Electro-Thermal Annealing Method for Recovery of Cyclic Bending Stress in Flexible a-IGZO TFTs

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***Abstract*— Amorphous In-Ga-Zn-O (a-IGZO) thin-film transistors (TFTs) fabricated by low-temperature processes on a flexible substrate can easily be degraded by mechanical deformation. Furthermore, lower performance in terms of the initial characteristics and reliability levels compared to those fabricated on glass substrates with relatively high heat treatments is inevitable. To solve these problems, a local electro-thermal annealing (ETA) method was applied to flexible a-IGZO TFTs processed at low temperature to enhance the inferior initial characteristics and reliability under a bending state. The enhancement of the characteristics and reliability by ETA can be attributed to the reduction of defects related to the oxygen through a localized Joule heat treatment with an extremely short duration (~1 ms). In addition, the effectiveness of ETA to recovery from bending stress even under harsh cyclic bending operation (strain condition of 0.833%) is verified.**

***Index Terms*— Bending stress, electro-thermal annealing (ETA), flexible In-Ga-Zn-O (a-IGZO) thin-film transistors (TFT), low-temperature process.**

I. Introduction

IN ACCORDANCE with the social needs for the rapid development of the Internet of Things given the flexible properties of related devices, amorphous In-Ga-Zn-O (a-IGZO) thin-film transistors (TFTs) have attracted attention as a candidate to meet these demands. The a-IGZO TFTs harness many advantages, such as high mobility [1], good uniformity due to the amorphous phase [2], low OFF-state current [3], and compatibility with low-temperature processes [4]. Nevertheless, there are still many reports about reliability problems related to electrical, mechanical, temperature, and light illumination stress [5]–[8]. Among these issues, excellent mechanical durability is becoming crucial for flexible electronic applications, and the influence of mechanical stress on a-IGZO TFTs has widely been investigated [9]–[11]. Several studies have reported instability origins of a-IGZO TFTs under mechanical stress during, for instance, cyclic or fixed bending conditions. The electrical performance degradation of a-IGZO TFTs due to mechanical stress stems from the altered atomic interval in the a-IGZO layer caused by tensile strain [12]–[14]. This can negatively affect the film density, defect density in the a-IGZO layer, and the contact properties of the metals used in the source and drain (S/D) electrodes.

On the other hand, Kim *et al.* [15] reported that electro-thermal annealing (ETA) could effectively reduce oxygen vacancies (V_O) in the a-IGZO bulk region. The reduced V_O by ETA resulted in an improvement of the poor electrical characteristics, i.e., irregularity of the threshold voltage (V_T), a low ON-state current (I_{ON}), and a high subthreshold swing (SS). These device parameters can be further exacerbated in flexible a-IGZO TFTs fabricated by low-temperature processes due to the immature ionic bonds between the metal atoms and oxygens which cannot completely be cured at a low temperature ($<$200 °C). Here, we demonstrate that the inferior initial characteristics of a-IGZO TFTs can be improved by ETA as a posttreatment step. Furthermore, it is confirmed that the instability due to mechanical stress can be recovered by ETA iteratively.

II. Experimental Setup

The a-IGZO TFTs with the top-gate bottom-contact structure were fabricated. Given that, the overall device structure, material configuration, and the thickness of each layer were mostly optimized for a traditional glass substrate in earlier work, the same architecture of the TFT was used in this paper [8], [15]. However, it was necessary to optimize the

Manuscript received March 12, 2017; revised May 17, 2017; accepted June 15, 2017. Date of publication June 26, 2017; date of current version July 21, 2017. This work was supported in part by the IT Research and Development program of MOTIE/KEIT under Grant 10042412, more than 60" transparent flexible display with UD resolution, transparency 40% for transparent flexible display in large area, in part by the Center for Integrated Smart Sensors funded by the Ministry of Science, ICT and Future Planning as Global Frontier Project under Grant CISS-2011-0031848, and in part by Nano·Material Technology Development Program through the National Research Foundation of Korea funded by the Ministry of Science, ICT and Future Planning under Grant 2016M3A7B4905609. The review of this paper was arranged by Editor X. Guo. *(Myung Keun Lee and Choong-Ki Kim contributed equally to this work.) (Corresponding author: Kyung Cheol Choi.)*

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Digital Object Identifier 10.1109/TED.2017.2717444

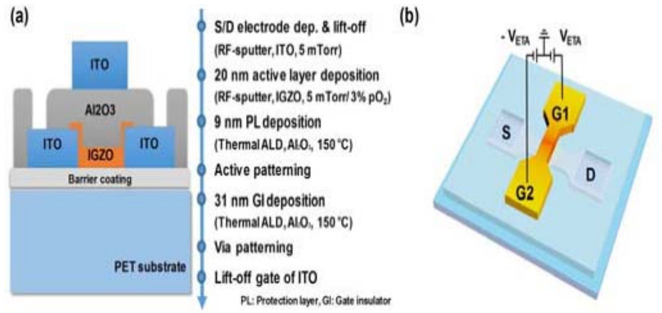

Fig. 1. Schematic of (a) device and fabrication process flow and (b) ETA of a-IGZO TFTs fabricated on PET substrates.

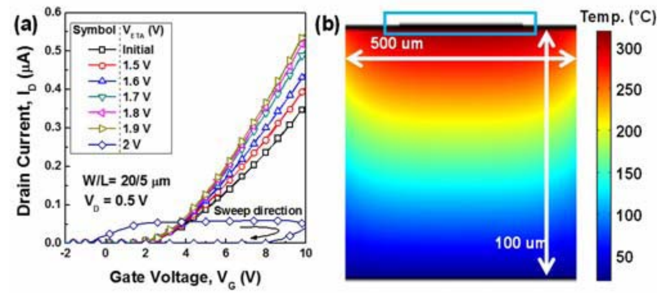

Fig. 2. (a) Transfer curves of an a-IGZO TFT according to V_{ETA} under 1 ms t_{ETA} condition. (b) Finite-element simulated temperature profile using COMSOL software [the box shown in sky blue corresponds to the single device depicted in Fig. 1(a)].

processes further so that the TFTs could be fabricated on a flexible substrate, which has a low thermal stability. The modified fabrication process is as follows: 1) polyethylene terephthalate (PET) was used as a flexible substrate owing to its tolerance for organic solvents such as a photoresist developer, acetone, and isopropyl alcohol, which are used for patterning and cleaning processes; 2) barrier layer composed of 10 nm of Al_2O_3 was deposited onto a PET surface to protect it from contamination and to mitigate the surface roughness. This step improves the adhesion of the electrodes to the surface; and 3) prebaking at 180 °C was done for two hours in order to shrink the PET enough to avoid further deformation in the subsequent thermal budget. To reduce the hysteresis of the transfer characteristics, three annealing processes were also conducted at 200 °C in an ambient air environment after every wet etching process. A schematic of the final device is shown in Fig. 1(a). All TFT characteristics were measured by means of a HP 4156C semiconductor parameter analyzer in an ambient atmosphere.

III. Results and Discussion

A. Low-Temperature Processed TFTs and Electro-Thermal Annealing

The initial transfer curve of the a-IGZO TFT on the PET substrate is shown in Fig. 2(a). Hysteresis-free characteristics were obtained through the aforementioned optimization of the annealing process. Nevertheless, it should be noted that the initial characteristics on the PET are inferior to TFTs fabricated on a rigid substrate such as nonalkali glass. This stems from the insufficient thermal annealing process at <200 °C. Therefore, localized ETA was applied to a-IGZO TFTs as a posttreatment step to improve these characteristics. To apply ETA to the a-IGZO TFTs in this case, ETA voltages (V_{ETA}) with identical absolute amplitudes but opposite signs were separately applied to connected dual-gate pads with a specific ETA time (t_{ETA}), i.e., one pad was positively biased while the other was negatively biased. As shown in Fig. 2(a), the initial inferior characteristics were linearly enhanced by increasing V_{ETA} [15]. However, the device characteristics were severely degraded at an excessive value of V_{ETA} due to the electrostatic breakdown of the ITO gate electrode under the strong electric field [16]. Fig. 2(b) shows the temperature profile of the a-IGZO TFTs on the PET substrates as simulated by the COMSOL finite-element method. It is noteworthy that the

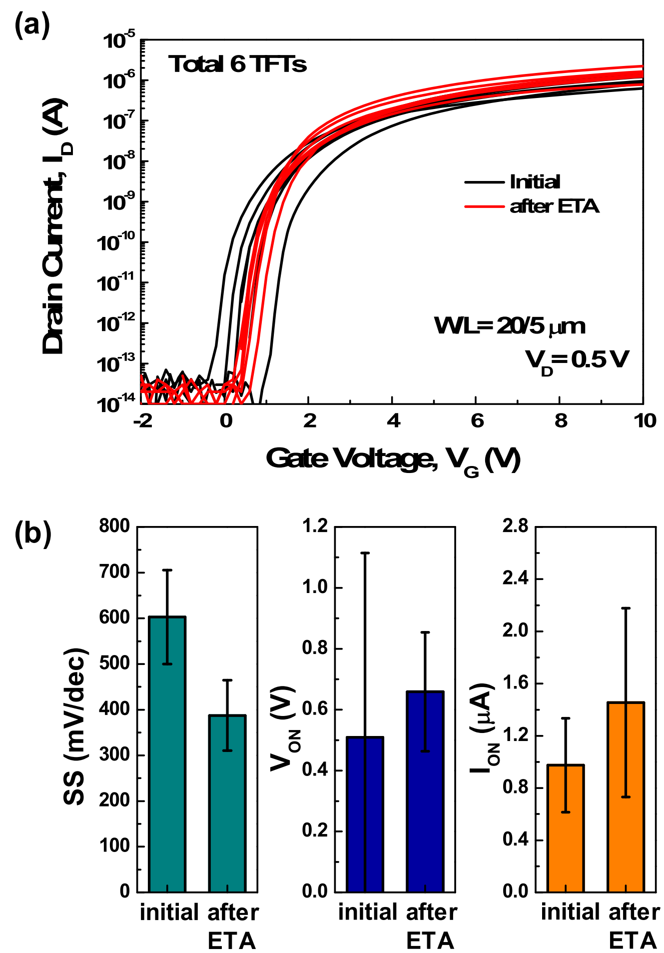

Fig. 3. (a) Transfer curves of six a-IGZO TFTs before applying ETA (black) and after ETA (red). (b) Summarized metrics in the initial state and after ETA was applied.

Joule heat above 300 °C generated by ETA is confined in the sub-500 × 100 μm^2 region. Therefore, this localized ETA can selectively be applied to a targeted TFT without global thermal annealing, making it applicable to the wafer (substrate) scale.

Because a-IGZO layers are formed by RF-sputtering, metal-oxide compositions are irregular, structural defects cannot be avoided, and a high density of V_O and/or weak bonded oxygen is inevitable owing to ion bombardment [17], [18]. Accordingly, if the sputtering process is not supported by

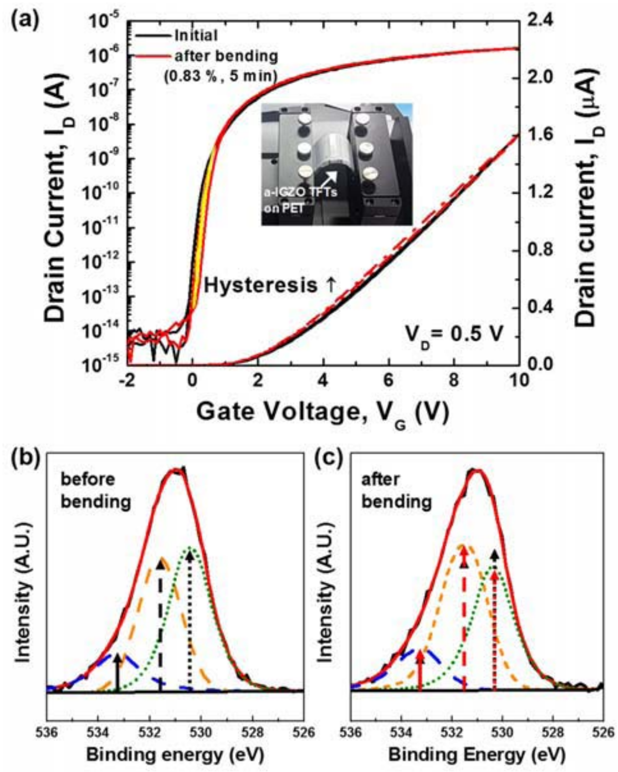

Fig. 4. (a) Transfer curves of an a-IGZO TFT in the initial state and after bending (tensile strain of 0.833%) for 5 min. (b) O 1 s spectra in an a-IGZO channel as measured by XPS in the initial state. (c) After bending for 5 min.

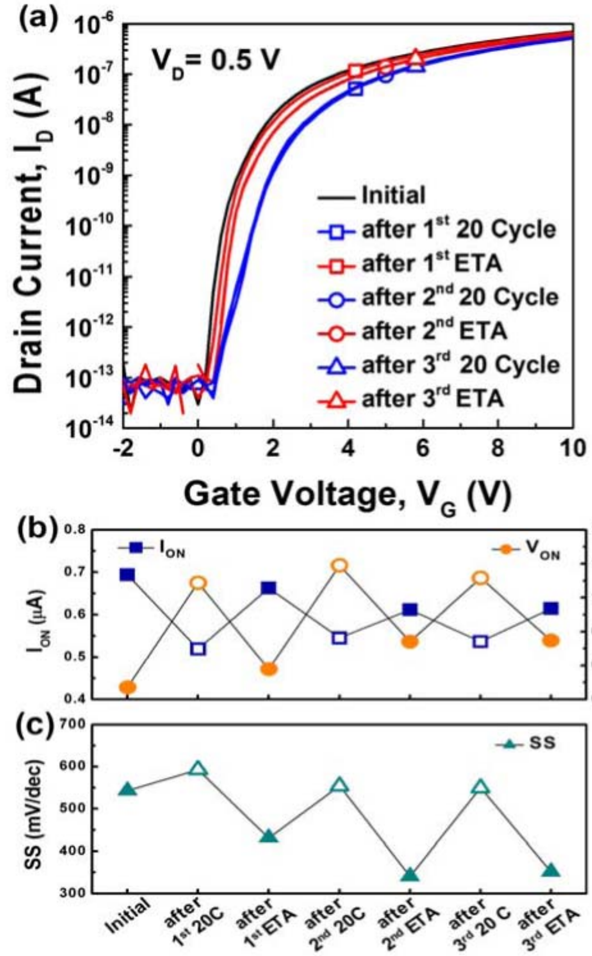

Fig. 5. (a) Transfer curves of an a-IGZO TFT according to iterative twenty bending cycles with tensile stress of 0.833% and ETA operation. (b) Summarized V_{ON}, I_{ON}, and (c) SS according to the operations.

sufficient thermal treatments, the uncured damage will negatively influence the a-IGZO channel properties, as shown in Fig. 3(a). It should be noted that the device-to-device uniformity and intrinsic electrical performance were poor in the initial state. However, these characteristics were improved with the ETA process. In fact, several studies have reported that thermal annealing can stabilize the electrical properties of an a-IGZO layer by reducing defect sites related to oxygen, disorganized metal cations, and residue on the surface after photolithography [19], [20] The proposed ETA reduces the total bulk trap density and the interface trap density of the channel layer, thus improving the electrical properties of the a-IGZO TFTs. A previous study by Kim *et al.* [15] reported a reduction of V_O in the a-IGZO bulk region upon the application of ETA. This process was effective in mitigating the negative bias illumination stress instability of the a-IGZO TFT, which is the most serious problem caused by ionized V_O. This effect can be attributed to the reduced V_O density and to the densification between the metal cations and the oxygen anions by ETA. To be specific, in this paper, the ON-state voltage (V_{ON}) variation of all six TFTs was reduced by the uniform ETA temperature with constant V_{ETA} and t_{ETA} levels, with improved I_{ON} and SS values in extremely short duration (1 ms). SS was obtained by taking the reciprocal of the slope of the tangent line when the current was $10 \times 10^{-}12$ A on the I_D–V_G curve. I_{ON} was defined as the drain current (I_D) at gate voltage (V_G) of 10 V and drain voltage (V_D) of 0.5 V. V_{ON} was defined as V_G when I_D equals $W/L \times 10^{-12}$ A. The summarized metrics are presented in Fig. 3(b).

B. Bending Stress on TFTs and Electro-Thermal Annealing

Meanwhile, bending stress exacerbated the hysteresis in the electrical characteristics of the TFTs [Fig. 4(a)]. Hysteresis began to appear after 5 min under a fixed tensile bending condition with a bending radius (R_B) of 1.5 cm, corresponding to 0.833% tensile strain parallel to the source-to-drain direction. As shown in Fig. 4(b) and (c), this is due to the increased V_O in the tensile strain condition and the degradation of the metal-oxygen bonds[12], [21]. An X-ray photoelectron spectroscopy (XPS) analysis of the center of large patterned (500×500 μm) a-IGZO active layer was conducted by Ar sputtering along the depth direction. The deconvolution process was done with three different Gaussian curves with a full-width-at-half-maximum of 2 eV. It is noteworthy that the binding energy peak (531.5 ± 0.2 eV) corresponding to V_O increased after bending, while the peak (530.5 ± 0.2 eV) related to the metal-oxygen bonds decreased. Therefore, the degraded electrical characteristics, e.g., increased hysteresis, by fixed bending stress can be well interpreted with XPS analyses [22]–[24]. Meanwhile, the binding energy peak related to M-OH (534±0.2 eV) shows higher intensity in the TFTs processed at a low temperature as compared to those processed at a high temperature, even prior to the application of bending stress. The numerous M-OH bonds also caused inferior characteristics in the a-IGZO TFTs.

Because cyclic bending stress is more terminal with regard to reliability than fixed bending stress for practical applications, mechanical endurance against cyclic bending stress was investigated in the samples. When the accumulated cyclic bending stress exceeded a critical level, recovery was not achieved via ETA. In contrast, when the number of continuous bending cycles was 20 or less, the recovery effect by the ETA was clearly observed, as shown in Fig. 5(a). This implies that iterative ETA is indispensable after every 20 bending cycles in order to enhance the lifetime under the cyclic bending conditions. SS degradation by the accumulation of bending stress can completely be recovered to the initial state or improved much, e.g., the SS_{after} ETA value is lower than the $SS_{initial}$ value. This indicates that both SS degradations caused by the preexisting oxygen related defects in the initial state and the additionally generated defects by mechanical stress can be recovered by ETA. ETA was then repeatedly applied to the TFTs after every 20 bending cycles. The electric characteristics degraded by cyclic bending stress were fully recovered. It is expected that ETA can serve as a solution to offer the semipermanent usage of a-IGZO TFTs even when continuous cyclic bending stress is applied in an actual usage environment. I_{ON} along with V_{ON} and SS are summarized in Fig. 5(b) and (c), respectively.

IV. Conclusion

In terms of electrical performance outcomes, amorphous a-IGZO TFTs fabricated on a flexible substrate with low-temperature annealing are inferior to those fabricated on a glass substrate due to the insufficient heat treatment. As a localized heat treatment method, ETA was demonstrated to improve the electrical performances of flexible a-IGZO TFTs. The temperature was suitably controlled through the optimization of the ETA voltage (V_{ETA}) and the ETA time (t_{ETA}). Furthermore, the proposed ETA recovered the damage caused by fixed or cyclic bending stress due to its ability to reduce defects related to oxygen in the a-IGZO channel. Finally, additional damage caused by the accumulation of cyclic bending stress was repaired by the iterative ETA process, thus, offering semipermanent operation of these devices even under harsh conditions involving mechanical stress.

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