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Light and bias stability of a-IGZO TFT fabricated by r.f. magnetron sputtering

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ABSTRACT

In this work, we examined the stability of amorphous IGZO TFT under electrical bias and light illumination. For the investigation of electrical bias effect on device stability, +20 V gate bias or −20 V gate bias was continuously applied on devices for 10000 s. For the investigation of illumination effect, we used monochromatic light source illuminating devices under the stress test. There was a specific stress condition to result in the degradation of device performance. Our IGZO TFT was considerably degraded only when the negative gate bias was applied with the light illumination. The subthreshold region was stretched in the negative direction and a humped shaped was observed in the middle of the subthreshold region. We propose two kinds of possible degradation mechanisms on the basis of experimental results and numerical simulations. The one is hole trapping in the gate insulator and the other is the change of transition level of deep donor states. The peculiar humped shape in the subthreshold region could be explained by the latter mechanism.

1. Introduction

Recently, oxide TFTs have received great attention for next-generation display pixel components [1–3]. ZnO based semiconductors are attractive for those applications because they have higher electron mobility than amorphous silicon and visible range transparency due to wide bandgap [4]. Among them, amorphous indium gallium zinc oxide (a-IGZO) is the most promising in the viewpoint of mass production because it can be deposited by commercial r.f. magnetron sputtering. Furthermore, IGZO thin film guarantees uniformity in both the productivity and electrical characteristics, which originates from its amorphous phase [5]. However, device stability under operation is an important issue for IGZO TFT to be utilized in practical applications such as liquid crystal display (LCD) or organic light emission display (OLED). The electrical bias is one of main factors which degrade the device performance as time passing but the effect of bright environment, which display components cannot avoid, should be also investigated [6].

In this work, we examined the stability of IGZO TFT under positive bias stress and negative bias stress respectively in dark state. After then the same tests were repeated with the light illumination. The possible mechanisms of light induced bias instability in our IGZO TFTs are discussed.

2. Experimental details

Fig. 1 shows the cross section view of our IGZO TFT fabricated in top gate structure on a glass substrate. The IGZO active layer was deposited by r.f. magnetron sputtering system. The metal electrodes were deposited by r.f. magnetron sputtering with indium tin oxide (ITO) target. The ITO gate is suitable for top-light illumination due to its visible range transparency. All the patterning processes were carried out in conventional photolithography and wet etch methods.

Stability tests were carried out with the system shown in Fig. 2. Test devices were isolated from external light by shielding box and all the stability tests were carried in it. Agilent 4155C semiconductor parameter analyzer and a probe station system were utilized for the electrical measurements and stress tests. The wave length of light utilized for illumination during the stress test was 430 nm which was achieved from the combination of Xe lamp and monochromator. The wavelength of 430 nm was selected because it is one of three points where peak intensity in LCD backlight spectrum is observed, and the wavelength is the shortest one suitable for achieving the highest photon energy. The power density of the incident light was set to be 0.1 mW/cm^2.

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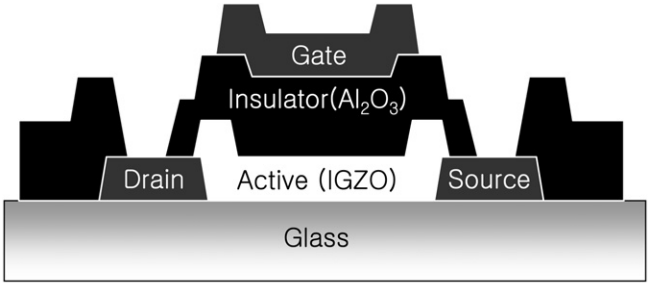

Fig. 1. Cross section view of IGZO TFT used in the study.

3. Results and discussions

For the investigation of electrical bias effect on device stability, we applied +20 V gate bias and −20 V gate bias respectively for 10000 s in dark state. The source and drain electrodes were connected to ground (0 V) terminal. In Fig. 3(a), the initial transfer characteristics of IGZO TFT and the transfer characteristics after +20 V gate bias stress are shown. There were little changes in device characteristics before and after the positive gate bias stress in dark state. The gate bias of +20 V is higher than conventional voltage level for switching TFT in ON state for LCD application and the time duration of 10000 s is equivalent to the sum of each switching ON times when LCD display works continuously for 2300 h. Therefore the positive gate bias stability under dark state is excellent.

In Fig. 3(b), the initial transfer characteristics of IGZO TFT and the transfer characteristics after −20 V gate bias stress are shown. There were also little changes in device characteristics before and after the negative gate bias stress in dark state. The time duration of 10000 s is not so much long considering that the accumulated switching OFF time is nearly equal to working time of LCD display. However, conventional voltage level for switching TFT in OFF state for LCD application is about −5 V, so the gate bias of −20 V is enough to accelerate the degradation during the test. The above two results imply that our IGZO TFT has highly stable characteristics in dark state. However, display components have to guarantee the stability under light illumination because some amount of light originated from illuminant source is inevitably guided into the components.

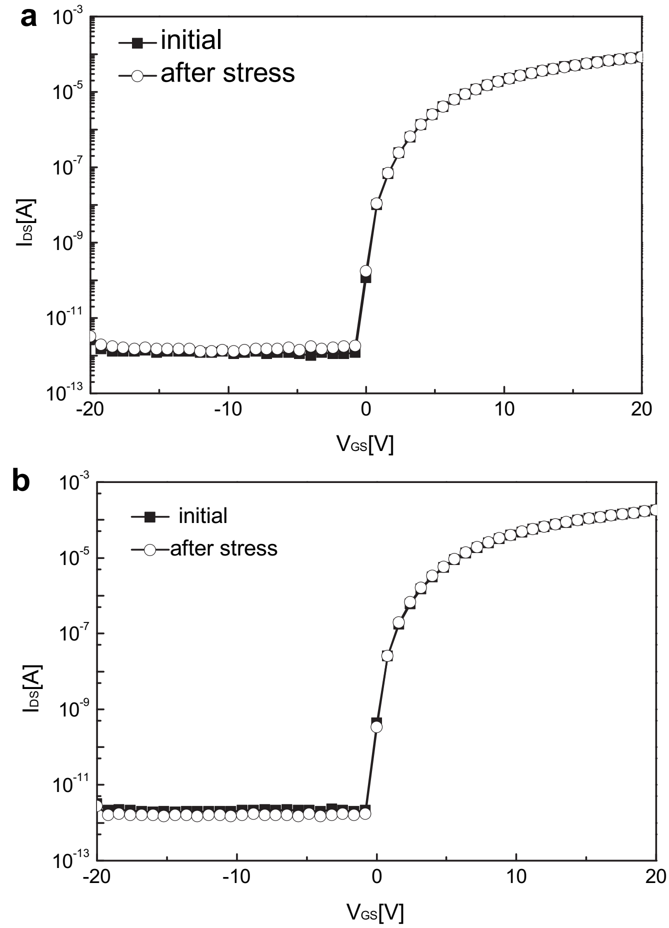

Fig. 3. Transfer characteristics of IGZO TFT before and after (a) +20V gate bias stress in dark state, (b) −20V gate bias stress in dark state.

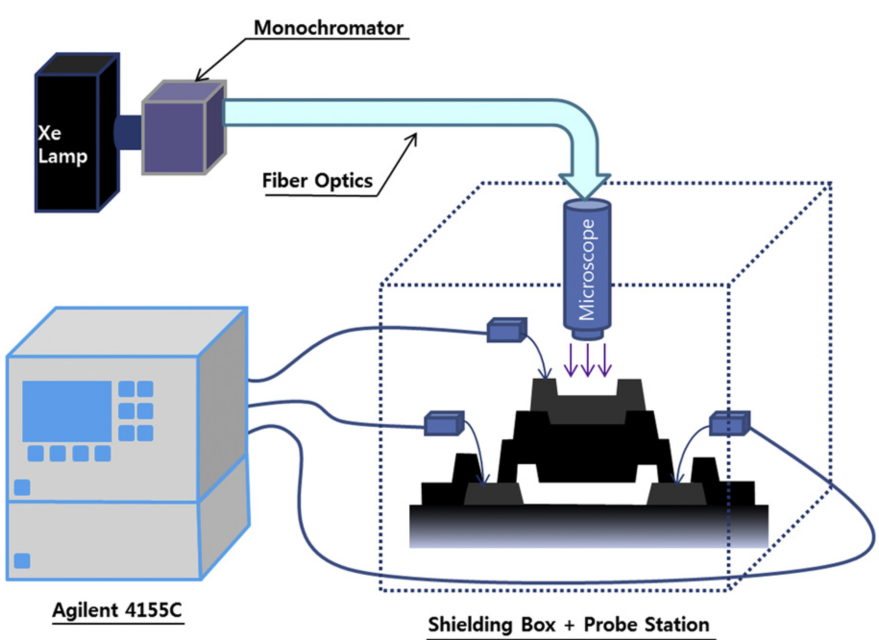

Fig. 2. The schematic diagram of experimental equipments used in the study.

Fig. 4(a) shows the initial transfer characteristics and the transfer characteristics after +20 V gate bias stress with 430 nm wavelength light illumination. The positive gate bias stress with light illumination did not make large difference in the device stability compared with the stress with bias only. In case of 430 nm wavelength, the photon energy is insufficient to generate electron hole pair via band to band transition. However, amorphous IGZO incorporates a lot of gap states, especially donor-like states related with oxygen vacancies [7], so that electron emission can occur by absorbing photon energy and leaving the positively ionized gap state. But the life time of the positive space charge may be very short because of recombination with abundant free electrons in conduction band, so that the light illumination does not make any significant difference compared with dark state in view of degradation factors.

Fig. 4(b) shows the initial transfer characteristics and the transfer characteristics after −20 V gate bias stress with 430 nm wavelength light illumination. In this figure, the significant change in the transfer curve can be found. The subthreshold region is stretched in the negative direction on the V_{GS} axis. Light illumination on negatively biased condition makes big difference compared with positively biased condition. The origin of such difference seems to be related with the generated holes in the valence band. When the Fermi level is lowered toward valence band by the negative gate bias, there would exist positively ionized gap states such as oxygen vacancies, so that hole emission from valence band is possible. If trap sites exist inside the insulator, the generated holes would be trapped there due to the electric field attracting them. The trapped holes provide positive bias effect on n-type channel when the transfer curve is measured after the stress, which results in the negative shift of the transfer curve. This procedure can be considered as a possible instability mechanism of our amorphous IGZO TFT.

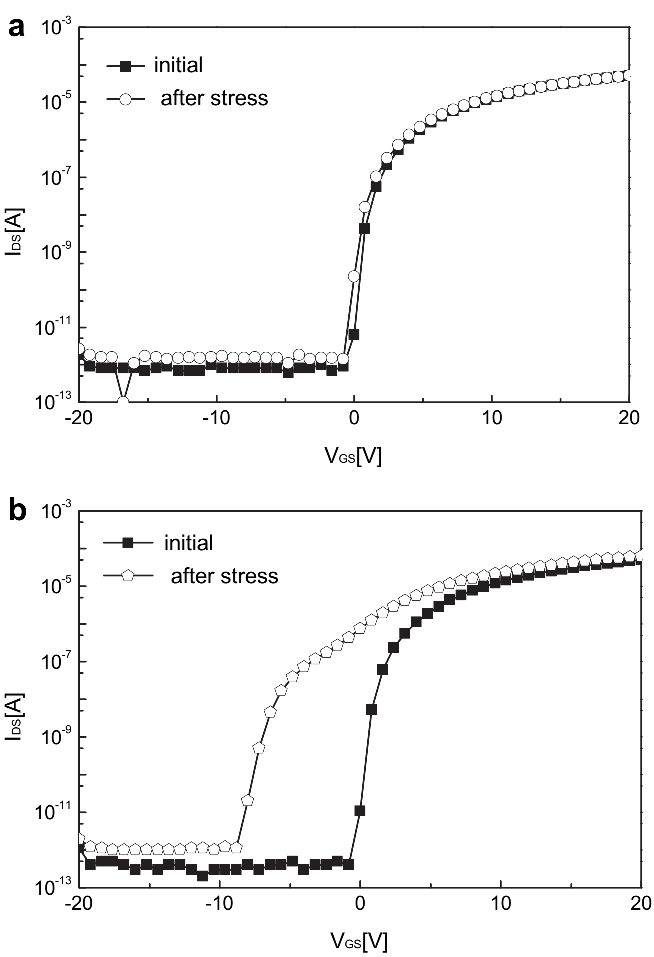

Fig. 4. Transfer characteristics of IGZO TFT before and after (a) +20V gate bias stress with light illumination, (b) −20V gate bias stress with light illumination.

However, the change in the transfer curve can not be stated as a negative shift only. The dominant change in the subthreshold region can not be explained by hole trapping solely, because charge trapping at insulator results in a parallel shift of a transfer curve. Under the light illumination on negatively gate-biased IGZO TFT, electron emission process should be considered in addition to hole emission. If the transition levels of donor-like states are widely distributed in the band gap, some of them can still remain in a neutral state under the negative gate bias. They can still act as deep donors under the negatively biased condition. There have been some reports on the species of deep donors such as oxygen vacancies possibly existing in IGZO film [8–10]. If electron emission occurs at these neutral sites, the life time of the positively ionized deep donors would be very long and maintain their ionized states during the negative gate bias stress duration, because electrons have been depleted by negative gate bias. It can be deduced that the ionized states are energetically unstable because the Fermi level is not lowered below their transition levels, so that they may bring some amount of structural modification around the oxygen vacancies. The positions of cation atoms around the positively ionized oxygen vacancy would move in outward directions from their initial positions, so that the transition level (2+/0 or +/0) of the oxygen vacancy can be elevated toward the conduction band. For the theoretical basis of this scenario, the latest papers, which report that oxygen vacancies in IGZO can play a role of shallow donor as well as deep donor according to the locations and species of cations surrounding the oxygen vacancy, can be referred to [11,12]. If the transition levels of deep donors jump near or above conduction band edge, parallel negative shift of a transfer curve is expected. If the transition level of deep donors is not so much elevated but up to the level below the conduction band edge by about 0.25 eV, they will deform the shape of the subthreshold region which results in a humped shape. We are considering these procedures as another possible instability mechanism of our amorphous IGZO TFT.

In order to verify the effect of transition level of donor-like state on the shape of transfer curve, we performed the numerical simulation with a device simulator ATLAS (Silvaco) [13]. This numerical simulator enables to simulate the electrical behavior of semiconductor devices constructed in two or three dimensions. For I-V simulation of TFT, a user should input the informations about geometries and materials adopted in a device and the profiles of subgap states such as donor-like states and acceptor-like states in the active material. According to the settled bias conditions, the simulator calculates the terminal currents. One of the various purposes of I-V simulation is to find out the effect of the subgap states on the electrical behavior of TFT. There are so many input parameters which affect a simulation result, that a user should select as few variables as possible among input parameters. In case of our IGZO TFT simulation, the subgap states were modeled as below.

$$g(E) = g_{TA}(E) + g_{TD}(E) + g_{GA}(E) + g_{GD}(E) \tag{1}$$

$$g_{GD}(E) = N_{GD}\exp\left(-\left(\frac{E - E_{GD}}{W_{GD}}\right)^2\right) \tag{2}$$

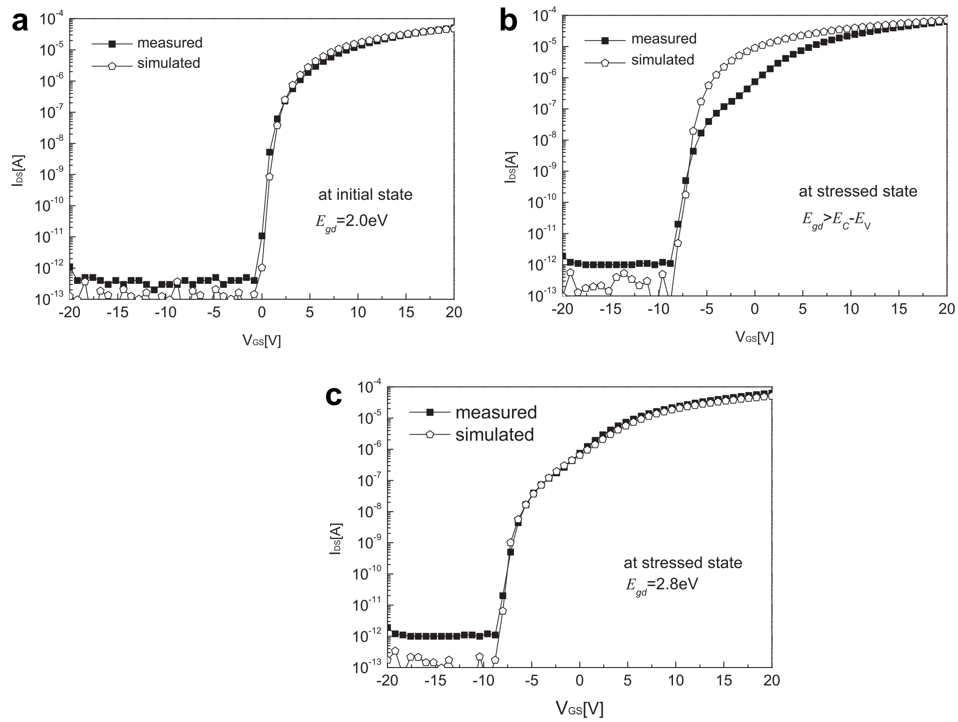

Fig. 5. Simulated transfer characteristics of IGZO TFT when E_{GD} is located (a) below the conduction band edge by 1eV, (b) above the conduction band edge, (c) below the conduction band edge by 0.25eV.

g_{TA} (E) and g_{TD} (E) are the volume density of acceptor-like and donor-like tail states at energy (E) respectively and modeled using a exponential function near the band edge. g_{GA} (E) and g_{GD} (E) are the volume density of acceptor-like and donor-like deep states at energy (E) respectively and modeled using a Gaussian function within the band gap. In our study, E_{GD} has the physical meaning of the central position of the transition level of donor-like states which is considered to be distributed in a Gaussian function in the band gap. E_{GD} was the sole variable in our simulations. In Fig. 5 (a), the open symbol represents the transfer curve simulated for the initial state and the closed symbol represents the measured one. The simulated one was achieved when E_{GD} was located below the conduction band edge by 1 eV ($N_{GD} = 1.4 \times 10^{19}$ cm^{-3} eV^{-1} , $W_{GD} = 0.05$ eV) [14]. Therefore all the donor-like states act as deep donors regardless of gate bais within the measurement range.

In Fig. 5 (b), the open symbol represents the transfer curve simulated for the stressed state and the closed symbol represents the measured data. The simulated one was achieved when E_{GD} was located above the conduction band edge. This simulation was performed to invesitigate an expeted result when the transition level of all the deep donors has jumped above the conduction band edge. The simulation result indicates the parallel shift of a transfer curve from the initial state, which is different with the result of our experiment. It should be noted that the above defect distribution condition in Fig. 5 (b) can be considered as n-type doping of which the volume density is 1.2×10^{18} cm^{-3}, which was calculated by integrating g_{GD} (E) on energy scale, and those effect on the change of a transfer curve is similar to that of hole trapping, i.e. parallel shift of the transfer curve.

The simulated curve in Fig. 5 (c) was achieved when E_{GD} was located below the conduction band edge by 0.25 eV. This simulation was performed for the case when the transition level comes close to the conduction band edge. In this case, the volume density of donor states is the same with that of Fig. 5 (a) and (b). In Fig. 5(c), however, the simulated curve shows that the subthreshold region is stretched in the negative direction and a humped shape is observable in the middle of the subthreshold region. This result is better fitted to the experimental result than in Fig. 5 (b).

4. Conclusion

In this work, the instabilities of amorphous IGZO TFT under the gate bias stress combined with light illumination have been examined. The transfer characteristics of our IGZO TFT was degraded showing negative shift in V_{GS} axis when the negative gate bias was applied in the existence of light illumination. We propose two kinds of degradation mechanisms. The one is hole trapping in the gate insulator and the other is the change of transition level of deep donor states. We have verified by the numerical simulation that the change of donor level can affect the transfer characteristics to shift in the negative direction. The gap states are responsible both the mechanisms because charge emissions under light illumination can not occur without the help of gap states in wide bandgap material.

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