Effect of Wavelength and Intensity of Light on a-InGaZnO TFTs under Negative Bias Illumination Stress

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We investigated degradation mechanism of a-IGZO TFTs under NBIS with different wavelengths λ and intensities I_L of light. Negative gate bias was applied for 4000 s while drain and source were grounded, and illuminations with λ = 450, 530, or 700 nm were applied. Illumination with photon energy exceeding ∼2.3 eV (530 nm) induced noticeable change in threshold voltage shift ΔV_{th}, which can be interpreted in terms of ionization of oxygen vacancies V_O. In addition, I_L of blue illumination (450 nm) was varied from 6 to 200 lux and saturation in ΔV_{th} was observed after exceeding a certain I_L. We suggest that the saturation occurs because V_O-ionization rate is saturated by outward relaxation of metal atoms in the a-IGZO film.

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Metal oxide-based materials have high carrier mobility, low off-current, and good transparency, so they are promising candidates for the channel material of thin film transistors (TFTs).[1] In particular, amorphous-InGaZnO (a-IGZO) TFTs have excellent properties such as high on/off ratio, good uniformity, and low processing temperature.[1] However, a-IGZO TFTs exhibit some instability problems.

Stability of a-IGZO TFTs is affected by several factors including bias/current stress, temperature, light illumination and passivation conditions.[2–5] Among several factors, bias stress is most widely studied because bias is always applied to TFTs in practical display applications. In darkness, the transfer curves of TFTs shift positively when positive bias stress (PBS) is applied to the gate, but shift relatively little when negative bias stress (NBS) is applied.[6,7] Although a-IGZO TFTs remain stable under NBS, their electrical characteristics degrade when it is combined with illumination,[7,8] i.e., negative bias illumination stress (NBIS).

Instability of a-IGZO TFTs under NBIS has been widely investigated and reported.[7–11] Though some papers dealt with the effect of light intensity on reliability of the TFT,[12,13] the effects of wavelength λ and intensity I_L of light during NBIS have not been fully explained yet, especially in terms of oxygen vacancy which is crucial factor affecting reliability of a-IGZO TFTs. In this paper, we investigated degradation mechanism of a-IGZO TFTs under NBIS with light of various λ and I_L. Degradation of a-IGZO TFT under NBIS with different λ, and the saturation of threshold voltage shift ΔV_{th} independent of I_L were identified. We propose that the saturation phenomenon can be explained by restriction in the ionization rate of oxygen vacancy V_O due to their effect on the structure of a-IGZO.

Method and Measurements

We fabricated a-IGZO TFTs with bottom gate, back channel etch structure (Fig. 1). A 500 nm-thick and 200 nm-thick SiO_2 were used as gate insulator and passivation layer, respectively. The a-IGZO active layer was formed with the channel width/length of 110 μm/6 μm. Transfer characteristics of the TFTs were measured after NBIS was applied. For bias stress, negative gate voltage was applied for 4000 s while drain and source were grounded. Illumination from white LED was passed through blue, green and red filters which have transmission peaks at λ = 450 nm, 530 nm, 700 nm, respectively. In a separate trial, I_L of blue illumination was varied from 6 to 200 lux to investigate how it affects stability.

For transfer characteristics measurements, gate voltage was swept from −20 to +20 V at a fixed drain voltage of 0.1 V for stress durations of 100, 200, 400, 1000, 2000 and 4000s. a-IGZO TFTs were measured at each stress durations without switching off the illumination. Threshold voltage V_{th} was determined as the gate voltage at which drain current was 10 nA × W/L. Measurements were conducted using an Agilent 4156A semiconductor parameter analyzer.

Results and Discussion

Transfer characteristics were measured after NBS and NBIS with negative gate voltage of −40 V were applied at 90°C (Fig. 2). In NBIS measurements, illumination sources with different λ were used with I_L = 100 lux after color filter. Shifts in transfer curve under red illumination and in dark condition were not significant (Figs. 2a, 2b). These results are reasonable because a-IGZO is basically n-type material and the energy (1.78 eV) of red illumination was less than the band-gap (∼3.1 eV) of a-IGZO.[14] Under green and blue illumination, however, noticeable negative shifts occurred in spite of their low energy (green: 2.3 eV; blue: 2.76 eV) compared to the band-gap of a-IGZO (Figs. 2c, 2d). Shifts were most severe under blue illumination.

To describe the instability mechanism of a-IGZO TFTs under NBIS, charge trapping and sub-gap state generation are usually considered.[7–11] In a-IGZO, V_O forms deep energy states which are located above the valence band maximum with high density.[16] Therefore, V_O can be ionized to V_O^{2+} states by sub-gap illumination and when negative gate bias drives migration of V_O^{2+} toward the gate insulator/IGZO interface, they can be trapped and result in negative ΔV_{th}.[8] In addition, though electron-hole pairs may not be band to

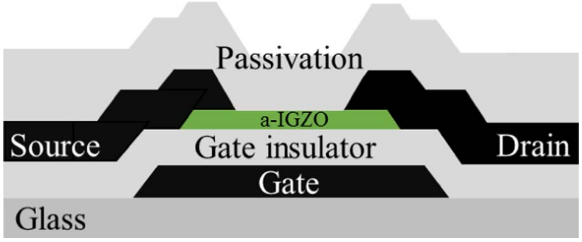

Figure 1. Schematic diagram of fabricated a-IGZO TFT with bottom gate, back channel etch structure.

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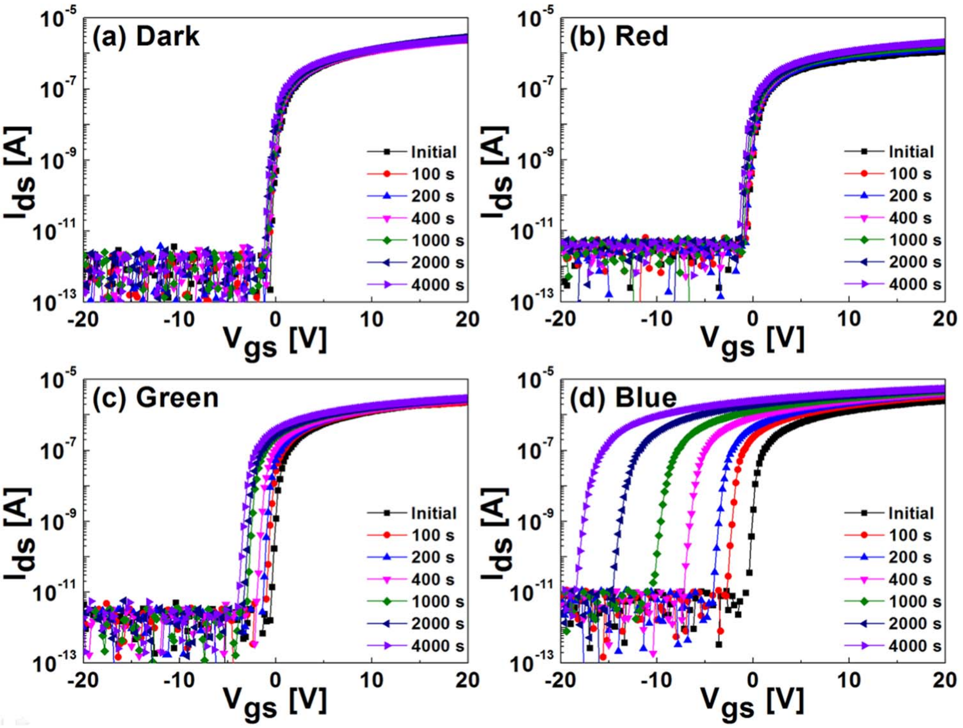

Figure 2. Changes in transfer curves after NBS in (a) dark and NBIS under (b) red, (c) green and (d) blue illumination with −40 V gate voltage at 90°C. V_{gs} was swept from −20 to +20 V at $V_{ds} = 0.1$ V.

band generated due to low photon energy, trap-assisted hole generation could occur in a-IGZO TFTs.[9,14] Especially, ionized V_O could help generation of holes by capturing electrons excited from valence band via light illumination.[14] Thus, hole trapping could also occur by virtue of ionized V_O.

Ionization of V_O to V_O^{2+} requires energy of ∼2.3 eV;[15,17] this value is consistent with our results, because both the green and blue illumination which were above and equal to 2.3 eV induced noticeable shifts, whereas red illumination and darkness did not. Especially for blue illumination, the subthreshold slope degraded and the transfer curve shifted significantly (Fig. 2d). Changes in subthreshold slope indicate that sub-gap states were generated during the stress, which is associated with ionized V_O in a-IGZO TFTs.[6,10,15]

To see the results quantitatively, ΔV_{th} values were extracted under various illumination conditions (Fig. 3). NBIS under white illumination without filter was tested to be compared with blue illumination. I_L was 4500 lux for white, and 100 lux for blue, green and red. ΔV_{th} after stress for 4000 s were about −16.8 V under white light, −16.7 V under blue, −3.4 V under green, −1.1 V under red and −0.8 V in darkness; i.e., despite much lower I_L, blue illumination induced comparable ΔV_{th} with that of white light. In addition, *SS* value changed from 0.2992 V/dec to 0.6282 V/dec in the blue illumination (Fig. 2d). Number of generated defects ΔN_t was calculated to be $2.473\times10^{11}/\text{cm}^2$ using $\Delta SS = \frac{\Delta N_t \ln(10)kT}{C_i}$ equation;[4,17] this amount of defect would induce only about −5.73 V change in V_{th}, which is lower than the extracted value (−16.7 V). Therefore, it strongly supports the occurrence of hole trapping.

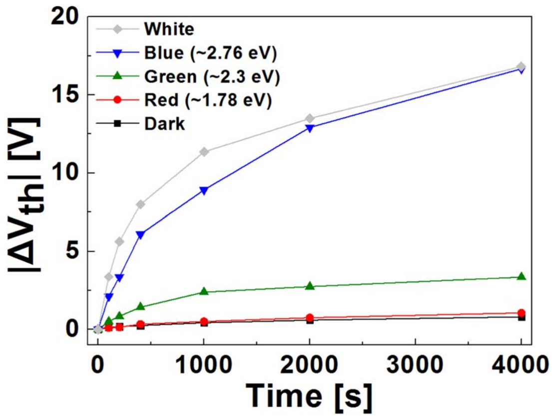

Figure 3. ΔV_{th} vs. stress time in darkness and under white, blue, green, and red illumination.

Hole trapping could occur by trap-assisted hole generation.[9,14] When V_O is ionized by illumination, it would not only result in negative shift of V_{th} but also act as mid-gap trap state. Photo-excited electrons from the valence band could be captured by ionized V_O which acts as mid-gap trap state and as a result, hole could be generated. Therefore, ionized V_O would enhance the hole generation and thus, further negative shift of V_{th} could occur by hole trapping under NBIS with blue illumination.

I_L of blue illumination was varied from 6 to 200 lux to clarify how it affects stability under same gate bias and temperature of −40 V and 90°C (Fig. 4). From $I_L = 6$ to $I_L = 25$ lux, ΔV_{th} and ΔSS increased noticeably as I_L increased; this trend occurs because V_O^{2+} generation rate increased as a result of increase in the number of incident photons with I_L. However, increase in ΔV_{th} and ΔSS decelerated at $I_L > 25$ lux. ΔV_{th} difference between 25 and 200 lux was less than 3.3 V, while it was more than 9 V between 6 and 25 lux.

ΔV_{th} value was expected to increase with increasing I_L, because there are more photons in illumination with higher intensity. However, final (4000 s) ΔV_{th} value saturated after exceeding a certain I_L at several temperatures T (30, 60 and 90°C) and stress voltages $V_{G.\text{stress}}$ (−20 V and −40 V) (Fig. 5). Saturation values of ΔV_{th} increased as T increased because ionization of V_O is facilitated at elevated T.[18] In addition, the saturation value of ΔV_{th} was approximately twice as large at −40 V stress than at −20 V stress at all T; this result suggests that migration of V_O^{2+} and holes depends on E-field.

Because ΔV_{th} is closely related to migration of ionized V_O and holes, ΔV_{th} saturation could also be interpreted in terms of V_O which

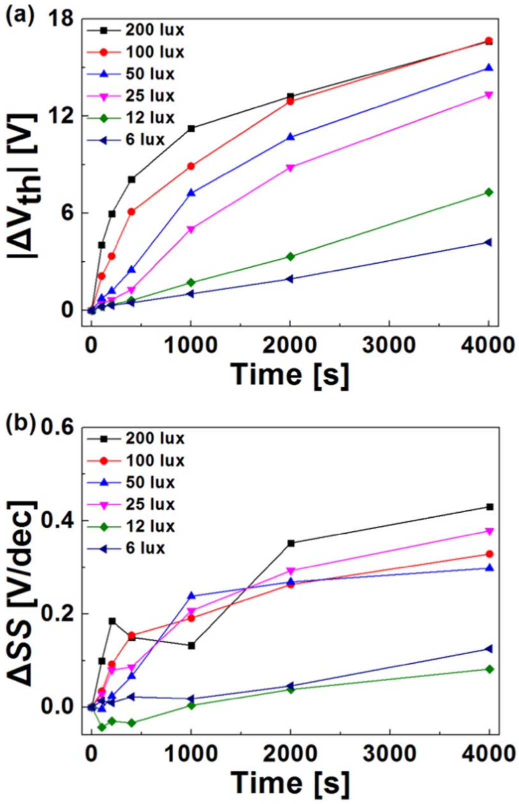

Figure 4. (a) ΔV_{th} vs. stress time and (b) ΔSS vs. stress time with different intensities I_L of blue illumination at 90°C. Increase in ΔV_{th} decelerated at $I_L > 25$ lux.

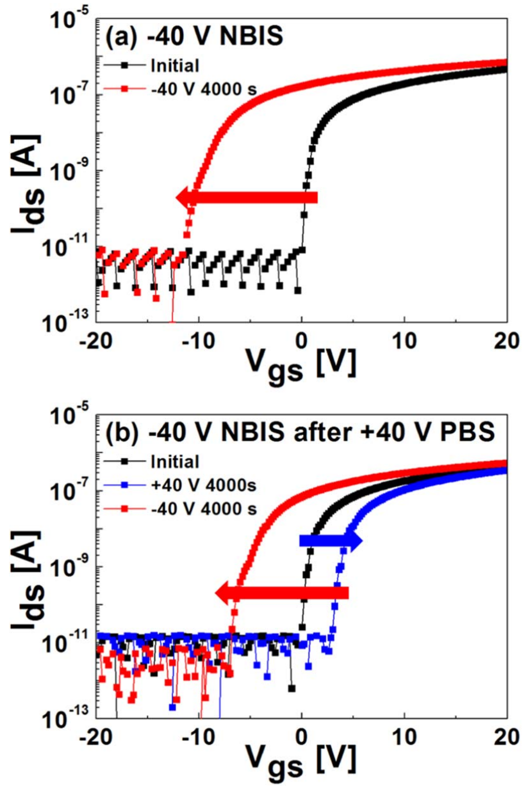

Figure 6. Changes in transfer curves with (a) −40 V NBIS and (b) −40 V NBIS after +40 V PBS at 60°C. I_L of blue illumination was 100 lux.

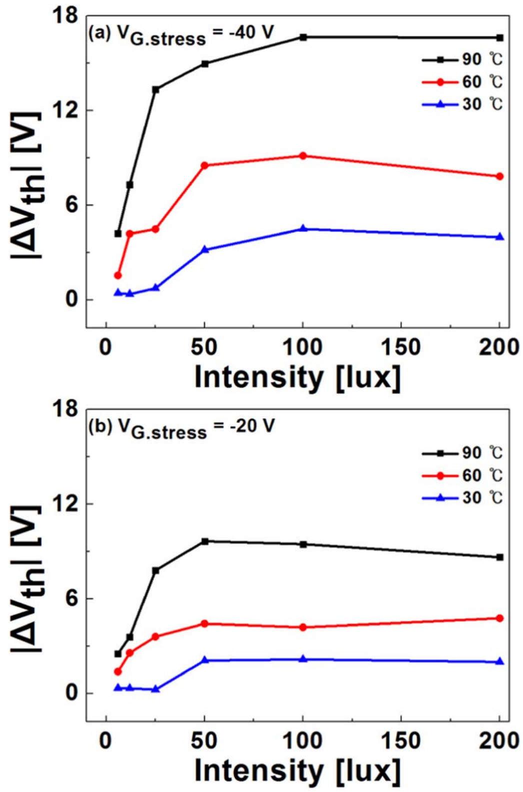

Figure 5. ΔV_{th} vs. intensity with gate bias of (a) −40 V and (b) −20 V with different temperatures. ΔV_{th} saturated in all stress conditions.

is important factor for ionized V_O and hole generation. Limitation in density of neutral V_O is not a complete explanation for the ΔV_{th} saturation because the increase in the ionization of V_O as T increased implies that V_O exists in sufficient amount. There are two possible mechanisms to explain the saturation of ΔV_{th}. (1) Trapped-electron limitation. ΔV_{th} shift saturates because, even though the rate of V_O-ionization increases persistently as I_L increases, the interface hosts a limiting number of trapped electrons, which are necessary for V_O^{2+} trapping; and (2) V_O-ionization rate saturation. Saturation of ΔV_{th} occurs because the ionization rate of indeed V_O saturates after certain I_L.

To verify the former mechanism, we applied PBS shortly before NBIS (blue, $I_L = 100$ lux). If ΔV_{th} saturation is due to the limited number of electrons at the interface, then if number of electrons trapped at the interface can be increased, the amount of ΔV_{th} is expected to increase. PBS increases the number of electrons trapped at the interface.[2,6] However, application of PBS (+40 V) just before NBIS (−40 V) caused almost no difference in ΔV_{th} compared to application of just NBIS (Fig. 6). Because I_L ($= 100$ lux) was sufficient to saturate ΔV_{th}, this result implies that the number of electrons trapped at the interface did not limit V_O^{2+} trapping.

V_O-ionization rate saturation could be the mechanism of ΔV_{th} saturation. When V_O is ionized, it induces outward relaxation of the neighboring metal atoms.[11,19,20] Metal ions are positively charged, so they retreat from V_O when it is ionized to V_O^{2+}. At relatively low I_L, the ionization rate will increase proportionally to the number of incident photons. On the contrary, after a certain I_L, additional photons will not be able to ionize additional V_O because ionization will be inhibited by the outwardly-relaxed metal atoms.

The proportion of photons that ionize V_O will be highest when outward relaxation has not taken place severely under low intensity (Fig. 7a). Although V_O^{2+} generated by photo-excitation pushes adjacent metal atoms, it will not have much influence on ionization of others which remain neutral. So there will be a room for

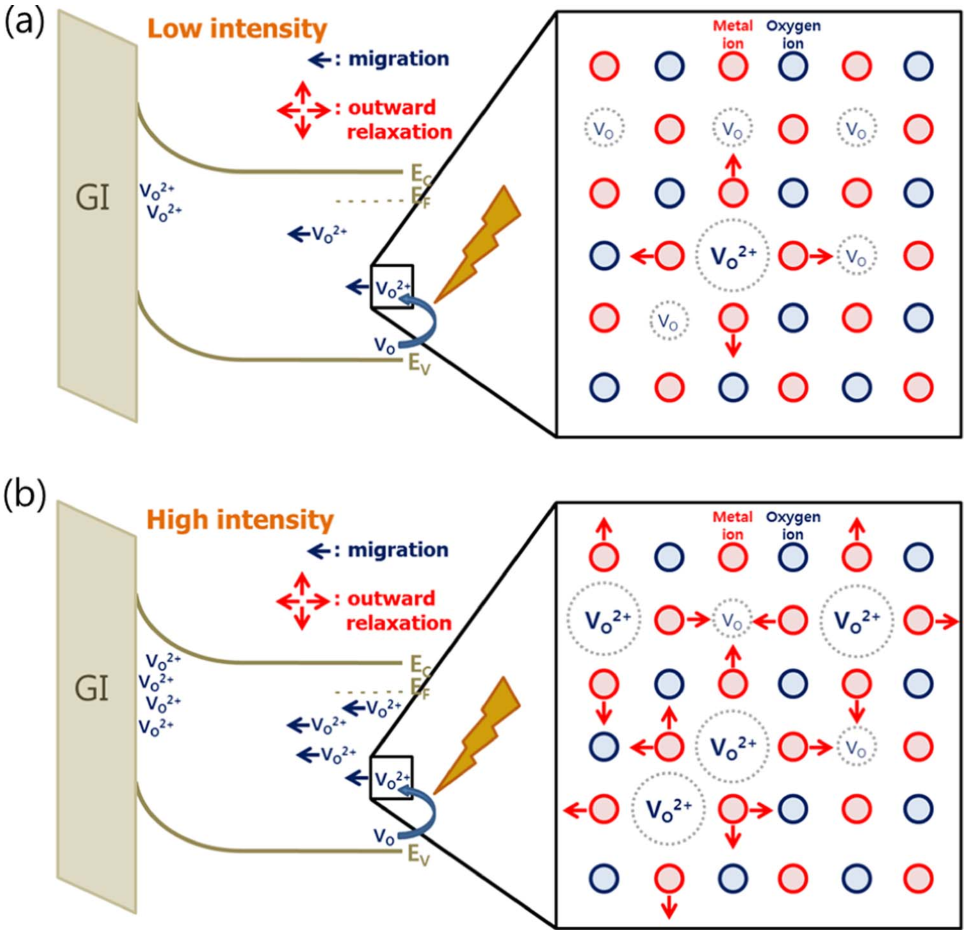

Figure 7. Qualitative description of band diagram and outward relaxation of metal atoms under NBIS with (a) low intensity and (b) high intensity illuminations.

additional V_O to be ionized and thus, ΔV_{th} increases as I_L increases. However, after a certain number of V_O are ionized, abundant outward relaxation of metal atoms (Fig. 7b) would occur, and inhibit further ionization of remaining neutral V_O states even if the number of incident photons increases. So the ionization rate will reach a plateau and as a result, ΔV_{th} also saturates even if I_L increases further.

Conclusions

We investigated how wavelength λ and intensity I_L of light affect the degradation in a-IGZO TFTs under NBIS. Illumination with photon energy higher than 2.3 eV was found to have a critical effect on a-IGZO TFTs in NBIS, which was the result of generation and migration of V_O^{2+} and holes. In addition, ΔV_{th} saturated after I_L exceeded a certain value in NBIS with blue illumination. We suggest that this is a consequence of saturation in V_O-ionization rate due to abundant outward relaxation of metal atoms when I_L exceeds certain level. Though further investigation is required to explain the mechanism quantitatively, our results and proposed mechanism could be a useful guideline in designing display backplanes incorporating a-IGZO TFTs.

Acknowledgments

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