Improved Stability of Atomic Layer Deposited ZnO Thin Film Transistor by Intercycle Oxidation

Himchan Oh, Sang-Hee Ko Park, Min Ki Ryu, Chi-Sun Hwang, Shinhyuk Yang, and Oh Sang Kwon

By inserting H_2O treatment steps during atomic layer deposition of a ZnO layer, the turn-on voltage shift from negative bias stress (NBS) under illumination was reduced considerably compared to that of a device that has a continuously grown ZnO layer without any treatment steps. Meanwhile, treatment steps without introducing reactive gases, and simply staying under a low working pressure, aggravated the instability under illuminated NBS due to an increase of oxygen vacancy concentration in the ZnO layer. From the experiment results, additional oxidation of the ZnO channel layer is proven to be effective in improving the stability against illuminated NBS.

Keywords: ZnO, thin film transistor, negative bias stress.

I. Introduction

With an effort to achieve process optimization, and by virtue of dense passivation layers made of SiO_2, Al_2O_3, and so on, ZnO-based thin film transistors (TFTs) have become highly reliable against bias, temperature, and environmental stresses in the absence of light [1]-[3]. However, such TFTs still suffer from a threshold voltage shift caused by negative bias stress (NBS) coupled with illumination. This means that negative bias instability (NBI) arises for inherent reasons, which originate particularly from the characteristics of active materials, not by external effects.

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Oxygen vacancy (V_O) is known as a common point defect in ZnO thin films with low formation energy and produces a high density of fully occupied subgap states near the valence band maximum (VBM) [4]-[7]. Hence, the wide band gap of ZnO is effectively reduced, causing photon-related instability even by a sub-band light [8]. Passivation of defects related to oxygen deficiency must therefore be a direct way to improve reliability of ZnO TFTs against negative bias illumination stress (NBIS).

Meanwhile, we have reported a transparent and photo-stable ZnO TFT using a low temperature (≤200ºC) atomic layer deposition (ALD) technique and demonstrated a 2.5-inch transparent active matrix organic light emitting diode (AMOLED) panel driven by the achieved TFT [9]. ALD provides fine-quality thin films at low temperature and precise thickness controllability on the atomic scale through alternating injections of the sources and reactants. Using these high-quality ALD-driven ZnO and Al_2O_3 thin films, our ZnO TFTs exhibit not only high electrical performance but also excellent stability against bias stress in the dark. Nevertheless, the ALD-deposited ZnO film has to be improved further in terms of defect concentration to endure NBIS. To achieve this, we have attempted to insert additional oxidation steps during the ZnO deposition to effectively reduce the number of oxygen vacancies in the film. Oxidation of every nanometer-thick or subnanometer-thick layer might only be possible through the unique feature of ALD.

In this letter, we report the impact of defect passivation in a ZnO active layer on NBI under illumination. The extent of turn-on voltage (V_{ON}, corresponding to the gate voltage that brings 10 pA of drain current) shift by NBIS is clearly varied with different kinds of oxidation steps, which result in different oxygen vacancy concentrations during ZnO deposition.

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II. Experimentation

The fabrication procedure of ZnO TFT has been reported in detail [3]. The fabricated TFTs have a top gate and bottom contact configuration. As a reference (device R), a 20-nm-thick ZnO active layer was continuously grown through 100 cycles of ZnO deposition without interruption. By introducing H_2O vapor (device H) or O_2 gas (device O), oxidation steps were performed every 10 cycles of ZnO deposition for 10 min. For comparison, steps for maintaining a vacuum (device V) without introducing any reactive gas were also performed every 20 cycles of ZnO deposition for 10 min to intentionally make the film oxygen deficient. In doing so, we were able to find that oxygen vacancy concentration significantly affects the instability of TFTs under NBIS. Finally, to verify the efficacy of the oxidation steps during deposition, we also treated the continuously grown ZnO film with H_2O vapor for 100 min (equal to 10 oxidation steps for 10 min each, for device S). The pressure of the chamber was kept at 3 torr during deposition and the additional treatment steps. The O_2 gas flow rate was 200 sccm, and the temperature of the H_2O bubbler was kept at 24ºC for each oxidation step. Figure 1 depicts a schematic diagram of the ALD and oxidation processes.

The active layers were efficiently passivated by the ALD-derived, approximately 120-nm-thick Al_2O_3 gate insulator. Therefore, we excluded the ambient effects on the NBI under illumination. A green light source was used, the intensity of which peaked at 530 nm, and the full-width-at-half-maximum

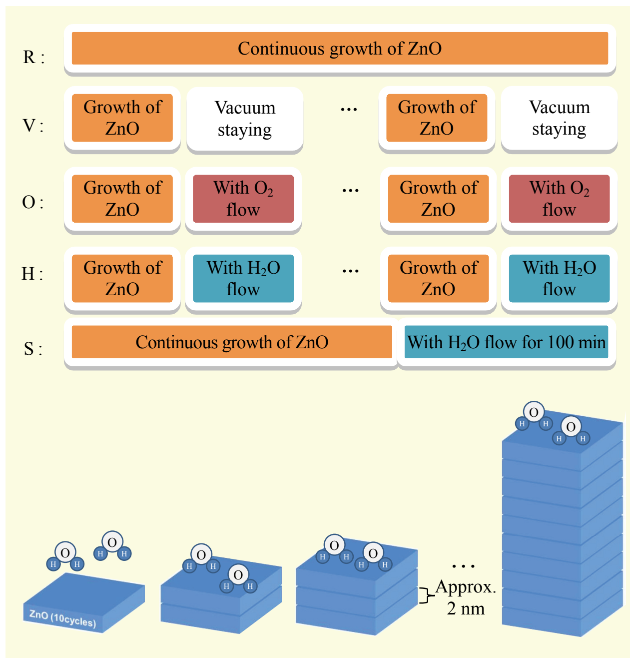

Fig. 1. Schematic diagram of ZnO ALD process with intercycle oxidation step.

at this point was 10 nm. The photo-intensity was 0.1 mW/cm^2, as calibrated through photometry. The channel width/length of the examined devices was 40/20 μm. All of the measurements were carried out at room temperature using an Agilent B1500A precision semiconductor parameter analyzer. A fresh device was used for each measurement.

III. Results and Discussion

Field effect mobilities (μ_{FE}) of the devices were calculated from the maximum transconductance using μ_{FE}=Lg_m/WC_iV_{DS}, where C_i and g_m are the gate capacitance per unit area and the transconductance, respectively. The subthreshold swing (SS=$dV_{GS}/d\log I_{DS}$) was extracted from the linear portion of the log (I_{DS}) versus V_{GS} plot. As a result, μ_{FE} of 3.2 cm^2/Vs to 3.5 cm^2/Vs and SS of 0.48 V/dec to 0.52 V/dec were obtained.

Figures 2(a) through 2(e) show the evolutions of the transfer curves as a function of applied NBS time in the dark for devices R, V, O, S, and H, respectively. In spite of a large applied electric field due to the relatively thin GI compared to other reported devices, all of the devices exhibit a small V_{ON} shift (< 0.5 V) after 3 h of a long NBS test. This is comparative to the state-of-the-art ZnO-based TFTs. In particular, device H, which is additionally oxidized by H_2O vapor during deposition, shifted only 0.14 V.

The parallel shift of the transfer curves by the NBS is due to the effective screening of the gate field by accumulated positive charges at the GI/semiconductor interface. The holes or unoccupied donor-like states are possible candidates as positive charges that can bring about this negative shift. In the dark, holes are hard to generate in n-type ZnO active layers due to the high density of occupied deep sub-gap states, which prevent the lowering of the Fermi-level and, therefore, inversion. The generation of free holes is possible in a particular case such as illumination on the active layer. Therefore, it can be said that a parallel shift by NBS in the dark is attributed to a migration of unoccupied donor-like states and that oxygen vacancy produces these states.

Fortunately, most V_O-induced donor states are situated in a deep energy level, and thus the de-trapping of electrons from these states is difficult to achieve as stated above. However, a small portion of donor states that lie at a relatively higher energy level could be unoccupied, and they will then be positively charged and accumulated at the GI/semiconductor interface by negative bias. Dramatic improvement of device H in terms of stability against a negative bias is therefore due to the reduction of oxygen vacancy, which is a potential source of positive charge as mentioned earlier. A relatively higher shift (0.37 V) of device S than that of device H means that intercycle oxidation is more effective than the surface oxidation to reduce

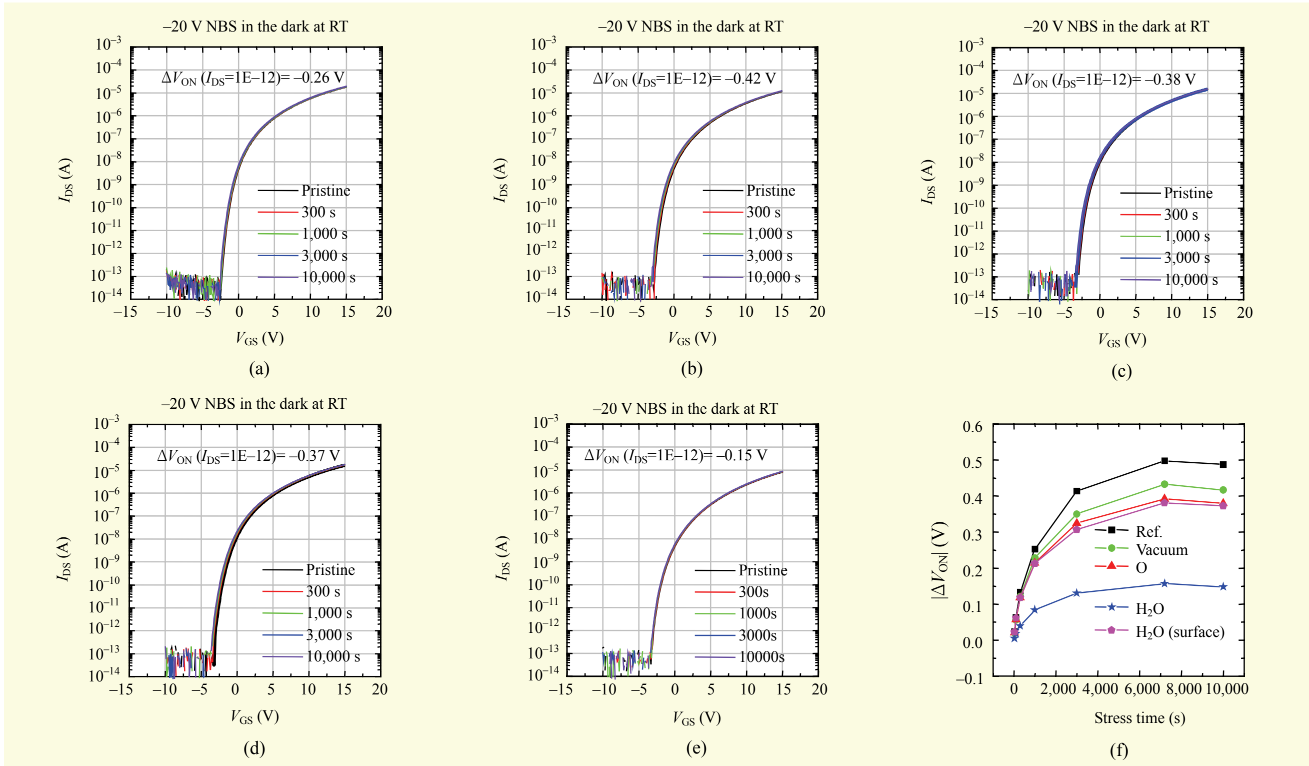

Fig. 2. Evolutions of transfer curves as a function of applied NBS time in the dark for devices: (a) R, (b) V, (c) O, (d) S, (e) H, and (f) NBS induced $|\Delta V_{ON}|$ versus stress time.

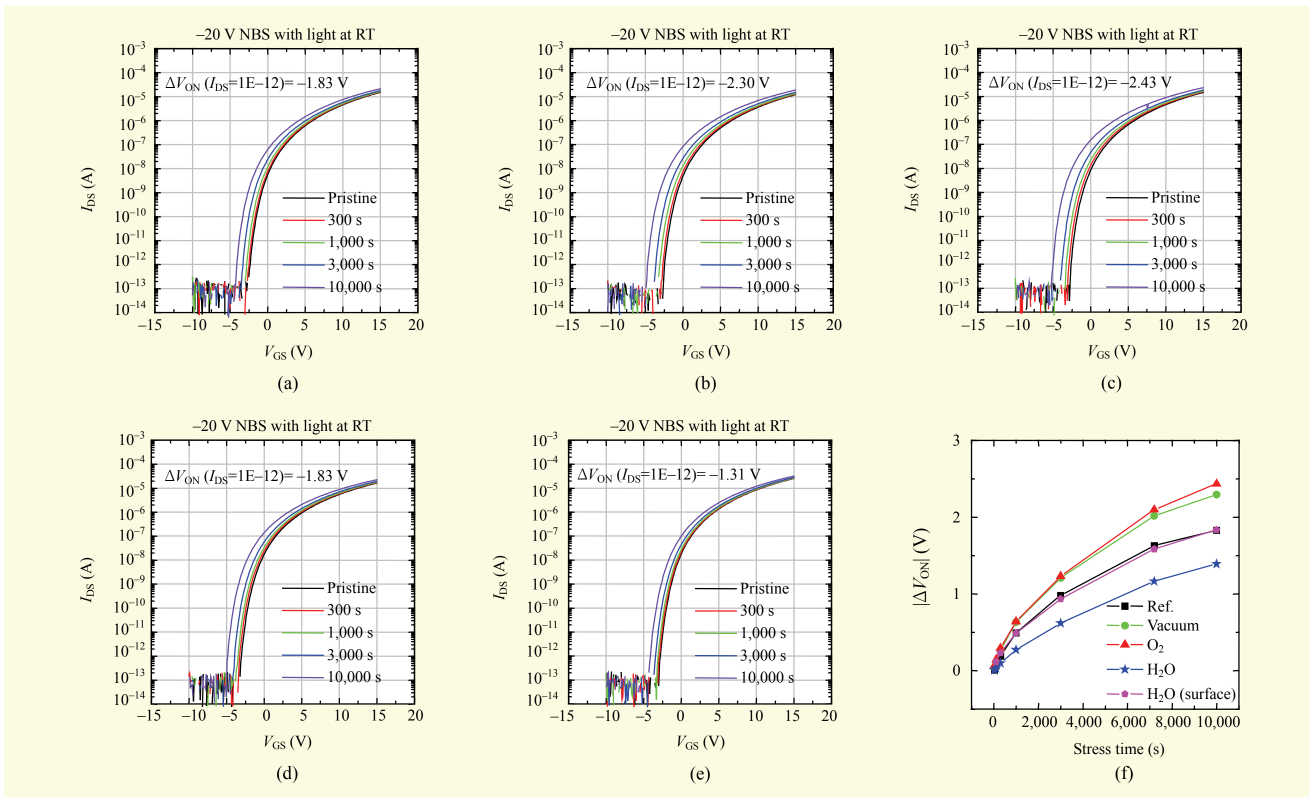

Fig. 3. Evolutions of transfer curves as function of applied NBIS time under green light exposure for devices: (a) R, (b) V, (c) O, (d) S, (e), H, and (f) NBIS induced $|\Delta V_{ON}|$ versus stress time.

the oxygen vacancy deep inside the active bulk. This also supports the idea that oxygen vacancies that exist quietly away from the gate insulator/semiconductor interface play an unfavorable role in the NBI.

Unlike the H_2O oxidation steps, an O_2 oxidation step cannot bring about an improvement in NBS stability. This might be due to the insufficient oxidation power of O_2 gas to overcome the low working pressure of 3 torr during the deposition and oxidation steps. In a similar vein, the V_{ON} shift of device V is the largest of all due to the rather reductive environment in a vacuum deposition chamber.

Under an NBIS condition, the V_{ON} of a device shifted toward the negative direction much more than under the NBS condition, as shown in Fig. 3. As mentioned earlier, there are V_O-induced donor states in ZnO. They can be photo-excited from V_O to V_O^{1+} or V_O^{2+}. These ionized oxygen vacancies will be neutralized to V_O, via the subsequent photo-excitation of electrons from the valence band and leave the free holes in there, or will keep the holes by themselves (V_O^{1+} or V_O^{2+}). The larger shift under an NBIS condition is attributed to these two photon-induced positive charges, that is, holes and ionized oxygen vacancies [10], [11]. Much faster movements of holes than the ionized species result in a large V_{ON} shift at the early stage of the NBIS test [12]. Also, the additionally photo-exited oxygen vacancies, which were neutral under a dark state, will cause a significant V_{ON} shift after a long NBIS test, although their migration is slow compared to the holes. Therefore, the reduction of oxygen vacancy content becomes more important when dealing with the stability under an NBIS condition. The improved photo-stability of device H compared to other devices supports this fact.

IV. Conclusion

The effect of various treatment steps during the ZnO ALD process was investigated. The insertion of oxidation steps between every 2-nm ZnO deposition cycle was found to be more effective in improving the NBIS-related stability than the surface oxidation after a continuous growth of the ZnO layer. This method can be applied toward the fabrication of ZnO-based oxide TFTs, which requires an enhanced photo-stability and a low processing temperature (< 200ºC).

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