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L. X. Qian, P. T. Lai, and W. M. Tang

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Effects of Ta incorporation in La$_2$O$_3$ gate dielectric of InGaZnO thin-film transistor

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The effects of Ta incorporation in La$_2$O$_3$ gate dielectric of amorphous InGaZnO thin-film transistor are investigated. Since the Ta incorporation is found to effectively enhance the moisture resistance of the La$_2$O$_3$ film and thus suppress the formation of La(OH)$_3$, both the dielectric roughness and trap density at/near the InGaZnO/dielectric interface can be reduced, resulting in a significant improvement in the electrical characteristics of transistor. Among the samples with different Ta contents, the one with a Ta/(Ta + La) atomic ratio of 21.7% exhibits the best performance, including high saturation carrier mobility of 23.4 cm$^2$/V·s, small subthreshold swing of 0.177 V/dec, and negligible hysteresis. Nevertheless, excessive incorporation of Ta can degrade the device characteristics due to newly generated Ta-related traps. © 2014 AIP Publishing LLC

Recently, amorphous InGaZnO (a-IGZO) thin-film transistors (TFTs) have been extensively explored for the application in various flat-panel displays. Compared to conventional amorphous silicon or organic TFTs with a field-effect carrier mobility of ~1 cm$^2$/V·s, a-IGZO TFTs typically exhibit a mobility higher than 10 cm$^2$/V·s, which can translate to higher switching speed for electronic devices. In addition, a-IGZO TFTs offer better uniformity in device characteristics compared with polycrystalline silicon TFTs and have more excellent transparency to visible light than all the silicon-based devices. In order to reduce their operating voltage, high-k materials have been adopted as gate dielectric in a-IGZO TFTs. Among them, rare-earth oxide La$_2$O$_3$ is regarded as one of the most promising candidates due to its relatively high dielectric constant and large band gap (~6 eV). However, La$_2$O$_3$ is hygroscopic, which can deteriorate both the dielectric constant and surface roughness of La$_2$O$_3$ film due to the formation of hydroxide La(OH)$_3$, and thus induce degradations in the electrical characteristics of a-IGZO TFTs. Fortunately, the doping of other elements, for example, Y, was reported to be an effective method to suppress the moisture absorption of La$_2$O$_3$ film. In this work, the doping of Ta in La$_2$O$_3$ film is proposed due to the fact that Ta$_2$O$_5$ can exhibit both very high dielectric constant and excellent step coverage, and accordingly the effects of Ta incorporation in La$_2$O$_3$ gate dielectric of a-IGZO TFTs are investigated. Three samples of a-IGZO TFTs with different Ta/(Ta + La) atomic ratios are prepared while one sample with pure La$_2$O$_3$ gate dielectric is also fabricated as the control sample. Each sample was fabricated on a p-type (100) silicon wafer with a resistivity of 0.01–0.02 Ω·cm which acted as both the substrate and gate electrode. First, a 40-nm dielectric film was deposited by a sputtering system under a radio-frequency (RF) power supply for a ceramic target of La$_2$O$_3$ and a direct-current (DC) supply for a metal target of Ta in a mixed ambient of Ar plus O$_2$. The RF power was fixed at 40 W while the DC supply was set to be 0 A, 0.03 A, 0.04 A, and 0.05 A for sample_La$_2$O$_3$, sample_LaTaO$_A$, sample_LaTaO$_B$, and sample_LaTaO$_C$, respectively, so as to realize different atomic ratios of Ta/(Ta + La) in dielectric films. Second, an annealing treatment at 400 °C in an N$_2$ ambient for 30 min followed. Subsequently, the four samples received the deposition of a 60-nm a-IGZO active layer through RF sputtering from a ceramic target (Ga$_2$O$_3$: In$_2$O$_3$: ZnO = 1: 1: 1). After that, a lift-off process was utilized to form the source/drain electrodes, which were composed of 20-nm Ti and 80-nm Au. The channel width (W) and channel length (L) were 100 μm and 10 μm, respectively. Finally, all the samples were annealed in a forming-gas (N$_2$: H$_2$ = 95: 5) ambient at 350 °C for 20 min so that the contact resistance of the source/drain electrodes was reduced. In addition, metal-insulator-semiconductor capacitor was also prepared beside each sample to monitor the gate-oxide capacitance per unit area ($C_{mn}$). The current-voltage (I-V) curves of the TFTs were measured by a HP 4145B semiconductor parameter analyzer. Furthermore, the structural properties of the dielectric films were studied based on X-ray photoelectron spectroscopy (XPS) and atomic force microscopy (AFM).

Fig. 1 shows the XPS spectra of (a) La 3d$_{5/2}$ and (b) O 1 s core levels for the dielectric films. The binding energies have been corrected for sample charging effect with reference to the C 1 s line at 285.0 eV. Accordingly to the XPS result, the atomic ratio of Ta/(Ta + La) is 0%, 21.7%, 30.6%, and 69.1% for sample_La$_2$O$_3$, sample_LaTaO$_A$, sample_LaTaO$_B$, and sample_LaTaO$_C$, respectively. As shown in Fig. 1(a), the La$_2$O$_3$ film exhibits an obvious shoulder at the high binding energy side of the La 3d$_{5/2}$ main peak, suggesting the presence of La-OH bond due to the moisture absorption of La$_2$O$_3$. Furthermore, the La 3d$_{5/2}$ peak of the La$_2$O$_3$ film (located at 834.7 eV) shifts to a higher binding energy compared to the ideal La$_2$O$_3$ reference peak (located at 834.0 eV) while being consistent with the reported peak for LaOOH film (located at 834.8 ± 0.2 eV) in peak location, further revealing the
The existence of La(OH)$_3$ in the La$_2$O$_3$ film. With Ta incorporation, the La 3d$_{5/2}$ main peak becomes sharper, which is more obvious for higher Ta/(Ta + La) atomic ratio in the LaTaO film. This result is presumably due to the enhancement in the moisture resistance of the La$_2$O$_3$ film and accordingly the suppression in the formation of La(OH)$_3$ after Ta incorporation. Nevertheless, the La 3d$_{5/2}$ peak related to sample LaTaO_C (located at 835.0 eV) shifts to an even higher binding energy in comparison to sample La$_2$O$_3$, suggesting the formation of La-O-Ta bond in the LaTaO film. The O 1s spectra of the La$_2$O$_3$ and LaTaO films are shown in Fig. 1(b), and each fitting peak follows the general shape of the Lorentzian–Gaussian function. As for the La$_2$O$_3$ film, the two O 1s peaks correspond to La-O bond (located at 528.9 eV) and La-OH bond (located at 531.7 eV), respectively. Moreover, the O 1s peak corresponding to La-OH bond has a much higher intensity compared with that corresponding to La-O bond, indicating that most of La atoms in the La$_2$O$_3$ film have been transformed into La(OH)$_3$ due to moisture absorption. With Ta incorporation, the intensity of the O 1s peak corresponding to La-OH bond decreases. Moreover, this effect becomes more obvious for higher Ta/(Ta + La) atomic ratio in the LaTaO film. This result further demonstrates the suppressed formation of La(OH)$_3$ due to the enhanced moisture resistance of the La$_2$O$_3$ film after Ta incorporation. Meanwhile, the O 1s peak corresponding to La-O bond has been completely replaced by that corresponding to La-O-Ta bond (located at a higher binding energy) for each Ta-incorporated sample. Moreover, the O 1s peak corresponding to La-O-Ta bond shifts to a higher binding energy with increased Ta/(Ta + La) atomic ratio as reflected by the comparison between sample LaTaO_C and the other two Ta-incorporated samples, and similar effect also occurs to the La 3d$_{5/2}$ spectrum in Fig. 1(a).

Fig. 2 shows the AFM images of the La$_2$O$_3$ and LaTaO films with a measurement area of 1 μm x 1 μm. The La$_2$O$_3$ film, with a RMS of 1.28 nm, exhibits the roughest surface among the dielectric films, which should result from non-uniform volume expansion of the La$_2$O$_3$ film after moisture absorption. With Ta incorporation, the dielectric roughness is significantly reduced, which is more obvious for higher Ta/(Ta + La) atomic ratio. Accordingly, the RMS value of LaTaO film in sample LaTaO_A, sample LaTaO_B, and sample LaTaO_C.

**FIG. 1.** XPS spectrum of (a) La 3d$_{5/2}$ and (b) O 1s for the dielectric films in sample La$_2$O$_3$, sample LaTaO_A, sample LaTaO_B, and sample LaTaO_C.

**FIG. 2.** AFM image of dielectric films in (a) sample La$_2$O$_3$, (b) sample LaTaO_A, (c) sample LaTaO_B, and (d) sample LaTaO_C.
sample LaTaO_C is 0.51 nm, 0.43 nm, and 0.30 nm, respectively, further demonstrating that Ta incorporation is an effective way to enhance the moisture resistance of La2O3 film and accordingly reduce its surface roughness. In addition, the enhanced moisture resistance of the La2O3 film also effectively suppresses the deterioration of its dielectric constant, and thus results in a continuous increase of dielectric constant associated with increasing Ta incorporation as listed in Table I. As compared to 3.9 of conventional SiO2 dielectric, a larger dielectric constant of the LaTaO film \((C/D)\) is conducive to achieving higher-performance TFT with smaller operating voltage and larger output current.

By comparing sample La2O3 and sample LaTaO_A, \(\mu_{sat}\) is nearly doubled from 12.1 \(\text{cm}^2/\text{V}\cdot\text{s}\) to 23.4 \(\text{cm}^2/\text{V}\cdot\text{s}\) with a reduction of SS from 0.234 V/dec to 0.177 V/dec due to the Ta incorporation in the La2O3 gate dielectric. It is believed that the reduction in dielectric roughness can induce a smoother a-IGZO/dielectric interface, thus resulting in an increase in carrier mobility due to reduced surface-roughness scattering on the carriers.16 In addition, carrier mobility can also be improved by reducing the trap density at/near the a-IGZO/dielectric interface because of the restraint of electron trapping. Hence, the increase in \(\mu_{sat}\) mentioned above can be attributed to smoother dielectric surface as well as lower trap density at/near the a-IGZO/dielectric interface, which are supported by the smaller values of RMS and SS, respectively.17 Furthermore, it was reported that a large number of oxygen vacancies are easily generated in rare-earth oxide film due to the formation of hydroxide after reacting with moisture.18 Hence, it is believed that the high trap density at/near the a-IGZO/dielectric interface in sample La2O3 is related to the oxygen vacancies originated from the hygroscopicity of La2O3. In addition, a smaller \(V_{TH}\) (1.85 V) of sample La2O3 in comparison to \(V_{TH}\) (2.40 V) of

\[ I_D = (\mu_{sat} C_{ox} W / 2L) (V_{GS} - V_{TH})^2. \]

FIG. 3. Transfer characteristics of the a-IGZO TFTs in sample La2O3, sample LaTaO_A, sample LaTaO_B, and sample LaTaO_C.

FIG. 4. Output characteristics of the a-IGZO TFTs: (a) sample La2O3; (b) sample LaTaO_A; (c) sample LaTaO_B; and (d) sample LaTaO_C.
sample_LaTaO_A can further reveal the existence of oxygen vacancies in the La_2O_3 gate dielectric as well as their reduction after Ta incorporation because oxygen vacancies can act as donor-like traps, inducing a negative shift of transfer curve and a degradation of SS in a-IGZO TFTs. Besides, I_on and I_off are increased from 494 μA and 1.5 × 10^7 to 810 μA and 2.6 × 10^7, respectively, by Ta incorporation due to the improvement in carrier mobility. However, for further increase of Ta incorporation in the gate dielectric, the electrical characteristics of the TFT start to degrade even with a smoother dielectric surface, as reflected by the results of sample_LaTaO_B and sample_LaTaO_C. This should be ascribed to the creation of new Ta-related traps because a high density of defect states generally exists in Ta_2O_5 film, which can be supported by the continual degradation of SS with increasing Ta/(Ta + La) atomic ratio in the LaTaO gate dielectric. Fig. 4 displays the output characteristics of the samples, which clearly exhibit an n-type enhancement mode. According to the comparison between sample_La_2O_3 and sample_LaTaO_A, the output current of the TFT is significantly increased by the Ta incorporation in the La_2O_3 gate dielectric due to the increase in carrier mobility. A continual reduction in output current with increasing Ta/(Ta + La) atomic ratio in the LaTaO gate dielectric is observed, which is consistent with the degradation in SS due to the generation of new Ta-related traps.

As shown in Fig. 5, the hysteresis properties of the samples are investigated according to the transfer characteristics measured under forward and reverse V_{GS} sweeps successively. \( \Delta V_H \) is defined as the V_TH shift in the hysteresis loop. It is found that sample_La_2O_3 exhibits an obvious antlockwise hysteresis with a negative \( \Delta V_H \) (−0.76 V), further revealing the existence of donor-like traps at/near the a-IGZO/dielectric interface, which is due to the introduction of oxygen vacancies in the La_2O_3 film after moisture absorption. These donor-like traps can induce electron-detrapping or hole-trapping and become positively charged during the forward V_{GS} sweep of the hysteresis measurement. As a result, a decrease of V_TH is observed during the subsequent backward V_{GS} sweep. With Ta incorporation in the La_2O_3 gate dielectric, negligible hysteresis is exhibited by sample_LaTaO_A (\( \Delta V_H = 0.10 \) V), which further demonstrates the reduction in the trap density at/near the a-IGZO/dielectric interface due to the enhanced moisture resistance of the dielectric film and thus suppressed generation of oxygen vacancies. In addition, the generation of new Ta-related traps, which are acceptor-like and prefer to capture electrons, has also been revealed by the continual enhancement of clockwise hysteresis with increasing Ta/(Ta + La) atomic ratio in the LaTaO gate dielectric. As a result, larger \( \Delta V_H \) is exhibited by sample_LaTaO_B (\( \Delta V_H = 1.29 \) V) and sample_LaTaO_C (\( \Delta V_H = 2.34 \) V). A similar phenomenon of different signs of \( \Delta V_H \) for hysteresis related to donor-like and acceptor-like traps has also been observed in other work.

In this work, the impact of Ta incorporation in La_2O_3 gate dielectric on the electrical characteristics of a-IGZO TFT has been studied. It is found that Ta incorporation can effectively enhance the moisture resistance of the La_2O_3 film and suppress the formation of La(OH)_3, thus reducing the dielectric roughness as well as the trap density at/near the a-IGZO/dielectric interface. Accordingly, the electrical characteristics of the TFT are significantly improved as reflected by nearly doubled \( \mu_{sat} \), reduced SS, suppressed hysteresis, and increased output current. However, excessive incorporation of Ta in the gate dielectric can degrade the device characteristics due to the creation of new Ta-related traps. In summary, these results demonstrate the potential use of LaTaO gate dielectric for making high-performance a-IGZO TFTs.

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