Abnormal positive bias stress instability of In–Ga–Zn–O thin-film transistors with low-temperature Al2O3 gate dielectric

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Low-temperature atomic layer deposition (ALD) was employed to deposit Al2O3 as a gate dielectric in amorphous In–Ga–Zn–O thin-film transistors fabricated at temperatures below 120 °C. The devices exhibited a negligible threshold voltage shift (ΔVT) during negative bias stress, but a more pronounced ΔVT under positive bias stress with a characteristic turnaround behavior from a positive ΔVT to a negative ΔVT. This abnormal positive bias instability is explained using a two-process model, including both electron trapping and hydrogen release and migration. Electron trapping induces the initial positive ΔVT, which can be fitted using the stretched exponential function. The breakdown of residual AlO-H bonds in low-temperature ALD Al2O3 is triggered by the energetic channel electrons. The hydrogen atoms then diffuse toward the In–Ga–Zn–O channel and induce the negative ΔVT through electron doping with power-law time dependence. A rapid partial recovery of the negative ΔVT after stress is also observed during relaxation. © 2016 AIP Publishing LLC.

Recently, amorphous In-Ga-Zn-O (a-IGZO) has attracted substantial attention for thin-film transistor (TFT) applications because of its numerous superior properties including high mobility (>10 cm2/V·s), low defect density, a low process temperature, and large-area uniformity.1,2 In addition to backplane transistors in active-matrix displays,3,4 the a-IGZO TFT has promising potential as the main building block of integrated circuits on arbitrary substrates (e.g., glass, plastics, and papers),5–7 which might lead to a new generation of electronics with the unprecedented advantages of low cost, large area, light weight, and flexibility. The integration on arbitrary substrates necessitates low-temperature processes including a-IGZO deposition and TFT device fabrication. Furthermore, by taking advantage of the wide bandgap of a-IGZO, a-IGZO TFTs have been investigated as high-voltage power transistors, which can be integrated monolithically with logic circuits for reducing the overhead of additional power management circuits at the I/O interface.8–10 For power transistor applications, bias instability in a high field and at an elevated temperature is the foremost concern.9 The a-IGZO TFTs are prone to a positive threshold voltage shift (ΔVT) induced by electron trapping in gate dielectrics during positive bias stress (PBS)11–13 and are prone to a negative ΔVT induced by hole trapping during negative bias stress (NBS), especially when assisted by photons and subgap defects under illumination.14–17

This letter investigates the bias stress instability of a-IGZO TFTs with Al2O3 gate dielectrics through atomic layer deposition (ALD). ALD Al2O3 was deposited at 120 °C, which is suitable for integration with plastic substrates. The higher dielectric constant of Al2O3 compared with conventional SiO2 or SiN is desirable for sustaining a sufficiently high breakdown voltage with low effective oxide thickness. Whereas the negative ΔVT under NBS was negligible, the a-IGZO TFT exhibited a more pronounced ΔVT under PBS with a characteristic turnaround behavior from the initial positive ΔVT to the negative ΔVT after long stress times. The mechanism for this ΔVT turnaround behavior was examined and correlated with residual hydrogen in low-temperature ALD Al2O3. A two-process model including both electron trapping and hydrogen release and migration was proposed for explaining the experimental results. This finding suggests that the optimization of the gate dielectric process, especially the hydrogen content, is critical for high-voltage a-IGZO devices fabricated at low temperatures.

Figure 1(a) shows the cross-sectional diagram of a top-gate a-IGZO TFT structure used in this study. The devices were fabricated on SiO2 (100 nm)/Si substrates. First, a-IGZO films with a thickness of 40 nm were deposited through radio-frequency (RF) magnetron sputtering by using an IGZO target with an In: Ga: Zn: O ratio of 1:1:1:4 at room temperature. The a-IGZO channel was then defined through photolithography and HF wet etching. The 25-nm Ti followed by 25-nm Ni layers were deposited using e-beam evaporation and patterned as the source/drain (S/D) contacts through a lift-off process. The Ni layer was used to protect the Ti layer from oxidation. Low-temperature ALD was applied for depositing the 30-nm-thick Al2O3 gate dielectric at 120 °C by using Al(CH3)3 (trimethylaluminum; TMA) and water as the precursors. Afterward, S/D contact holes were opened by patterning the Al2O3 layer through dry etching. Finally, the Ni gates were deposited using DC magnetron sputtering and patterned by a lift-off process.

The stability of the low-temperature a-IGZO TFTs was evaluated using gate stress voltages of 10 V and −10 V (3.3 MV/cm) for PBS and NBS, respectively, at room temperature. Figure 1(b) shows the device transfer curve (drain current (ID) versus gate voltage (VG)) for PBS and NBS, respectively, at room temperature.
hole generation in a-IGZO without illumination,\textsuperscript{14,15} thus suppressing the hole trapping in the gate dielectric. By contrast, Fig. 1(c) shows $V_T$ turnaround characteristics under PBS. The $V_T$ first shifted positively during the initial 100 s, but it then shifted negatively with longer PBS times. The initial positive $\Delta V_T$ is explained by the electron trapping in Al$_2$O$_3$,\textsuperscript{11,12} which is also evident in an a-IGZO TFT with a high-temperature ALD Al$_2$O$_3$ dielectric deposited at 250°C, as shown in Fig. 1(d). However, the characteristic $V_T$ turnaround phenomenon existed only in the sample with low-temperature ALD Al$_2$O$_3$. The extracted electron saturation mobility and subthreshold slope for the device with 120°C ALD Al$_2$O$_3$ were 0.5 cm$^2$/V s and 104 mV/decade, respectively, while those for the device with 250°C ALD Al$_2$O$_3$ were 5.3 cm$^2$/V s and 145 mV/decade, respectively. The improved electron mobility with high-temperature ALD Al$_2$O$_3$ is attributed to the annealing effect on a-IGZO\textsuperscript{2} during the ALD process. Furthermore, this $V_T$ turnaround effect depended strongly on the stress voltages and temperatures. Figure 2 shows that the magnitude of negative $\Delta V_T$ increased and the turnaround stress time decreased at larger stress voltages or elevated temperatures. Note that $V_T$ was extracted using a constant current method at 1 nA throughout this study.

We analyzed the compositions of ALD Al$_2$O$_3$ deposited at different temperatures through secondary ion mass spectrometry (SIMS), as shown in Fig. 3. The most obvious difference between these two samples was the higher hydrogen content in the low-temperature ALD Al$_2$O$_3$ film. The increased hydrogen content at a low deposition temperature is consistent with those reported in previous studies on ALD Al$_2$O$_3$ by using a deposition temperature ranging between 33° and 350°C and TMA and H$_2$O as the precursors.\textsuperscript{18,19} The hydrogen concentrations were determined by Rutherford backscattering spectrometry (RBS) at $1.5 \times 10^{16}/\text{cm}^2$ and $9 \times 10^{15}/\text{cm}^2$ for films deposited at 120°C and 250°C, respectively.\textsuperscript{18} One previous study determined that, at lower temperatures, the surface coverage of hydroxyl species is higher on the Al$_2$O$_3$ surface, and the chemical reaction between TMA and AlO-H is less complete, resulting in considerable hydrogen residues in Al$_2$O$_3$.\textsuperscript{20} In addition, residual hydrogen in low-temperature ALD Al$_2$O$_3$ films is present in the form of AlO-H species.\textsuperscript{20}

To explain the $V_T$ turnaround phenomenon under PBS, we constructed a two-process model including both electron trapping and hydrogen release and migration, as shown in Fig. 4. Electron trapping in traps located at the interface and bulk Al$_2$O$_3$ layers was responsible for the initial positive
\( \Delta V_T \) and was modeled using a stretched exponential equation,\(^{12,21} \) as follows:

\[
\Delta V_T = \Delta V_{T,+\text{MAX}} \left( 1 - \exp\left( -\frac{t}{\tau_1} \right)^{\beta} \right),
\]

where \( \Delta V_{T,+\text{MAX}} \) represents the maximal positive \( \Delta V_T \) at an infinite time, \( \tau_1 \) is the characteristic trapping time of carriers, and \( \beta \) is the stretched exponential exponent. The stretched exponential equation considers both electron trapping at the interface and the redistribution effect in bulk Al\(_2\)O\(_3\). The hydrogen release and migration process in low-temperature ALD Al\(_2\)O\(_3\) is similar to that established in negative-bias temperature instability (NBTI) theory for Si MOSFETs,\(^{22,23} \) where Si-H bonds at the dielectric interface are broken. However, because of the high hydrogen concentration in low-temperature ALD Al\(_2\)O\(_3\), the breakage of the AlO-H bonds likely occurred throughout the entire bulk of Al\(_2\)O\(_3\).

The negative \( \Delta V_T \) under PBS can be explained by the hydrogen migration and incorporation into IGZO. Hydrogen is known as an effective electron donor to IGZO through the reaction of \( H^0 \) (from outside) + O\(^2-\) (in a-IGZO) \text{ }\rightarrow\text{ } -OH^- \text{ } (\text{in a-IGZO}) + e^- .\(^2 \) The negligible \( \Delta V_T \) under NBS might be attributed to two possible reasons: (1) The breakage of the AlO-H bonds is triggered by energetic channel carriers, which are unavailable under NBS because of the lack of holes; and (2) the released hydrogen species are positive hydrogen ions, which drift away from the IGZO channel under NBS. According to the NBTI theory, various dissociation energies of Si-H bonds lead to the power-law time dependence of the interface state generation and \( \Delta V_T \).\(^{23} \) We adopted the similar expression for a negative \( \Delta V_T \) by considering the various dissociation energies of AlO-H bonds in disordered Al\(_2\)O\(_3\), as follows:

\[
\Delta V_T = \Delta V_{T,-\text{MAX}} \left( 1 + \frac{1}{(t/\tau_2)^{\sigma}} \right),
\]

where \( \Delta V_{T,-\text{MAX}} \) represents the maximal negative \( \Delta V_T \) at an infinite time, \( \tau_2 \) is the characteristic time of hydrogen release, \( \alpha = kT/\sigma \), and \( \sigma \) represents the spread of the dissociation energy. The \( V_T \) turnaround phenomenon under PBS can be fitted reasonably (Fig. 2) at various temperatures and bias voltages by summing Eqs. (1) and (2). For simplicity, we assumed that the electron trapping and the breakage of AlO-H bonds were uncorrelated. However, their correlation should be examined carefully in future studies. Although the spread of the dissociation energy of AlO-H bonds in Al\(_2\)O\(_3\) has not yet been reported, the extracted value of \( \sigma = 0.112 \text{ eV} \) appears to be a reasonable estimation.

A rapid recovery of the hydrogen doping effect was also observed by interrupting the continuous positive bias, as

FIG. 3. SIMS analysis on ALD Al\(_2\)O\(_3\) deposited on a-IGZO films for (a) Al\(_2\)O\(_3\) deposited at 250 °C and (b) Al\(_2\)O\(_3\) deposited at 120 °C.

FIG. 4. Schematic diagram illustrating the two-process mechanism under PBS, including electron trapping in Al\(_2\)O\(_3\) (1) and the hydrogen release and migration (2). The released hydrogen atoms diffuse toward the IGZO channel (3), bond with O\(^2-\) to form OH\(^-\) (4), and dope the IGZO channel with free electrons (5).
shown in Fig. 5. A 50-s relaxation time was inserted after each 200-s PBS cycle at 50 °C. The negative ∆VT induced by hydrogen doping can be partially recovered during the relaxation phase, whereas the relaxation time for the positive ∆VT induced by electron trapping is substantially longer and went unobserved at this timescale. Furthermore, the recovery was not facilitated by the opposite negative bias, suggesting that the main migration species is likely to be the neutral hydrogen atom instead of the positive hydrogen ion. This phenomenon of rapid recovery might be due to the hydrogen diffusion from IGZO back to Al2O3 when the incoming flux of hydrogen was removed without bias.22

In summary, the abnormal PBS instability in the a-IGZO TFTs with low-temperature ALD Al2O3 gate dielectrics was attributed to the combined effect of electron trapping and hydrogen release and migration. Electron trapping induces the initial positive ∆VT, which can be fitted using the stretched exponential equation. The breakage of residual AlO-H bonds in the low-temperature ALD Al2O3 is triggered by energetic channel electrons. Hydrogen atoms then diffuse toward the a-IGZO channel and induce the negative ∆VT through electron doping with power-law time dependence. This model was supported by the experimental data at various temperatures and PBS voltages, SIMS analysis on hydrogen content in ALD Al2O3, and the rapid recovery of the negative ∆VT during relaxation. Because the a-IGZO channel is sensitive to hydrogen, the process optimization of gate dielectric deposition is critical for high-voltage a-IGZO TFTs fabricated at low temperatures.

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