The impact of gate dielectric materials on the light-induced bias instability in Hf–In–Zn–O thin film transistor

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This study examined the effect of gate dielectric materials on the light-induced bias instability of Hf–In–Zn–O (HIZO) transistor. The HfO2 and SiNx gated devices suffered from a huge negative threshold voltage (Vth) shift (>11 V) during the application of negative-bias-thermal illumination stress for 3 h. In contrast, the HIZO transistor exhibited much better stability (<2.0 V) in terms of Vth movement under identical stress conditions. Based on the experimental results, we propose a plausible degradation model for the trapping of the photogenerated hole carrier either at the channel/gate dielectric or dielectric bulk layer. © 2010 American Institute of Physics. [doi:10.1063/1.3513400]

The implementation of Zn-based oxide thin film transistors (TFTs) into commercial electronic products such as active-matrix liquid crystal displays (AMLCDs), organic light-emitting diodes and flexible displays has been accelerated by the considerable improvement in oxide semiconductor materials and processing.1–4 However, optoelectronics application requires photostability and bias-thermal stability because various light sources including the outer sunlight, backlight or self-emitting light would be irradiated steadily during the application of negative-bias-thermal illumination stress. In contrast, the HIZO transistor exhibited much better stability (<2.0 V) in terms of Vth movement under identical stress conditions. Based on the experimental results, we propose a plausible degradation model for the trapping of the photogenerated hole carrier either at the channel/gate dielectric or dielectric bulk layer. © 2010 American Institute of Physics.

This study examined the light-induced instability of the Hf–In–Zn–O (HIZO) TFTs under NBTS conditions. The major focus was on the effect of the gate dielectric material and structure on the resulting light-induced bias thermal instability (BTI). The photon-induced BTI was affected significantly by the underlying gate dielectric materials.

The fabrication procedure of bottom gate HIZO transistors has been reported in detail.15 A 400 nm thick SiNx thin film as a gate dielectric layer was deposited by plasma-enhanced chemical vapor deposition (PECVD) on Mo/SiOx/glass substrates at a substrate temperature of 350 °C. The effect of the interfacial gate insulator material on the light-induced BTI of HIZO TFTs was examined by inserting other gate dielectrics, such as 50 nm thick SiOx, HfO2, and AlOx thin films, into the active channel layer and depositing a 350 nm thick SiNx gate dielectric layer. Therefore, in the case of a bilayer gate dielectric, the total thickness of the gate insulator was fixed to 400 nm. A secondary 50 nm thick SiOx film was deposited by PECVD at 350 °C, whereas 50 nm thick HfO2 and AlOx thin films were grown by atomic layer deposition. The HIZO composition was fixed to Hf:In:Zn=10:56:34. Electrical characterization was carried out using a Keithley 4200 high resolution parameter analyzer. During the illumination stress test, the luminance from a white halogen lamp on the device surface was fixed to 180 lumen/m². The experiments were carried out in N2 at 1 atm to eliminate the effect of oxygen or moisture on the unpassivated device. The instability measurement procedure was as follows. First, the chamber system was evacuated to 10−6 torr. The sample stage was then heated to 60 °C. N2 gas was fed into the chamber until the chamber pressure reached approximately 1 atm. Subsequently, the specific gate and drain biases were applied to the HIZO TFTs (VGS =−20 V, VDS=−10 V), followed by the application of light. The stress experiments were considered to have begun with illumination.

Figures 1(a)–1(c) show the evolution of the transfer characteristics for the (a) HfO2, (b) SiNx, and (c) SiOx, respectively, as a gate interfacial dielectric layer. The pristine device characteristics correspond to the transfer curves mea-

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The largest negative movement of \( V_{th} \) (~15 V) after applying a negative bias thermal illumination stress (NBTS) for 3 h was observed for the TFTs with a HfO\(_2\) dielectric, as shown in Fig. 1(d). The device with the SiN\(_x\) gate dielectric also suffered from a significant negative shift (~11 V) in \( V_{th} \). In contrast, the highest reliability (\( \Delta V_{th} = 0.97 \) V) was observed for the SiO\(_x\) gate dielectric. The device with the AIO\(_x\) gate dielectric also exhibited much better reliability (\( \Delta V_{th} = 1.9 \) V) than the HfO\(_2\) and SiN\(_x\) devices, as shown in Fig. 1(d). It is noted that the application of only NBTS or light illumination stress caused the negligible \( V_{th} \) movement (<1 V) to the negative direction, compared to the application of NBTS and light combination stress irrespective of the gate insulator materials. Although the precise origin of the enhanced negative \( V_{th} \) shift under NBTS conditions is unclear, the possible mechanisms can be classified into the following three models in the introduction. The first model is based on the trapping or/and injection of the photoinduced hole carrier.\(^9,13\) Under a negative gate bias (\( V_{GS} \)), the generated hole carrier as a result of photoexcitation will be attracted toward the interface of the channel layer and gate dielectric layer due to the negative charge at the gate electrode. This accumulated hole can be trapped at the interfacial trap sites or injected into the underlying gate dielectric layer, leading to a more enhanced negative \( V_{th} \) shift compared to that under only dark NBTS conditions [see Fig. 2(a)]. Similarly, the negative \( V_{th} \) shift can be explained by oxygen photodesorption at the back surface of the channel.\(^10\) Oxygen adsorption from ambient on the oxide channel layer causes electron depletions, which results in upward bend bending. Exposure to photons can cause the desorption of oxygen species on the channel surface. This photodesorption of adsorbed oxygen releases delocalized electrons in the channel region. Hence, the free electron density will be enhanced compared to that of the dark state, leading to a negative shift. An entirely different model assumes that photon irradiation causes the transition of neutral oxygen vacancies [\( V_{O}^- \)] to the [\( V_{O}^{2+} \)] charged state in ZnO-based oxide materials. The [\( V_{O}^- \)] is a nonconducting deep state and the excited [\( V_{O}^{2+} \)] state donates two delocalized free electrons into the conduction band via resonance with the conduction band. Therefore, the photoinduced [\( V_{O}^{2+} \)] formation can result in an increase in free electron density, leading to a negative \( V_{th} \) shift. [see Fig. 2(b)] The metastable [\( V_{O}^{2+} \)] state can still exist after exposure to light because there is a non-negligible thermal barrier (0.2–0.3 eV) to escape from the charge state to the ground \( [V_{O}^-] \) state.\(^17,19\)

First, the possibility of oxygen photodesorption was excluded because the oxygen-free ambient in this study was used to evaluate the NBTS-induced reliability. This argument was also confirmed by the fact that the passivated device in the ambient still exhibited photo-enhanced \( V_{th} \) degradation (data not shown). Furthermore, the light-induced negative BTI (NBTI) is not entirely a bulk effect of the channel layer only. In the epilaxial or polycrystalline growth of the channel layer, the depositing layer is greatly affected by the quality of the underlying gate dielectric layer. However, an amorphous active film would be less affected by the material quality itself, as in this study. Hence, the channel layer quality on various gate dielectric substrates would be quite similar. Therefore, the effect of the gate dielectric material on the NBTS-induced NBTI of the HIZO TFTs would be negligible if the photogenerated donor (third model) in the bulk active film is responsible for device degradation. Obviously, this is not the case considering the significant impact of the gate dielectric material on the light-induced NBTI of HIZO TFTs. This consideration indicates the hole trapping model to be the most plausible explanation. Figure 3 shows the ideal band diagrams for various gate dielectric materials/HIZO stack
structures, which were constructed to understand the light-induced bias instability. The band offsets were calculated using the values reported in the literature. Indeed, this observation is well reconciled with the trapping or injection model of photogenerated holes. The excellent stability of the SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} device can be explained by the wide band gap of \textasciitilde 8.8 eV and 8.7 eV, respectively, and the comparatively high quality with fewer trapping centers than SiN\textsubscript{x} and HfO\textsubscript{2-x}. On the other hand, SiN\textsubscript{x} films have a smaller band gap and higher trap density than SiO\textsubscript{2} thin films, which is why SiN\textsubscript{x} films are often used as the charge trap layer in flash memory devices. Therefore, the inferior stability of the nitride device compared to SiO\textsubscript{2} can be attributed to the enhanced hole injection or trapping due to the smaller valence offset (~0.15 eV) and greater hole trap density. It would be interesting to examine why the HfO\textsubscript{2} dielectric device exhibited the worst reliability, even though the valence offset (~1.30 eV) was larger than that (~0.15 eV) of the SiN\textsubscript{x} dielectric device. Obviously, the energy barrier of hole injection for the HfO\textsubscript{2} device will be higher than that for the SiN\textsubscript{x} device. However, high-\textit{k} dielectrics, such as HfO\textsubscript{2}, suffer from high leakage conduction via a Poole–Frenkel trapping center, which would facilitate hole injection into the HfO\textsubscript{2} dielectric. Indeed, the initial rapid negative shift in \textit{V\textsubscript{th}} for 30 min in the case of the HfO\textsubscript{2} device would be the instantaneous injection of photoinduced holes into the large hole trapping center of HfO\textsubscript{2}. The possibility of faster hole trapping into the interfacial deep level at the HfO\textsubscript{2}/HIZO layer than at the SiN\textsubscript{x}/HIZO interface cannot be excluded. The gate leakage current of the HfO\textsubscript{2} device was similar to that of the SiN\textsubscript{x} device (data not shown), which suggests that the worst reliability of the HfO\textsubscript{2} device cannot be attributed to the poor leakage characteristics of the HfO\textsubscript{2} itself. Therefore, the worst reliability of the HfO\textsubscript{2} device would originate from rapid injection into the underlying HfO\textsubscript{2} bulk film of the photoinduced hole carrier at the HfO\textsubscript{2}/HIZO interface.

The hole trapping or injection model can also account for the strong band-gap dependence on the NBTIS-induced \textit{V\textsubscript{th}} shift in the HIZO TFTs. The smaller band gap will facilitate the generation of electron-hole pairs upon light illumination. The negative gate bias will repel the photogenerated electron carrier into the back channel, where accumulated electrons would migrate toward the drain electrode. Therefore, the net accumulated hole carrier density at the dielectric/channel layer will be increased with smaller band gap semiconductor, leading to more trapping or injection of holes.

In summary, the \textit{V\textsubscript{th}} instability of HIZO TFTs is dependent on the selection of the underlying gate dielectric material. The HfO\textsubscript{2} and SiN\textsubscript{x} gated devices exhibited inferior \textit{V\textsubscript{th}} stability after the application of NBTIS for 3 h. The device stability (\textit{AV\textsubscript{th}} = \textasciitilde 0.97) against NBTIS was improved dramatically by adopting the SiO\textsubscript{2} gate dielectric material, which is acceptable as a switching transistor for the large-sized (>50 in.) and ultrahigh definition (>2000 × 4000 resolution) AMLCD panel. These results suggest that the trapping of photogenerated carrier carriers rather than the creation of photexcited donor states is responsible for the degradation.

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