Influence of External Forces on the Mechanical Characteristics of the a-IGZO and Graphene Based Flexible Display

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Abstract: Thin film transistors (TFTs) based flexible displays have optically transparent and mechanically flexible properties that are attractive for next-generation display technologies. In particular, “amorphous indium-gallium-zinc-oxide” (a-IGZO) and graphene have attracted much attention due to the advantages of their excellent uniformity and compatibility with transparent and flexible substrates. To maintain these characteristics, it is important to confirm the deformation characteristics of TFTs with applied external forces, such as compressive or tensile stress, distortion effects, and temperature. The mechanical characteristics of modeled devices applied to different active layers on TFTs, such as a-IGZO and graphene, were investigated under various external conditions. The distributions of the stress-strain curve on each active layer and the deformed shapes were assessed graphically.

Key words: thin film transistors (TFTs), flexible display, amorphous indium-gallium-zinc-oxide (a-IGZO), graphene, active layer

1. Introduction

Recently, many consumers want not only portable electronic devices with high-performance and high-efficiency, but also small and light ones. Accordingly, the display market has started to focus on flexible displays for compact arrangements in limited spaces in electronic devices. The flexible organic light-emitting diode (FOLED) has received much attention because of its advantages, such as lower materials costs, color purity, light-weight, and high light-emitting efficiency for applications in flexible displays and lighting.[1] The FOLED is a type of organic light-emitting diode (OLED) incorporating a flexible plastic substrate on which the electroluminescent organic semiconductor is deposited. The device can be bent or rolled while still operating. Currently a focus of research in industrial and academic groups, FOLEDs represent one method of fabricating a rollable display. Flexible displays built-in to commercial electronic devices are being released all the time. Thus, various researches are studying transparent thin-film transistor (TFT), because there is growing interest in oxide active layers. TTFTs have mainly been used with transparent conducting oxides (TCOs), and amorphous indium-gallium-zinc-oxide (a-IGZO) [2] or graphene [3], which are being studied widely. The a-IGZO satisfies various requirements for such applications: it has very high transmittance in the visible range and high electron mobility so many researchers have studied the a-IGZO.[4-8]
Graphene has a large theoretical specific surface area ($2,630 \text{ m}^2\text{g}^{-1}$), high intrinsic mobility ($200,000 \text{ cm}^2\text{v}^{-1}\text{s}^{-1}$) [9,10], and thermal conductivity ($\sim 5,000 \text{ Wm}^{-1}\text{K}^{-1}$). Moreover, its optical transmittance ($\sim 97.7\%$) and good electrical conductivity are notable advantages for many potential applications. In this study, the mechanical characteristics of a-IGZO and graphene based flexible displays were investigated under the influence of external forces, such as tensile, compressive, and torsional forces at constant temperature. When an electronic device is operated, it is very difficult to maintain both the electrical and mechanical characteristics due to the generation of heat in the device. Additionally, the stress and strain energy density (SED) distributions at the active layer of the modeled device with TFTs were calculated using a commercial code, COMSOL multiphysics, and various deformed shapes were obtained.

2. Numerical Details

The schematic diagrams of the simplified TFTs for numerical analyses are shown in Figure 1. The modeled TFT is composed of a total of six different layers, and its detailed configurations are as follows: The top layer is the source/drain electrode (aluminum, Al). The second layer is the active layer (a-IGZO or graphene) as a target layer, and is located below the top layer. The third layer is an insulator (aluminum oxide, Al$_2$O$_3$). The fourth layer is an insulator (polyvinylphenol, PVP). Finally, the bottom layer is a flexible substrate (polyimide, PI). The material properties of each layer in the modeled TFTs are provided in Table 1. To assess the mechanical characteristics of the a-IGZO or graphene based flexible display, a simulation of the TFTs was performed with various applied external forces ($5.7 \times 10^8 \text{ N/m}^2$), [13] as shown in Figure 2. The surrounding temperature was set at room temperature, 20°C. The heating temperature of the modeled TFTs was set at 50°C to simulate the operating condition of the electronic device. Table 2 shows the cases of simulations with various external forces. The number of elements in the modeled TFT layer was generated approximately, from 16,000 to 19,000.

![Schematic diagrams of the modeled TFT for numerical analyses.](image-url)
Figure 2 Grid systems of the model for the applied external forces.

Table 1. Material properties of each layer of the modeled TFT.

| Materials | Young’s modulus [GPa] | Poisson’s ratio | Density [kg/m$^3$] | Coefficient of thermal expansion [$10^{-6}$/K] |
|-----------|------------------------|-----------------|---------------------|------------------------------------------|
| Al        | 68                     | 0.36            | 2700                | 0.00099                                  |
| a-IGZO    | 137                    | 0.36            | 5600                | 4.31                                     |
| Graphene  | 1000                   | 0.24            | 313008              | 0.000095                                 |
| Al$_2$O$_3$ | 370                    | 0.22            | 3960                | 0.0022                                   |
| PVP       | 0.8                    | 0.34            | 1166                | 100                                      |
| Ni        | 207                    | 0.31            | 8880                | 0.048                                    |
| PI        | 29                     | 0.34            | 1880                | 0.23                                     |
Table 2. Simulations with various external conditions.

| Active layer | External forces | Case 1 | Case 2 | Case 3 | Temperature [°C] |
|--------------|-----------------|--------|--------|--------|-----------------|
| a-IGZO       | Tension         | -      | -      | -      | 50              |
| Graphene     | Compression     | -      | -      | -      | 20              |
| Surroundings | Torsion         | -      | -      | -      |                 |

3. Results And Discussion

The influences of external forces on the von Mises stress and SED distributions were investigated numerically to determine the mechanical characteristics of the a-IGZO and graphene based flexible displays.

The results of von Mises stress and SED in the active layers are presented in Figures 3 and 4. It can be seen from the results in Figure 3(a), when a tensile force was applied along the x-direction of the modeled TFTs, the von Mises stress in the a-IGZO was larger than that in graphene. Figure 3(b) shows similar stress tendencies in both the a-IGZO and graphene active layers, and the deformed shapes rose convexly in the z-direction when a bending moment was generated at the edge of the modeled TFTs by a compressive force. When a clockwise torsional force was applied to the nano layer structure in the x-axis, the graphene layer showed a greater value of von Mises stress than that of the a-IGZO one. In particular, as shown in Figure 3(c), stress was concentrated in the center of the active layer.

![Figure 3](image-url)

Figure 3 Influence of external forces on von Mises stress distributions in the active layers.
It is also seen from Figure 4(a) that the SED of the a-IGZO was greater than that of graphene in the x-direction when a tensile force was applied. When the bending moment was applied to the modeled TFTs by a compressive force, the deformation was small on both sides along the x-direction. The results also showed that the SED appeared largely at the center of active layer, and both active layers rose convexly in the z-direction. Additionally, the SED of graphene was higher than that of a-IGZO (Fig. 4(b)). A clockwise torsional deformation was generated on both sides along the x-direction when a clockwise torsional force was applied to the modeled TFTs. Furthermore, a larger value of SED was represented at the center of the graphene active layer (Fig. 4(c)), resulting from the stress concentration phenomenon.

![Figure 4](image)

(a) Tensile force (Case 1)

(b) Compressive force (Case 2)

(c) Torsional force (Case 3)

(i) a-IGZO

(ii) Graphene

Figure 4 Influence of external forces on strain energy density distributions in the active layers.

As shown in Fig. 5, when the tensile force was applied to the TFTs structure, the values of von Mises stress and SED showed almost the same tendency in both active layers. However, the graphene layer showed slightly higher than those of a-IGZO layer.

Also, from the results of Figure 6(a), the value of von Mises stress in the graphene active layer was greater than that of a-IGZO when the compressive force was applied. The maximum value difference was 25.2630×1013 N/m2. Similarly, the SED of the graphene layer was also higher than that of a-IGZO (Fig. 6(b)), and the maximum value difference was 35.6456×1015 J/m3.
Figure 5 Comparison of von Mises stress and strain energy density distributions between the a-IGZO and graphene active layers with tensile force.
Figure 6 Comparison of von Mises stress and strain energy density distributions between the a-IGZO and graphene active layers with compressive force.

Figure 7 Comparison of von Mises stress and strain energy density distributions between the a-IGZO and graphene active layers with torsional force.
When the torsional force was applied to the modeled TFTs, the values of von Mises stress and SED of the graphene layer were higher than those of the a-IGZO active layer. As shown in Figure 7, the maximum value differences for von Mises stress and SED were 23.0498×10⁸ N/m² and 3.3233×10⁶ J/m³, respectively.

4. Conclusions

In this study, the mechanical characteristics of a-IGZO and graphene based flexible displays were investigated numerically under the influence of external conditions, such as tensile, compressive, and torsional forces at a constant operating temperature of 50°C. The following conclusions were reached:

1) The a-IGZO and graphene active layers showed similar tendencies in mechanical characteristics; indeed there was no significant difference when a tensile force was applied to the TFT structures.

2) The values of von Mises stress and SED in the graphene layer were greater than those for the a-IGZO layer when a compressive or torsional force was applied. In particular, these mechanical characteristics were superior at the thin edges of the graphene layer.

3) The graphene active layer had better mechanical characteristics in terms of flexibility and strength than the a-IGZO layer when TFT multi-layers received external forces. Thus, it may be concluded that the graphene is worth investigating for use in next-generation flexible displays, that will be capable of bending or rolling.

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