Structural and electrical characteristics of high-κ \( \text{Er}_2\text{O}_3 \) and \( \text{Er}_2\text{TiO}_5 \) gate dielectrics for a-IGZO thin-film transistors

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Abstract

In this letter, we investigated the structural and electrical characteristics of high-κ \( \text{Er}_2\text{O}_3 \) and \( \text{Er}_2\text{TiO}_5 \) gate dielectrics on the amorphous indium-gallium-zinc-oxide (a-IGZO) thin-film transistor (TFT) devices. Compared with the \( \text{Er}_2\text{O}_3 \) dielectric, the a-IGZO TFT device incorporating an \( \text{Er}_2\text{TiO}_5 \) gate dielectric exhibited a low threshold voltage of 0.39 V, a high field-effect mobility of 8.8 cm²/Vs, a small subthreshold swing of 143 mV/decade, and a high \( I_{\text{on}}/I_{\text{off}} \) current ratio of \( 4.23 \times 10^7 \), presumably because of the reduction in the oxygen vacancies and the formation of the smooth surface roughness as a result of the incorporation of Ti into the \( \text{Er}_2\text{TiO}_5 \) film. Furthermore, the reliability of voltage stress can be improved using an \( \text{Er}_2\text{TiO}_5 \) gate dielectric.

Keywords: Amorphous InGaZnO, Thin-film transistor, \( \text{Er}_2\text{O}_3 \), \( \text{Er}_2\text{TiO}_5 \)

Background

Amorphous indium-gallium-zinc-oxide (a-IGZO) thin-film transistors (TFTs) are being extensively explored as a replacement for amorphous and polycrystalline silicon TFTs in large-area display technologies, such as active-matrix liquid crystal display devices and active-matrix organic light-emitting displays [1]. This is due to their high field-effect mobility, low leakage current, excellent optoelectronic characteristics, good uniformity and stability, and low temperature fabrication [2].

To achieve a high drive current at a low gate voltage, we can either employ high-κ materials or thinner gate dielectrics [3]. However, the decrease in the thickness of gate dielectric is limited due to the occurrence of electron tunneling. Consequently, high-κ gate dielectric materials, including \( \text{Al}_2\text{O}_3 \) [4], \( \text{ZrO}_2 \) [3], \( \text{Y}_2\text{O}_3 \) [5], and \( \text{HfO}_2 \) [6], have been studied to reduce the electron tunneling and maintain the large capacitance. However, \( \text{HfO}_2 \) dielectric film has a critical disadvantage of high charge trap density between the gate electrode and gate dielectric, as well as the gate dielectric and channel layer [7]. Recently, rare earth (RE) oxide films have been extensively investigated due to their probable thermal, physical, and electrical performances [6]. To date, the application of RE oxide materials as gate dielectrics in a-IGZO TFTs has not been reported. Among the RE oxide films, an erbium oxide (\( \text{Er}_2\text{O}_3 \)) film can be considered as a gate oxide because of its large dielectric constant (approximately 14), wide bandgap energy (>5 eV), and high transparency in the visible range [8,9]. The main problem when using RE films is moisture absorption, which degrades their permittivity due to the formation of low-permittivity hydroxides [10]. The moisture absorption of RE oxide films may be attributed to the oxygen vacancies in the films [11]. To solve this problem, the addition of Ti or \( \text{TiO}_x \) (κ = 50 to approximately 110) into the RE dielectric films can result in improved physical and electrical properties [12]. In this study, we compared the structural and electrical properties of \( \text{Er}_2\text{O}_3 \) and \( \text{Er}_2\text{TiO}_5 \) gate dielectrics on the a-IGZO TFT devices.

Methods

The \( \text{Er}_2\text{O}_3 \) and \( \text{Er}_2\text{TiO}_5 \) a-IGZO TFT devices were fabricated on the insulated \( \text{SiO}_2/\text{Si} \) substrate. A 50-nm TaN film was deposited on the \( \text{SiO}_2 \) as a bottom gate through a reactive sputtering system. Next, an approximately 45-nm \( \text{Er}_2\text{O}_3 \) was deposited by sputtering from an Er target, while an \( \text{Er}_2\text{TiO}_5 \) thin film (approximately 45 nm) was deposited through cosputtering using both Er and Ti targets at room temperature. Then, postdeposition annealing was
performed using furnace in O2 ambient for 10 min at 400°C. The a-IGZO channel material (approximately 20 nm) was deposited at room temperature by sputtering from a ceramic IGZO target (In2O3/Ga2O3/ZnO = 1:1:1). Top Al (50 nm) source/drain electrodes were formed by a thermal evaporation system. The channel width/length of examined device was 1,000/200 μm. The film structure and composition of the dielectric films were analyzed using X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS), respectively. The surface morphology of the films was investigated by atomic force microscopy (AFM). The capacitance-voltage (C-V) curves of the Al/Er2O3/TaN and Al/Er2TiO5/TaN devices were measured using a HP4284 LCR meter. The electrical characteristics of the a-IGZO TFT device were performed at room temperature using a semiconductor parameter Hewlett-Packard (HP) 4156C (Palo Alto, CA, USA). The threshold voltage \( \langle V_{\text{TH}} \rangle \) was determined by linearly fitting the square root of the drain current versus the gate voltage curve. Field-effect mobility (\( \mu_{\text{FE}} \)) is derived from the maximum transconductance.

**Results and discussion**

Figure 1 displays the XRD patterns of the Er2O3 and Er2TiO5 thin films deposited on the TaN/SiO2/Si substrate. A strong Er2O3 (400) and weak TaN (101) peaks appeared in the Er2O3 film, while only TaN (101) reflection peak was presented in the Er2TiO5 film, revealing that Er2TiO5 thin film was amorphous. The insets (a) and (b) of Figure 1 depict the AFM images of the Er2O3 and Er2TiO5 thin films, respectively. The Er2O3 sample shows a higher surface roughness compared with the Er2TiO5 sample. This is attributed to the increase in the growth of the grain size, which is consistent with the XRD result. Another cause for a rough surface is the nonuniform volume expansion of Er2O3 film because of the nonuniform moisture absorption of the film [10].

Figure 2a,b presents the Er 4d_{5/2} and O 1s XPS spectra of the Er2O3 and Er2TiO5 dielectric films, respectively. In the three sets of spectra, each fitting peak is assumed to follow the general shape of the Lorentzian-Gaussian function: one peak represents the Er-OH bonds (located at 170.4 eV), the second the Er-O-Ti bonds (located at 169.9 eV), and the third the Er-O bonds (located at 168.4 eV) [13]. The Er 4d_{5/2} peak of the Er2O3 film has two intensity peaks corresponding to Er2O3 and Er(OH)x. For the Er2TiO5 film, the intensity of Er 4d_{5/2} peak corresponding to Er2TiO5 was larger than that of Er2O3. Furthermore, the Er 4d_{5/2} peak corresponding to Er2O3 for Er2TiO5 sample had a lower intensity compared with Er2O3 sample. These results are due to the reaction of TiOx with the Er atom to form an Er2TiO5 structure. The O 1s spectra of the Er2O3 and Er2TiO5 films are shown in Figure 2b with their appropriate peak curve-fitting lines. The O 1s signal comprised three peaks at 530.2, 531, and 532.7 eV, which we assign to Er2O3 [14], Er2OTi6, and Er(OH)x, respectively. The intensity of O 1s peak corresponding to Er(OH)x bonding for the Er2O3 film was larger in comparison with the Er2TiO5 film, indicating that the reaction between the Er and water caused hydroxide units in the film. The O 1s peak of the Er2TiO5 film exhibits a large intensity peak corresponding to Er2TiO5 and two small intensity peaks corresponding to Er2O3 and Er(OH)x. This result indicates that the reaction of TiOx with Er atom forming an Er2TiO5 film suppresses the formation of Er(OH)x.

Figure 3a shows the C-V curves of the Al/Er2O3/TaN and Al/Er2TiO5/TaN capacitor devices. The Al/Er2TiO5/TaN capacitor exhibited a higher capacitance density than the Al/Er2O3/TaN one. In addition, the \( \kappa \) value of the Er2O3 and Er2TiO5 dielectric films is determined to be 13.7 and 15.1, respectively. Figure 3b depicts the current–voltage characteristics of the Al/Er2O3/TaN and Al/Er2TiO5/TaN devices. The Al/Er2TiO5/TaN device exhibited a lower leakage current than the Al/Er2O3/TaN device. This result is attributed to the formation of a smooth surface at the oxide/channel interface.

The transfer characteristics of the a-IGZO TFT devices using Er2O3 and Er2TiO5 gate dielectrics were shown in Figure 4a. The \( V_{\text{TH}} \) value of the Er2O3 and Er2TiO5 a-IGZO TFT devices is 1.5 and 0.39 V, respectively. For the Er2TiO5 a-IGZO TFT devices is 1.5 and 0.39 V, whereas the \( I_{\text{on}}/I_{\text{off}} \) ratio is 1.72 × 10^6 and 4.23 × 10^4, respectively. The moisture absorption of the Er2O3 film generates a rough surface due to the formation of Er(OH)x, thus causing degradation in the electrical characteristics. Furthermore, the \( I_{\text{on}} \) current can be improved by bottom
gate pattern to reduce the leakage path from the gate to the source and drain. Furthermore, the $\mu_{FE}$ of the Er$_2$O$_3$ and Er$_2$TiO$_5$ TFT devices is 6.7 and 8.8 cm$^2$/Vs. This result is due to the smooth roughness at the oxide-channel interface [15]. The subthreshold swing (SS) of the Er$_2$O$_3$ and Er$_2$TiO$_5$ TFT devices is 315 and 143 mV/dec, respectively. The titanium atoms can effectively passivate the oxygen vacancies in the Er$_2$TiO$_5$. The effective interface trap state densities ($N_{it}$) near/at the interface between the dielectric and IGZO were estimated from the SS values. By neglecting the depletion capacitance in the active layer, the $N_{it}$ can be calculated from the relationship [6]:

$$N_{it} = \left( \frac{SS}{\ln 10} \frac{q}{kT} \right) \frac{C_{ox}}{C_1},$$

where $q$ is the electronic charge; $k$, the Boltzmann’s constant; $T$, the temperature; and $C_{ox}$, the gate capacitance density. The $N_{it}$ values of IGZO TFTs using Er$_2$O$_3$ and Er$_2$TiO$_5$ gate dielectrics are about $6.92 \times 10^{12}$ and $2.58 \times 10^{12}$ cm$^{-2}$, respectively. Figure 4b shows the output characteristics of the a-IGZO TFT devices using the Er$_2$O$_3$ and Er$_2$TiO$_5$ gate dielectrics. As is seen, the driving current increases significantly for the Er$_2$TiO$_5$ dielectric material. This outcome may be attributed to the higher mobility and smaller threshold voltage.

To explore the reliability of an a-IGZO transistor, the dc voltage was applied to the high-$\kappa$ Er$_2$O$_3$ and Er$_2$TiO$_5$ a-IGZO TFT devices. Figure 5a shows the threshold voltage and drive current degradation as a function of stress time. The voltage stress was performed at $V_{GS} = 6$ V and $V_{DS} = 6$ V for 1,000 s. The shift in threshold voltage and the degradation in drive current are associated with the trap states in the dielectric layer and the interface between the dielectric film and channel layer [16]. The large $V_{TH}$ shift (1.47 V) of the Er$_2$O$_3$ TFT can be due to more electrons trapping near/at the interface between the Er$_2$O$_3$ and IGZO layer [6], whereas the low $V_{TH}$ shift (0.51 V) of the Er$_2$TiO$_5$ TFT device may be attributed to the reduction of the trapped charge in the film. With increasing $V_{GS}$, interface states are substantially generated, which are normally regarded to be Er dangling bonds (=Er*), originating from the dissociation of
weak Er-OH bonds at the oxide/channel interface. The dissociation of Er-OH bonds under dc stressing is proposed to be associated by the electrons in the oxide surface as follows:

\[
\text{Er-OH + e}^- \rightarrow \text{Er}^+ + \text{OH}^- \rightarrow \text{H}_2\text{O} + \text{O}^+ + 2e^-
\]

(2)

The physical model to be presented is based on the structure of the Er$_2$O$_3$ and Er$_2$TiO$_5$ surfaces, as schematically depicted in Figure 5b,c, respectively. Briefly speaking, during dc stress, hydroxyl ions (OH$^-$) are released from the erbium hydroxide (Er-OH) by breaking the Er-OH bonds. The electrons in the oxide have gained enough energy from the applied gate and drain voltages. They collide with strained Er-O-Er or Er-O-Ti bonds to generate trapped charges in bulk oxide, causing a threshold voltage shift. On the other hand, a-IGZO TFT with the Er$_2$O$_3$ dielectric has a larger drive current degradation than that with the Er$_2$TiO$_5$ one. The hygroscopic nature of RE oxide films forming hydroxide produces oxygen vacancies in the gate dielectric, leading to a larger flat-band voltage shift and higher leakage current [11]. The incorporation of Ti into the Er$_2$O$_3$ dielectric film can effectively reduce the oxygen vacancies in the film.

Conclusions

In conclusion, we have fabricated a-IGZO TFT devices using the Er$_2$O$_3$ and Er$_2$TiO$_5$ films as a gate dielectric. The a-IGZO TFT incorporating a high-$κ$ Er$_2$TiO$_5$ dielectric exhibited a lower $V_{TH}$ of 0.39 V, a larger $μ_{FE}$ of 8.8 cm$^2$/Vs, a higher $I_{on}/I_{off}$ ratio of $4.23 \times 10^7$, and a smaller subthreshold swing of 143 mV/dec than that of Er$_2$O$_3$ dielectric. These results are attributed to the addition of Ti into the Er$_2$O$_3$ film passivating the oxygen vacancies.
in the film and forming a smooth surface. Furthermore, the use of Er2TiO5 dielectric film could improve the stressing reliability. The Er2TiO5 thin film is a promising gate dielectric material for the fabrication of a-IGZO TFTs.

Competing interests
The authors declare that they have no competing interests.

Authors’ contributions
FHC designed the experiment, measured the a-IGZO TFT device data, and drafted the manuscript. JLH provided useful suggestions and helped analyze the characterization results. YHS performed the experiment and measured the electrical characteristics. YHA helped in the technical support for the experiments. TMP supervised the work and finalized the manuscript. All authors read and approved the final manuscript.

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