Quantitative Analysis of Negative Bias Illumination Stress-Induced Instability Mechanisms in Amorphous InGaZnO Thin-Film Transistors

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Abstract

Physical origins of the negative bias illumination stress (NBIS)-induced threshold voltage shift (ΔV_T) in amorphous InGaZnO (a-IGZO) thin-film transistors (TFTs) under ambient light from the backlight unit are quantitatively and systematically investigated. Furthermore, the methodology for extracting the instability parameters is proposed and demonstrated. For quantitative analysis, the subgap density-of-states (DOS)-based DC *I-V* model is intensively used. The NBIS time-evolution of the measured I_{DS}-V_{GS} characteristics are reproduced very well via the proposed methodology and instability parameters. Consequently, it is found that the photo-excited electron detrapping followed by the ionization of oxygen vacancies (V_O^{+2}) and the field-enhanced V_O^{+2} diffusion followed by the hole trapping into gate insulator are dominant mechanisms on NBIS-induced instability of a-IGZO TFTs.

I. Introduction

The amorphous oxide semiconductor (AOS) thin-film transistors (TFTs) have attracted much attention in terms of significant merits such as the viability for flexible and transparent displays, large-area uniformity, low temperature process, and high carrier mobility. Especially, as representative AOS materials, amorphous InGaZnO (a-IGZO) TFTs have emerged as one of promising candidates substituting a-Si:H and/or organic TFTs as switching/driving devices in AMLCDs and/or AMOLED displays. Very recently, the bias stress/light illumination-induced/temperature instabilities have been challenging issues for mass products [1-3]. Therefore, the projection of instability becomes very important with respect to manufacturability. However, to date, the quantitative analysis on bias or photo instability has been rarely reported.

In this paper, we quantitatively investigate origins of negative bias illumination stress (NBIS)-induced threshold voltage shift (ΔV_T) in a-IGZO TFTs under ambient light from the backlight unit. The NBIS condition is consistent with actual operation in AMLCD display pixels because switching TFTs lie in NBIS condition during most of frame time. For quantitative analysis, the subgap density-of-states (DOS)-based DC *I-V* model is intensively used. Through our methodology for extracting instability parameters, the physical origins of NBIS-induced ΔV_T are decomposed into the creation of shallow donor (oxygen vacancy: V_O) states g_{OV}(E), the photon-assisted electron detrapping from deep donor states $g_{TD}(E)$ followed by the ionization of V_O ($V_O \rightarrow V_O^{2+}$), and the V_O^{+2} diffusion toward the interface between the gate insulator and AOS active thin-film followed by the hole trapping into the gate insulator.

II. Device Structure

The fabricated TFT has the bottom gate structure with an etch stopper as shown in Fig. 1(b), and the a-IGZO active thin-film is deposited by RF magnetron sputtering at room temperature. The thickness of gate insulator (SiN_x/SiO_x), the a-IGZO thin-film thickness (T_{IGZO}), channel length (L), and channel width (W) are designed to be 400/50 nm (EOT: T_{ox}=258 nm), 50 nm, 100 μm, and 200 μm, respectively.

III. Instability Model and Parameter Extraction

Fig 1(a) show the schematic illustrating a typical energy distribution of subgap DOS in a-IGZO TFTs, which is composed of acceptor-like states g_A(E), deep donor (or donor-like tail) states $g_{TD}(E)$, and shallow donor states $g_{OV}(E)$. Physical mechanisms on the NBIS-induced negative ΔV_T are schematically illustrated in Fig. 2(a). Three mechanisms are as follows: ①: the creation of shallow donor states $g_{OV}(E)$ [4, 5], ②: the photon-assisted electron detrapping from deep states $g_{TD}(E)$ followed by the ionization of oxygen vacancies ($V_O \rightarrow V_O^{+2}$), and ③: the V_O^{+2} diffusion toward the interface between the gate insulator and AOS active thin-film followed by the hole trapping into the gate insulator[5, 6].

On the other hand, the used subgap DOS-based DC *I-V* model is summarized in Table I. Details of deriving model equations was shown in [7]. Here, it should be noted that the DC *I-V* model is based not on fitting parameters BUT on physical parameters such as the conduction band mobility (μ_{Band}), $g_A(E)$, $g_{TD}(E)$, $g_{OV}(E)$, the effective DOS in conduction band (N_C), flat band voltage (V_{FB}), and E_{FB} defined by the energy difference between Fermi-level E_F and conduction band minimum (E_C) at V_{GS}=V_{FB} condition.

The methodology for extracting the NBIS instability parameters is shown in Fig. 3. Initially, the basic input parameters such as μ_{Band}, $g_A(E)$, $g_{TD}(E)$, $g_{OV}(E)$, N_C, T_{IGZO}, L, W, and T_{ox} are given. The $g_A(E)$ is experimentally extracted by using multi-frequency *C-V* method [8]. The details of DOS extraction are shown in [7]. Then, V_{FB} and E_{FB} are calculated by using Table I. Here, the subgap DOS is extracted during NBIS, and subsequently, the DOS variation-induced modulation of E_{FB} is calculated, as seen in Fig. 2(b). Then the calculated I_{DS}-V_{GS} characteristic is compared with the measured one during NBIS. Unless it agrees with the measured one, the charge density from the ionization of V_O ($Q_{detrapped}$) is assumed to be nominal value, and then, both V_{FB} and E_{FB} are updated by using the assumed $Q_{detrapped}$, as seen in Fig. 2(c). Meanwhile, the charge density due to the hole trapping into the gate insulator (Q_{OX}) is also assumed to be another nominal value, and both V_{FB} and E_{FB} are updated in similar way. In these manners, both $Q_{detrapped}$ and Q_{OX} are adjusted until the consistency between the calculated I_{DS}-V_{GS} characteristic and the measured one self-consistently is satisfied.

The NBIS time-evolutions of the measured I_{DS}-V_{GS} characteristics are compared with models calculated as shown in Fig.4. Here, the NBIS conditions are $V_G/V_D/V_S$=-20/10/0 [V], total stress time=1.1×10^5 [sec] under the backlight unit with the brightness of 300 [cd/m^2]. The models reproduce the measured NBIS time-evolution of the I_{DS}-V_{GS} characteristic very well. It shows that our methodology and parameter are reasonable.

Fig. 5 shows the quantitative analysis of the NBIS-induced ΔV_T by using the procedure in Fig. 3. Here, V_T is extracted by using a constant current method at I_{DS}=1×10^{-8} [A]. Q_{OX} and $Q_{detrapped}$ are saturated after NBIS time of 2×10^3 [sec] and 5×10^3 [sec] as seen in Figs. 5(a) and (b). Therefore, the NBIS-induced negative ΔV_T is saturated with the increase of stress time. It is because either the ionization of V_O or the hole trapping is the self-limiting process.

In addition, as seen in Fig. 5(c), ΔV_{OV}, $\Delta V_{detrapped}$, and ΔV_{OX} correspond to the ΔV_{FB} component resulting from the $\Delta g_{OV}(E)$-induced E_{FB} modulation (① in Fig. 2(a)), the electron detrapping followed by V_O^{+2} (② in Fig. 2(a)), and the hole trapping into gate insulator (③ in Fig. 2(a)), respectively. Finally, all components affecting ΔV_T after 1.1×10^4 s under NBIS can be decomposed into three mechanisms as shown in Fig. 5 (c). The experimental results show that ΔV_{OX} (from ΔQ_{OX}), $\Delta V_{detrapped}$ (from $\Delta Q_{detrapped}$) and ΔV_{OV} (from ΔQ_{OV}) affect the portion of 64-69 %, 24-28 % and 5-8 % of a total NBIS-induced ΔV_T, respectively. Therefore, it should be emphasized that ΔV_{OX} and $\Delta V_{detrapped}$ are dominant mechanisms on NBIS-induced instability of a-IGZO TFTs. It means that the NBIS condition makes the photon-excited creation and diffusion of V_O^{+2} followed by the hole trapping most probable[5].

IV. Conclusion

We quantitatively investigate origins of the NBIS-induced ΔV_T in a-IGZO TFTs under ambient light from the backlight unit. In addition, the methodology for extracting the instability parameters is proposed and demonstrated. For quantitative analysis, the subgap DOS-based DC *I-V* model is intensively used. The NBIS time-evolution of the measured I_{DS}-V_{GS} characteristics are reproduced very well via the proposed methodology and instability parameters. Consequently, it is found that physical mechanisms affecting the NBIS-induced ΔV_T are decomposed into three parts: the $\Delta g_{OV}(E)$-induced E_{FB} modulation (5-8 %), the electron detrapping followed by V_O^{+2} (24-28 %), and the hole trapping into gate insulator (64-69 %).

Acknowledgements

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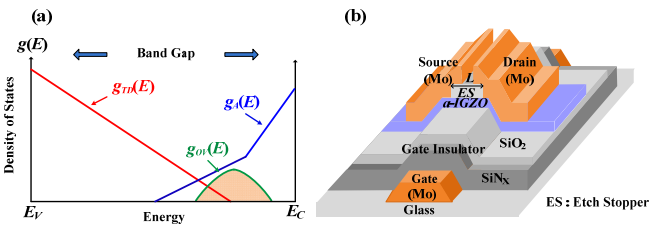

Fig. 1. (a) Schematic diagram of subgap DOS of a-IGZO TFT. (b) The schematic of integrated a-IGZO TFT with the commonly used inverted staggered bottom gate structure.

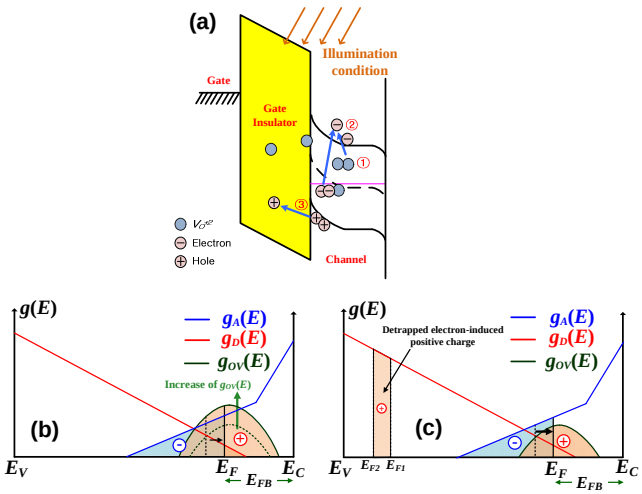

Fig. 2. (a) Diagram illustrating physical mechanisms of the NBIS-induced negative ΔV_T in AOS TFTs. ①: the creation of shallow donor states $g_{OV}(E)$, ②: electron detrapping from deep states $g_{TD}(E)$ followed by the ionization of oxygen vacancies ($V_O \rightarrow V_O^{+2}$), and ③: the V_O^{+2} diffusion toward the interface between the gate insulator and AOS active thin-film followed by the hole trapping into the gate insulator. The schematics illustrating the NBIS-induced reduction of E_{FB} due to (b) the increase of $g_{OV}(E)$ and (c) the electron detrapping from deep states $g_{TD}(E)$.

Table I. Equations used in subgap DOS-based DC *I-V* model for AOS TFTs

$$g_A(E) = g_{DA}(E) + g_{TA}(E) = N_{DA} \times \exp\left(\frac{E-E_C}{kT_{DA}}\right) + N_{TA} \times \exp\left(\frac{E-E_C}{kT_{TA}}\right)$$

$$g_D(E) = g_{TD}(E) + g_{OV}(E) = N_{TD} \times \exp\left(\frac{E_V-E}{kT_{TD}}\right) + N_{OV} \times \exp\left[-\left(\frac{E_{OV}-E}{kT_{OV}}\right)^2\right]$$

$$I_{DS} = q\frac{W}{L}\int_{V_S}^{V_S+V_D}\int_0^{x=T_{GIZO}} n_{free}(x,V_{CH}) \times \mu_{CH}(x,V_{CH})\,dx\,dV_{CH}$$

$$= \mu_{BAND} q \frac{W}{L}\int_{V_S}^{V_S+V_D}\int_{\phi_B}^{\phi_S} \frac{Q_{free}(\phi,V_{CH})}{Q_{free}(\phi,V_{CH})+Q_{loc}(\phi,V_{CH})}\frac{n_{free}(\phi,V_{CH})}{E_{GIZO}(\phi,V_{CH})}\,d\phi\,dV_{CH}$$

$$Q_{loc} = q\int_{x=x}^{x=T_{IGZO}}\left[\int_{E_V}^{E_C} g_{TD}(E)[1-f(E)]dE - \int_{E_V}^{E_C} g_A(E)f(E)dE\right]dx$$

$$Q_{free} = q\int_{x=x}^{x=T_{IGZO}} n_{free}(x,V_{CH}(y))dx = q\int_{x=x}^{x=T_{IGZO}} \frac{2}{\sqrt{\pi}} N_C F_{1/2}(\eta_F)\,dx$$

$$\mu_{CH}(x,V_{ch}) = \mu_{BAND} \times \frac{Q_{free}}{Q_{free}+Q_{loc}}$$

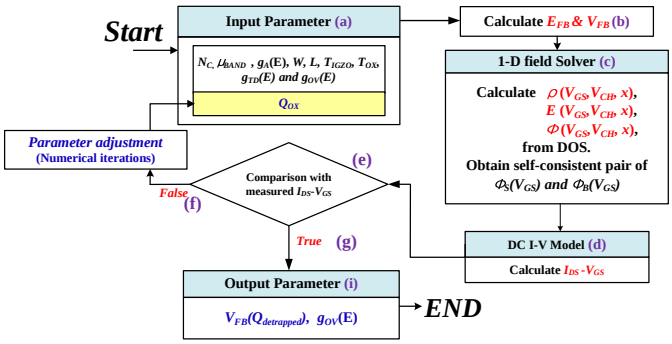

Fig. 3. The methodology for extracting instability parameters of AOS TFTs.

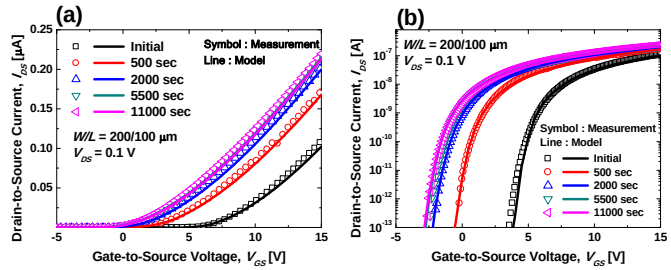

Fig. 4. The NBIS time-evolutions of the measured I_{DS}-V_{GS} characteristics in comparison with the calculated ones by using DeAOTS. (a) Linear and (b) log scale. The NBIS conditions are $V_G/V_D/V_S$= -20/10/0 V, total stress time=1.1×10^5 sec under the backlight unit with the brightness of 300 cd/m^2.

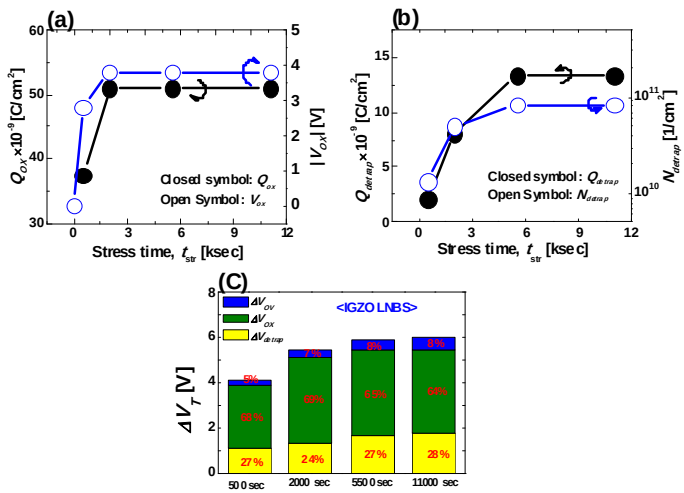

Fig. 5. Quantitative analysis of the NBIS-induced ΔV_T by using the procedure in Fig. 3. The NBIS time-evolution of (a) the gate oxide charge density Q_{OX} resulting from the hole trapping into the gate oxide and (b) the ionized oxygen vacancy V_O^{+2} charge density Q_{detrap} due to the electron detrapping.