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

Photon-accelerated negative bias instability involving subgap states creation in amorphous In–Ga–Zn–O thin film transistor

Himchan Oh,[a] Sung-Min Yoon, Min Ki Ryu, Chi-Sun Hwang, Shinhyuk Yang, and Sang-Hee Ko Park
Oxide Electronics Research Team, Electronics and Telecommunications Research Institute, Daejeon 305-700, Republic of Korea

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We investigated the visible photon accelerated negative bias instability (NBI) in amorphous In–Ga–Zn–O (a-IGZO) thin film transistor (TFT). As reported in previous works, the rigid shift in transfer curves with insignificant changes in field-effect mobility and subthreshold swing was observed. On the other hand, there is substantial change in capacitance-voltage characteristics caused by created subgap states. The suggested nature of created states is the ionized oxygen vacancy (V_O^{2+}) by the combination of visible light and negative bias. The generated V_O^{2+} states enhance the NBI under illumination as increased deep hole trapping centers. Furthermore, the photoexcitation of V_O to stable V_O^{2+} yields excess free carriers in conduction band. The increased carrier density also enhances the negative shift in turn-on voltage of a-IGZO TFT. © *2010 American Institute of Physics*. [doi:10.1063/1.3510471]

Recently, transparent thin film transistors (TFTs) using amorphous zinc oxide based semiconductors[1,2] as active layers have made rapid progress in terms of device performance and reliability. It is fairly easy to obtain high performance including high field effect mobility (μ_{FE}) and low subthreshold swing (SS). On the other hand, the stable operation against the gate bias, thermal, and light stress is rather difficult to achieve. Thus, the device instabilities caused by aforementioned stress conditions in the dark or under light illumination have been intensively studied.[3–7] As results, significant advances in reliability have been made including process developments and underlying physics. Nevertheless, instability incurred by negative bias stress (NBS) under illumination is still remained issue.[8–11] Since switching TFTs of active-matrix liquid crystal displays or organic light emitting diodes are almost always negatively biased and exposed to light during their operation, instability caused by the NBS combined with light is crucial problem to be resolved. To achieve this, it is important to understand the mechanism of NBI under light illumination.

It was reported that the environmental effects, such as photodesorption of oxygen molecules[10] or metastable gap state induced by water molecules[9] could accelerated negative bias instability (NBI). But these ambient effects would be eliminated by proper passivation layer on the active layers.[10,12] Indeed, the NBI under illumination still occurs even with efficient passivation layer.[10] This suggests that the NBI is arisen by inherent reasons. In most of previous studies on NBI under illumination, it was reported that the photogenerated holes were simply trapped at the gate insulator (GI)/semiconductor interface and/or injected into the gate dielectric bulk under negative bias and caused negative shift in threshold voltage (V_{th}).[9,11] In general, charge trapping causes parallel shift in transfer curve without significant changes in mobility and SS while the state generation does not. Thus, shape preserved shifts in transfer curve in previous reports on the NBI under illumination seem to be occurred by simple charge trapping without state creation. However, we revealed that this would not be the case.

In this letter, we report that the combination of subband gap photon and NBS creates subgap state in amorphous In–Ga–Zn–O (a-IGZO) TFT that accelerates NBI under illumination. The creation of subgap states under light exposure is detected by capacitance-voltage (C-V) method not from the transfer characteristics which exhibit parallel shift without significant changes in mobility and SS.

The effects of ultraviolet illumination ($\lambda < 350$ nm) on the NBI is rather clear because it has over-band (>3.54 eV) photon energy and therefore, electron-hole pairs will be simply generated via band to band transition. Thus, we focused on the effects of visible subband (~<3 eV) light. The green light source was used of which intensity peaks at 530 nm and full-width-at-half-maximum at this point is 10 nm. Its photointensity is 0.1 mW/cm^2, as calibrated by photometry. We fabricated top gated a-IGZO TFT. 150 nm thick of ITO films were sputtered for the gate and source/drain electrodes. A 30 nm thick of a-IGZO film was also deposited by sputtering method as an active layer. The a-IGZO layer was efficiently passivated by atomic layer deposition derived 176 nm thick of Al_2O_3 GI. Thus, we could exclude the ambient effects which were reported as the enhancement factors in bias instability not only in the dark but also under illumination.[10] All patterning processes were performed with conventional photolithographic method and wet etching process. Finally, the fabricated device was annealed at 300 °C for 2 h under an O_2 atmosphere. The channel width/length of examined device was 160/160 μm. All the measurements were carried out at room temperature using Agilent B1500A precision semiconductor parameter analyzer. During the NBS test, we shined the green light on top of the device and the light was temporarily turned off while the sampling of transfer characteristic was performed. A fresh device was used for each measurement except for the evaluation of recovery characteristics after stress.

[a] Author to whom correspondence should be addressed. Electronic mail: fullchan@etri.re.kr.

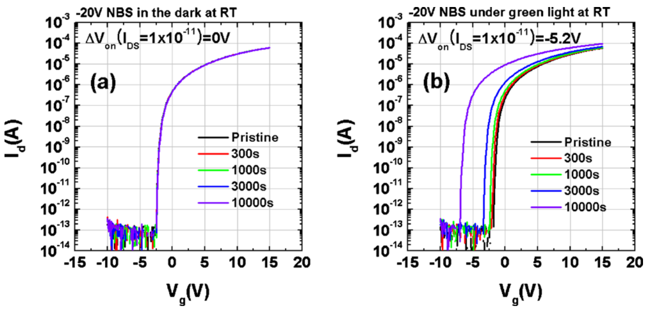

FIG. 1. (Color online) The evolution of transfer curves as a function of the applied −20 V NBS time (a) in the dark and (b) under green light exposure for 1×10^4 s.

Figures 1(a) and 1(b) show the evolution of transfer curves as a function of the applied NBS time in the dark and under illumination, respectively. The gate voltage stress of −20 V was applied for 1×10^4 s. The device did not suffer from any V_{on} (corresponding to the gate voltage that brings 10 pA of drain current) shift by NBS in the dark. Meanwhile, quite V_{ON} shift of −5.2 V with insignificant change in SS was observed under illumination. Consequently, the NBI under illumination seemed to be caused by simple charge trapping. To clarify this rigid shift, the μ_{FE} was calculated from the maximum trans-conductance using $\mu_{FE} = Lg_m/WC_iV_{DS}$, where C_i and g_m are the gate capacitance per unit area and transconductance, respectively. The SS ($SS = dV_{GS}/d \log I_{DS}$) was extracted from the linear portion of the $\log(I_{DS})$ versus V_{GS} plot. As results, the μ_{FE} of 18 cm^2/V s was not altered by the NBS under illumination. The estimated SS value increased very slightly from 0.14 to 0.17 after the stress. The results seemed not to be different from previous works on NBI under illumination this far.

The resulting negative shift by NBS under visible light illumination was quite large despite of superior interface characteristic between GI and semiconductor of a-IGZO TFT as proven by the NBS test in the dark and its excellent performance, i.e., high μ_{FE} and low SS. Thus, we supposed that combination of photon and negative bias would change the GI/semiconductor interface property. To investigate the interface characteristics in detail, C-V analyses were performed. Figures 2(a) and 2(b) show the transfer and C-V characteristic at 2 kHz frequency of pristine device and those of the device after subjected to NBS under green light for 1×10^4 s. Unlike the rigid shift in transfer curves, C-V curves were significantly distorted. The C-V curve of pristine device is steep with low density of interface states and its capacitance starts to rise simultaneously with turning-on of TFT. While, the C-V curve of the device subjected to NBS under green light was largely stretched out, which means that in-

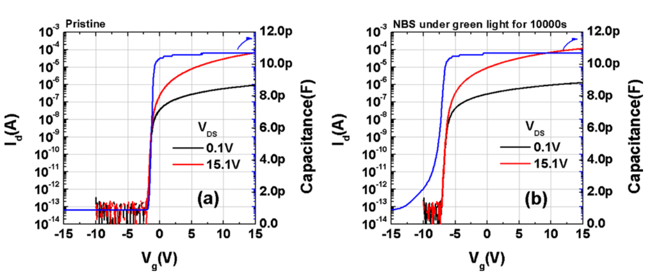

FIG. 2. (Color online) Transfer and C-V curves at 2 kHz frequency of (a) the pristine device and those of (b) the device subjected to −20 V NBS under green light exposure for 1×10^4 s.

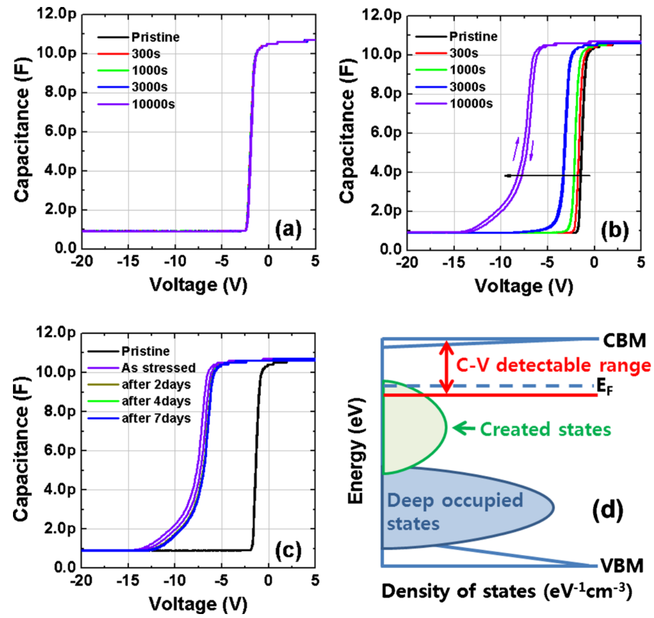

FIG. 3. (Color online) The evolution of C-V curves as a function of the applied −20 V NBS time (a) in the dark and (b) under green light exposure. (c) The recovery characteristic of C-V curve after NBS under green light exposure. (d) The schematic band diagram of a-IGZO after NBS under illumination.

terface states were generated. Note that, the distorted part of C-V curve compared to that of pristine device is especially ranged in the gate voltage regime that corresponds to where the TFT is being turned off. It implies that transfer characteristic was not significantly altered by the created interface states because most of them were located at deep energy levels and thus, already occupied before the gate voltage reached to its turn-on voltage. As the turn-on starts with accumulation of electrons, most of the stretched-out portion of C-V curve is ranged before the flat-band condition. Thus, it can be said that generated interface states are located near and below the Fermi level. But, the lower limit of energy level that created states existed at is unclear. Since the high density of occupied sub gap states near the valence band maximum (VBM, from VBM to ~1.5 eV) pinned the Fermi level as reported by Nomura *et al.*[13] Thus we can only observe the C-V characteristic which is the response of quite upper part of the band gap and detect the small portion of the deeply created interface states as depicted in Fig. 3(d). Nevertheless, there is definite change in C-V characteristic by the NBS under illumination.

Figure 3(a) shows the C-V curves of the device that subjected to NBS in the dark which did not shift at all and was not distorted. The evolution of C-V curves as a function of −20 V NBS time under green light exposure is shown in Fig. 3(b). As the stress duration increased, C-V curves were stretched-out toward negative direction by the positive charges due to the increased interface states. The voltage shift by this interface charge decreased as the gate voltage swept toward positive direction which means that they are positive when empty and neutral when electrons are occupied, as the donorlike states. We believe that these donorlike states were originated from the ionized oxygen vacancy (V_O^{2+}) which is positively charged when it is unoccupied same as the interface states we found by C-V method.

In the semiconducting oxide materials such as ZnO, a-IGZO, etc., the defect induced subgap states are frequently related to oxygen vacancies (V_O).[14–18] It has been reported that the oxygen vacancies form fully occupied states near the VBM in high density which was supported by the first-principle studies[15,16,18] and the experimental observation.[13] When large negative bias is applied, quasi-Fermi level at the surface is lowered about to near midgap level then V_O could be photoexcited and became V_O^{2+}.[17,18] If the excited V_O^{2+} states locate at higher energy level in the band gap by the photon-energy, then it will remain unoccupied states by virtue of lowered Fermi level as long as the large negative bias is being applied. This charge state transition of V_O to V_O^{2+} causes outward relaxation of the neighboring metal atoms.[18] If the NBS time is short, the degrees of outward movements of metal atoms will not be significant therefore they could be easily recovered to their initial positions with neutralization of V_O^{2+} to V_O. But during the about 3 h of NBS time in this report, the outward relaxations of neighboring metal atoms are significant and could also cause the changes in the positions of the atoms around them, including the ones that located quiet far away from V_O^{2+}. In this case, the total energy needed for returning to their initial positions is raised high, results the stabilization of V_O^{2+}. Although this is the suggestion for the origin of created states and the exact nature is uncertain now, stable remaining of the created states was confirmed. Once the states were generated, it remained stable even after a week past from the day we last measured the C-V characteristic as shown in Fig. 3(c). It is expected to exist far longer. Accordingly, we suggest that the states are newly 'created' rather than just temporally transited to upper energy level.

The created V_O^{2+} states play two critical roles in NBI under illumination and accelerate the V_{ON} shift significantly as follows. Firstly, the deep-level lying V_O^{2+} states act as the positive fixed charge which were located at the interface, including the ones that initially created in the active bulk region then attracted to the interface by negative bias. Therefore, they effectively screen the gate bias and result larger negative shift in transfer curves. Note that, the stretch-out of C-V curves is mainly caused by the interface states which were placed at less deep energy level rather than the deeper lying states which can act as electrically inert fixed charge. Secondly, photoexcited electrons from V_O state to the conduction band can be survived without direct recombination with the excess holes because these holes are "trapped" in the stable V_O^{2+} states during the NBS coupled with visible light illumination. Thus, they are donated as free carriers in a-IGZO semiconductor. Due to the increased carrier density, turn-on voltage of TFT will shift negatively further. The creation of V_O^{2+} states and involved doping mechanism are schematically depicted in Fig. 4.

In conclusion, we observed subgap states creation by the NBS under visible light illumination via C-V method in a-IGZO TFT. The suggested nature of created states is ionized oxygen vacancy (V_O^{2+}) based on the electrical measurement and previously reported first principle studies. The creation of V_O^{2+} states accelerates the NBI further by being as deep hole trapping centers and n-type doping in a-IGZO TFT. From these results, one could miss the changes in GI/

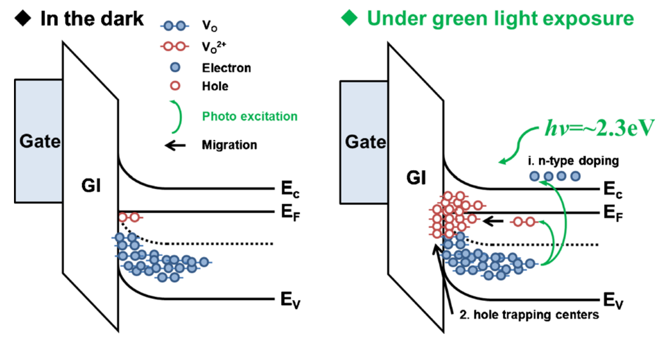

FIG. 4. (Color online) The creation V_O^{2+} state and involved n-type doping mechanism.

semiconductor interface by concerning only on the transfer characteristics for the examination of NBI under illumination. Therefore, including C-V analysis and other appropriate characterization methods should be conducted together to study NBI under illumination properly and in detail. Finally, it is obvious that (i) defects related to oxygen deficiency should be lowered or effectively passivated and (ii) some structural rigidity is needed to improve the reliability characteristic of oxide TFTs under illumination.

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