TFT with a LHO gate insulator of field effect mobility (μ_{FE}), saturation mobility (μ_{SAT}), subthreshold swing (S), and I_{ON}/I_{OFF} were obtained as 2.77 cm^2/Vs, 3.55 cm^2/Vs, –0.35 V/decade, and 10^7, respectively. It can be concluded that a multi-component high-k LHO gate insulator has advantages to be highly successful in the development of the display industry. In order to ensure the possibility of application in industry, further studies of the stability in a ZnO-TFT with a LHO gate insulator are still needed. However, these results are still of interest in that they present the potentiality of producing a ZnO-TFT with a high performance. And we believe that these results will be very helpful to the application of the next generation of displays.

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