Competing Degradation Mechanisms in Flexible Dual-Gate InGaZnO Thin-Film Transistor under Mechanical Stresses

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Abstract

The effect of mechanical stress on the electrical characteristics of dual-gate a-IGZO TFTs was studied. Identical devices under mechanical stress in different directions exhibited distinctly different degradation behaviors. When the bending axis was perpendicular to the channel length direction, the electrical characteristics of the devices showed a negative threshold voltage shift, counterclockwise hysteresis, and increased on-state current. When the bending axis was parallel to the channel length direction, a positive threshold voltage shift, clockwise hysteresis, and decreased on-state current were observed. This indicates the presence of two degradation mechanisms at least, and their relative strengths were determined through dynamic bending experiments with 45° direction to the channel length, the results of which shows the mechanism making transfer characteristics negatively drift is dominant.

Author Keywords

dual-gate thin-film transistors; amorphous InGaZnO; flexible; degradation mechanism; mechanical stress direction

1. Introduction

In recent years, flexible electronic products, being lightweight and unbreakable, have attracted increasing research attention. As the basic element of flexible electronics, a-IGZO thin-film transistors (TFTs) have the advantages such as high carrier mobility, good large area uniformity and low-temperature processing [1-3] and are widely used in flexible displays [4] and circuits application.[5] In the use condition, flexible electronic products will subject to sustained mechanical stress, such as bending stress in either dynamic [8] or static [6,9] mode. Therefore, the reliability of a-IGZO TFTs under mechanical load is a concerned issue. Furthermore, the DG structure is more advanced due to its stronger gate control capabilities and better stability than the single-gate structure.[7]

Generally, the TFT characteristic will degrade during stress application. With more stress application, the deterioration will be worse. However from relevant researches the degradation induced by mechanical stress load can make the transfer characteristic negatively [9] or positively [10,11] drift and the degree of degradation with magnitude of mechanical load can be not of consistency. The different action of deterioration suggests that there is not only one kind of degradation mechanism which is not clear. While according to these results it is common that the deterioration under tensile mechanical stress is harder than that under compressive mechanical stress. In order to obtain DG TFTs with high bending stress stability, the influences of mechanical stress on the DG a-IGZO TFTs need to be thoroughly inquired to uncover the underlying mechanisms.

In the present work, a-IGZO TFTs fabricated on PI substrates are investigated. In order to further reveal the degradation mechanism of mechanical stress, static tensile load with different direction to the channel is applied. The disparate deterioration action of unlike direction under mechanical stress means at least two kind of mechanisms, the competition of which is determined by applying dynamic mechanical bending test with 45° to the channel. The mechanism conducing to negative drift of transfer characteristics is dominant.

2. Experimental Details

The schematic structure of the flexible dual-gate a-IGZO TFT is shown in Figure 1, and the processing step is as follows: First, deposit 200 nm SiN_x on PI glass by PECVD at 300°C, followed by the deposition of 300 nm SiO_2 as the buffer layer. The reaction gases for SiN_x are SiH_4, N_2, and NH_3, while the reaction gases for SiO_2 are SiH_4 and N_2O. Next, 100 nm molybdenum (Mo) on the buffer layer deposited by DC magnetron sputtering and patterned by wet etching to form the bottom gate electrode. Then, deposit 100 nm SiO_2 as the bottom gate insulator (BGI) by PECVD at 300°C. TFTs are then annealed at 300°C for 1.5 hours in O_2 atmosphere. The active layer is 40 nm a-IGZO deposited by DC magnetron sputtering, followed by annealing at 350°C for 1 hour in O_2 atmosphere. A ceramic target, consisted of In_2O_3:ZnO_2:Ga_2O_3 at a ratio of 1:1:1, was used. After annealing, the active layer was patterned by wet etching. Subsequently, deposit 100 nm SiO_2 as the top gate insulator (TGI) after N_2O plasma treatment at 150°C, followed by a 3-hour annealing at 300°C. Then, deposit 100 nm Mo and 30 nm ITO through DC magnetron sputtering and pattern them by wet etching to form the top gate electrode. A ceramic target, which consists of In_2O_3:SnO_2 at a ratio of 9:1, was used. Next, remove TGI by dry etching and make S/D conductive by Ar bombardment. Afterward, grow 200 nm SiO_2 as a passivation layer (PL) by PECVD at 150°C. Form contact holes for S/D and gate electrodes by dry etching, and then deposit 100 nm Mo as the contact metal through DC magnetron sputtering and pattern it using wet etching. Finally, peel the device off with the PI film from the glass substrate by Laser Lift-off (LLO) with temperature sensitive adhesive.

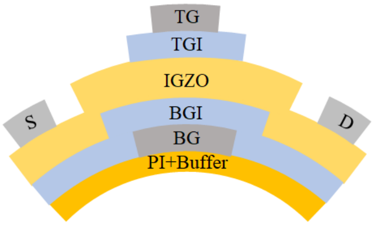

Figure 1. The schematic structure of the flexible dual-gate TFTs.

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The dual gate TFT has three operation modes with different gate biases, including BG, TG, and DG modes, as shown in Figure 2. In this work, only the electrical characteristics of TG mode is shown here. The B1500 (Agilent Technologies) semiconductor parameter analyzer was used to test the electrical characteristics of TFTs. The static mechanical stress load is under 10-mm-bending radius for one-hour and that of dynamic mode is to bend at the frequency of 1 Hz under the same situation with 45° angle between the bending axis and the channel length.

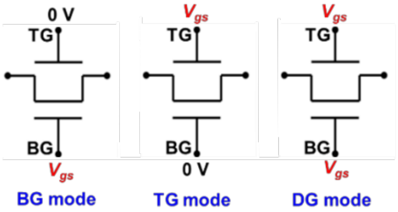

Figure 2. Three different operating modes of dual-gate TFTs.

3. Results and Discussion

Under mechanical stress applied in the perpendicular direction, the device performance exhibits significant changes, as shown in Figure 3. Prior to bending, the TFT's on-state current I_{on} was measured to be 5.17×10^{-7} A, with a threshold voltage V_{th} of 0.15 V. After bending, the on-state current increased to 8.12×10^{-7} A, and the threshold voltage shifted to $V_{th} = -0.21$ V. The increase in I_{on} and the negative shift of the threshold voltage indicate the generation of donor defects within the channel under perpendicular bending stress.

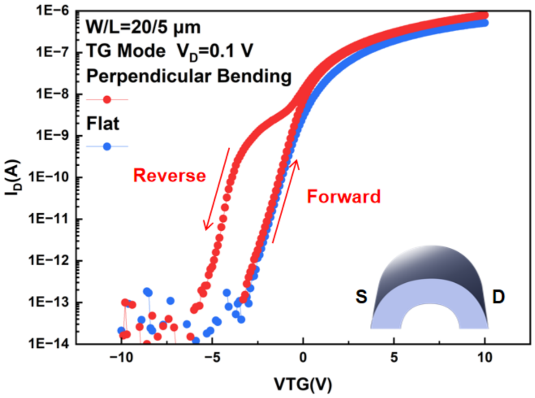

Figure 3. Comparison of transfer characteristics after perpendicular bending.

More importantly, after reverse scanning, the device exhibited pronounced hysteresis characteristics. When the current was 5×10^{-13} A, the hysteresis voltage difference was 2.31 V. The appearance of counterclockwise hysteresis suggests that during forward scanning, some of electrons are captured by interface traps and bulk defect states. When reverse scanning commences and the gate voltage decreases from positive to negative values, the direction of the electric field changes lead to the release of the trapped electrons. This results in a higher channel carrier concentration during reverse scanning compared to forward scanning, leading the appearance of hysteresis characteristics. Additionally, the manifestation of counterclockwise hysteresis as a hump indicates that the mechanical stress applied in the channel width direction is non-uniform.

Conversely, after being subjected to bending stress in the parallel direction, the device exhibits entirely opposite degradation behavior. Compared to the flat device, the threshold voltage of the bent TFT changes from -0.176 V to 3.13 V, and the on-state current decreases from 5.52×10^{-7}A to 2.08×10^{-7} A， as shown in Figure 4. This indicates that under bending stress parallel to the channel, a substantial number of acceptor defects are generated within the channel. These defects reduce the concentration of free electrons, causing a positive shift of the threshold voltage and a decrease in the on-state current. During reverse scanning, the release of electrons trapped by defects is slow and cannot immediately contribute to effective free carriers. At this time, the defects can also act as negative charge centers, enhancing scattering, reducing electron mobility, and leading to clockwise hysteresis in the device. Considering that the channel's width may be too large, making the hysteresis less pronounced, mechanical stress tests were performed on a device with width-to-length ratio = 10/5 μm. It was confirmed that mechanical stress applied in the parallel direction indeed leads to clockwise hysteresis, indicating that mechanical stress induces the generation of acceptor defects

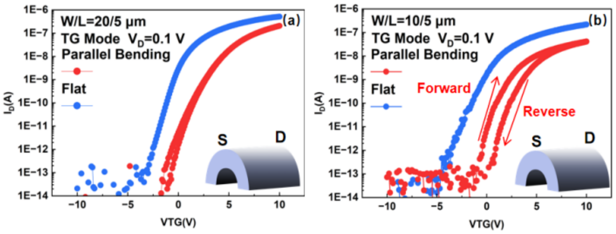

Figure 4. Effect of parallel bending on the performance of flexible DG TFTs: (a) W/L=20/5 μm (b) W/L=10/5 μm.

The above observations illustrate that the degradation mechanisms induced by mechanical stress are not singular, one tends to cause a negative shift in the transfer characteristics, while the other tends to cause a positive shift. The former primarily induces donor defects, whereas the latter primarily induces acceptor defects. Therefore, a competing relationship must exist between the two degradation mechanisms, with one mechanism dominating under specific mechanical stress directions. However, which degradation mechanism is the dominant one?

To elucidate the relative strength of two mechanical degradation mechanisms, devices with a width-to-length ratio of 50/50 μm underwent 7,000 cycles of dynamic bending tests at a 45° diagonal direction. As shown in the Figure 5, the transfer characteristics exhibit a negative shift and the emergence of a hump, confirming that the mechanism inducing donor defects is predominant.

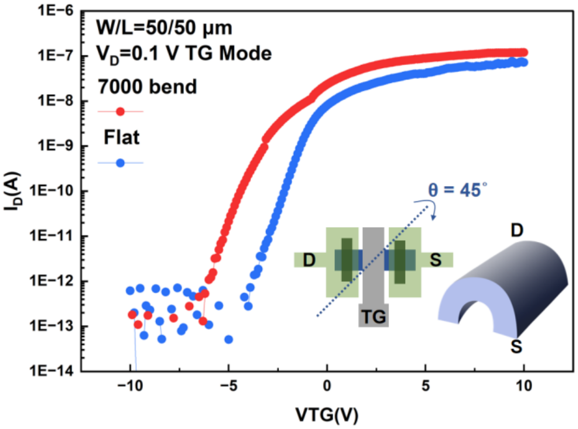

Figure 5. Effect of dynamic bending with 45° direction to the channel of DG TFTs.

Figure 6 illustrates the changes in the density of states (DOS) associated with the degradation mechanisms. Mechanical stress induces the generation of both donor and acceptor defects, possibly originating from the breaking of M-O bonds to form oxygen vacancies V_O and interstitial oxygen O_i. As the mechanical stress intensifies, the generation of donor defects becomes the dominant process.

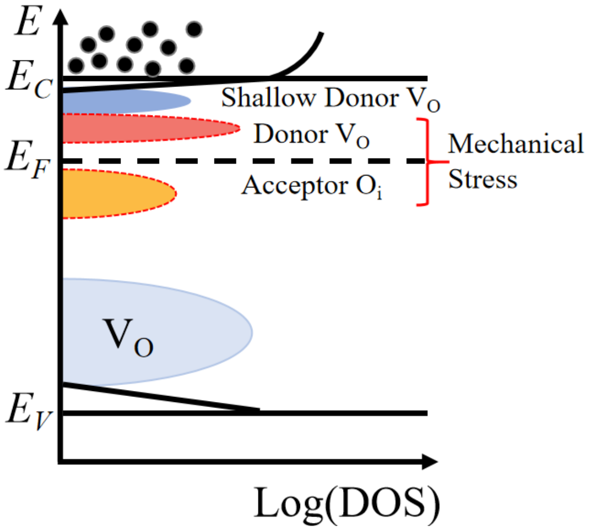

Figure 6. Density of states(DOS) of IGZO under mechanical stress.

4. Conclusion

In flexible IGZO TFTs, the degradation behavior of devices under bending stress in different directions is a key research focus. This study analyzed the degradation behavior of TFTs under 10-mm-bending-radius in both orthogonal and parallel directions to the channel length. It was found that the bending direction significantly affects the degradation behavior: orthogonal bending leads to a negative shift in transfer characteristics, while parallel bending results in a positive shift. The corresponding degradation mechanisms and their relative strengths were investigated. The negative and positive shifts are caused by donor and acceptor defects, respectively, which are induced by mechanical stress. These defects may arise from the breaking of M-O bonds due to mechanical stress, leading to V_O and O_i. Dynamic bending experiments at a 45° direction demonstrated that the degradation mechanism inducing donor defects is the dominant mechanism.

5. Acknowledgements

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