

Capping of Indium-Gallium-Zinc Oxide Thin-film Transistors Using ALD Materials

Julia Okvath, Dr. Karl Hirschman, Prashant Ganesh, and Tarun Mudgal

Abstract—Indium-gallium-zinc oxide (IGZO) thin-film transistors (TFTs) used in LCD display technologies exhibit significant instability when exposed to thermal stress above 100°C. Bottom-gate TFTs subjected to prolonged heat treatment at 140°C experience a voltage shift of 2 V over 120 minutes. Double-gate TFTs experience an even more pronounced shift of 7 V over 120 minutes. This instability is believed to be associated with water molecules incorporated in the PECVD TEOS SiO₂ passivation layer, with an enhanced response in the double-gate device due to the liberation of monatomic hydrogen from the reaction of water with the top-gate metal. This research investigates the effectiveness of atomic-layer deposited Al₂O₃ and HfO₂ films as capping materials for IGZO TFTs. After being exposed to thermal stress at 140°C, capped devices demonstrate a significant improvement, with minimal variation in electrical characteristics.

Index Terms—IGZO, TFTs, atomic-layer deposition (ALD).

I. INTRODUCTION

ONE of the key components in modern LCD or OLED display technologies is the transistor. An array of transistors is typically used as the switches for the pixels in the back-plane of the display. In order to maintain precise control over the pixel, the transistors should have fast switching speeds and their V_{on} should be stable over time. Therefore, the channel material needs to be chosen carefully.

One material that has been used previously is amorphous silicon, however the mobility is not as high when compared to other material options. Polycrystalline silicon has a much higher mobility than amorphous silicon but the cost associated with manufacturing thin-film transistors with poly-Si channels is high [1]. In comparison, IGZO has both a higher mobility than amorphous silicon and is significantly more cost effective to manufacture than poly-Si devices [1]. Due to this, IGZO is the preferred channel material for TFTs in display technologies.

However, recent studies done at the Rochester Institute of Technology have shown that the voltage control of IGZO TFTs degrades significantly after exposure to thermal stress above 100°C. This degradation is believed to be caused by the reaction of water in the passivation oxide with the IGZO channel. It is very important to try and eliminate this thermal instability because back-end processing done to integrate the TFTs with the liquid crystals or the OLEDs can exceed temperatures of 100°C. This paper investigates the use of atomic-layer deposited Al₂O₃ and HfO₂ films as efficient water barriers for IGZO TFTs.

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II. THEORY AND BACKGROUND

There are two types of IGZO devices that are studied in this research: bottom-gate (BG) and double-gate (DG). Cross-sections of these devices can be seen in Figures 1 and 2.

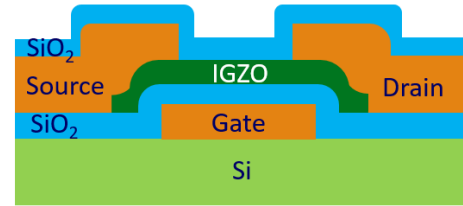


Fig. 1: Bottom-gate TFT cross-section

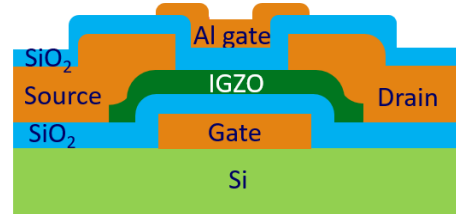


Fig. 2: Double-gate TFT cross-section

Preliminary current-voltage characteristics corresponding to thermal stress studies performed on DG devices at temperatures of 100°C, 120°C, 130°C, and 140°C are shown in Figure 3. It is seen that the turn on voltage of these devices shifts left with increasing temperature.

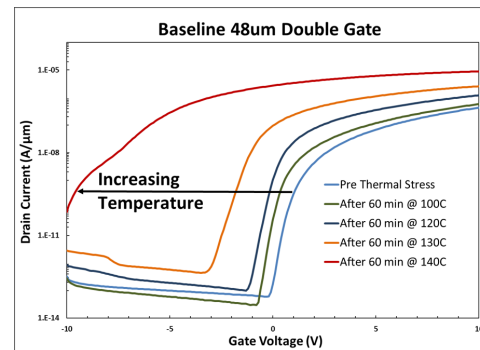


Fig. 3: Preliminary thermal stress results for double-gate devices.

The hypothesis for this behavior comes from the well-known sintering mechanism used in the processing of silicon

MOS capacitors. Sintering is the process of annealing MOS capacitors at elevated temperatures so that the adsorbed water in the oxide reacts with the metal gate. This reaction creates a metal oxide interface which effectively passivates the interface traps and releases monatomic hydrogen [2]. This effect is a desired because it improves device characteristics of the MOS capacitors.

However, when this mechanism is applied to the IGZO TFT structures the effect becomes detrimental. For BG devices, the H_2O present in the passivation oxide begins to react with the IGZO interface when subjected to elevated temperatures. This reaction effectively raises the overall electron concentration in the channel which makes the channel more conductive and a left shift in the I-V characteristics is observed. Respectively, for DG devices, this effect is worsened due to the top metal reacting with the water in the oxide which releases the monatomic hydrogen that is then free to diffuse towards the IGZO channel. The monatomic hydrogen added with the water reaction greatly increases the electron concentration in the channel of the DG devices and an even bigger shift is seen in the I-V characteristics.

To prevent this failure mechanism, ALD materials are used as a capping layer to reduce the amount of water that the top passivation oxide adsorbs. Previous studies have shown that ALD hafnia, alumina, and titanium dioxide are all sufficient capping materials [3], [4]. Due to processing limitations, this paper only reviews the effectiveness of hafnia and alumina ALD materials. The DG cross-section shown in Figure 4 demonstrates where the capping layer is placed.

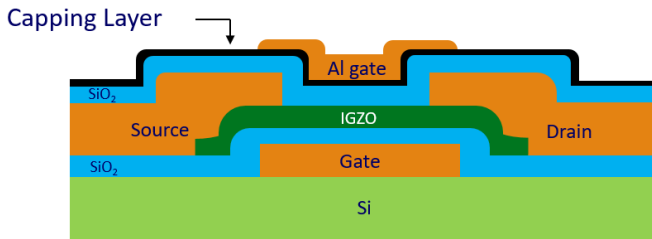


Fig. 4: Double-gate cross-section of an IGZO TFT with an ALD capping layer.

III. EXPERIMENT

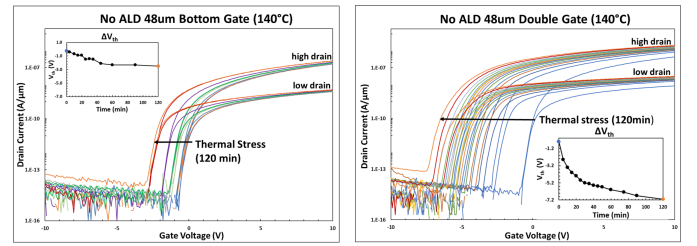
Three BG and three DG device wafers received 1000 Å of passivation oxide on top of 50 nm of IGZO sputtered by Corning Inc. All six wafers were then annealed at 400°C for 10 hours in a pure oxygen ambient to drive out any water that adsorbed into the oxide previously. Immediately after the anneal, one BG and one DG wafer received 15 nm of ALD HfO_2 while another pair of BG and DG wafers received 15 nm of ALD Al_2O_3 . The remaining pair of BG/DG wafers did not receive any capping layer. It should be noted that the DG alumina wafer was originally mis-processed which resulted in necessary rework which may have effected the final device characteristics.

Once the devices were fabricated, two thermal experiments were conducted. For the first experiment, several devices from

each wafer were subjected to a hot-plate anneal of 140°C for a total of 120 minutes. For the second experiment, all devices were subjected to a hot-plate anneal for 200°C for a total of 60 minutes. All devices in both experiments were electrically tested before and after the hot-plate treatments.

IV. RESULTS AND DISCUSSION

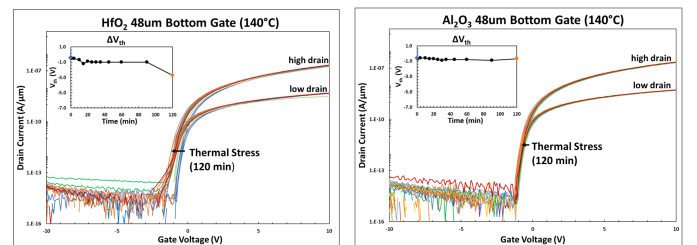
Figure 5 shows the BG and DG results for the devices without any capping layer. It is seen that both BG and DG devices see a shift in V_{on} , with DG devices seeing a bigger shift, when subjected to 140°C for 120 minutes. The bigger voltage shift seen by the DG devices indicates that the release of monatomic hydrogen by the reaction of H_2O with the top metal gate significantly increases the conductivity of the IGZO channel.



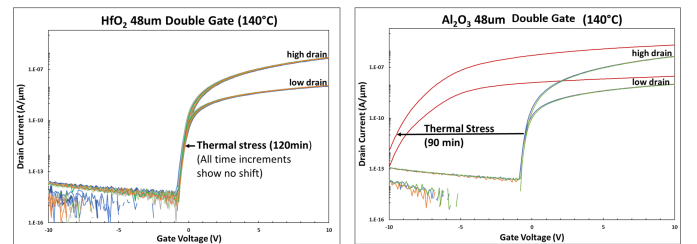
(a) BG device without ALD capping (b) DG device without ALD capping

Fig. 5: (a) shows that BG devices without a capping layer have a voltage shift of about 2 V over 120 minutes at 140°C. (b) shows that similar DG devices see an even greater voltage shift of 7 V.

The effects that the hafnia and alumina capping layer has on both BG and DG devices can be seen in Figure 6.



(a) BG device with HfO_2 capping (b) BG device with Al_2O_3 capping



(c) DG device with HfO_2 capping (d) DG device with Al_2O_3 capping

Fig. 6: (a), (b) show the thermal stability of ALD capped BG devices. (c) shows that the hafnia DG device are stable as well. (d) shows that alumina capped DG devices are very unstable.

It is immediately observed that the addition of an ALD capping layer greatly improves the thermal stability of the TFTs. Little to no shift is seen in the hafnia and alumina BG device characteristics as well as the hafnia DG device characteristics. It is noted that the DG alumina wafer shows an extreme left shift however. This could be a factor of the rework of the devices.

Figure 7 shows the 200°C experimental results for BG and DG devices without a capping layer. Note that the BG devices see a very notable left shift where as the DG devices become completely conductive after the 60 minute thermal stress treatment. Once again, this indicates that the monatomic hydrogen significantly increases the electron concentration of the IGZO channel.

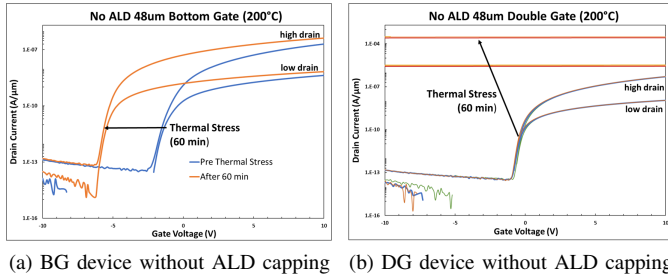


Fig. 7: (a) shows that the BG devices without a capping layer have a voltage shift of about 4 V over 60 minutes at 200°C. (b) shows that similar DG devices become completely conductive after exposure to thermal stress at 200°C.

Alternatively, the results for the capped devices can be seen in Figure 8.

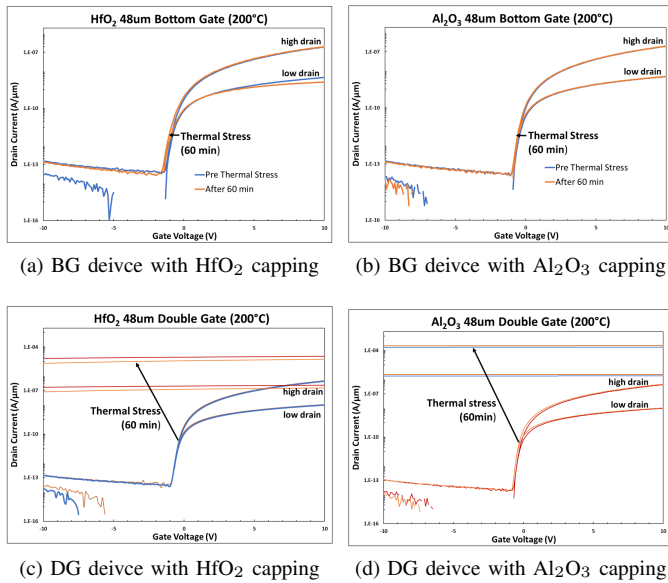


Fig. 8: (a), (b) show the thermal stability of BG devices when hafnia and alumina are used as capping layers. (c) (d) show that the DG devices become completely conductive after thermal stress at 200°C.

Even when subjected to 200°C, the BG devices do not show any thermal instability, regardless of the capping material used. However, the DG devices fabricated with hafnia or alumina become completely conductive after the 200°C heat treatment. This could be caused by the thin ALD layer reacting with the top metal of the device at temperatures above 140°C however, further investigation must be done to confirm this.

V. CONCLUSION

The results obtained in this study support the hypothesis that the water adsorbed in the passivation oxide is responsible for the instability of the IGZO TFTs after thermal treatment. Using ALD hafnia and alumina films as a capping layer for BG devices results in a significant improvement in stability, regardless of the thermal treatment temperature. DG devices show a similar improvement when subjected to 140°C however, hydrogen liberation appears to render the devices conductive at 200°C.

To confirm the DG results observed, future work should be done on more alumina and hafnia devices. The effectiveness of other ALD capping materials, such as TiO₂, should also be investigated to ensure that the optimum material is used to cap the IGZO TFTs.

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REFERENCES

- [1] R. Triggs, "Display technology explained: A-Si, LTPS, amorphous IGZO, and beyond," *Android Authority*, 02-Jul-2014. [Online]. Available: <http://www.androidauthority.com/amorphous-igzo-and-beyond-399778/>. [Accessed: 08-May-2017].
- [2] B. E. Deal, E. L. MacKenna, and P. L. Castro, "Characteristics of Fast Surface States Associated with SiO₂-Si and Si₃N₄-Si Structures," *Journal of the Electrochemical Society*, vol. 116, no. 7, pp. 997-1005, 1969.
- [3] L. H. Kim, et al., "Optimization of Al₂O₃/TiO₂ nanolaminate thin films prepared with different oxide ratios, for use in organic light-emitting diode encapsulation, via plasma-enhanced atomic layer deposition," *Physical Chemistry Chemical Physics*, vol. 18, pp. 1042-1049, Jan 2016.
- [4] M. H. Tseng, et al., "Low-temperature gas-barrier films by atomic layer deposition for encapsulating organic light-emitting diodes," *Nanotechnology*, vol. 27, Jul 2016.