TFT-type Strain Sensors for Implementing Hidden Pixel Structure in Active-Matrix Stretchable Displays

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ABSTRACT

In this study, we proposed a strain-sensor-in-pixel (S-SIP) system by introducing hidden pixels that are activated only when the display is stretched to maintain the pixel density. For the system, the strain-sensor integrated InGaZnO thin-film transistors (TFTs) were fabricated to control the TFT on/off operation depending on the stretching state.

1 Introduction

With recent advancements in the display industry, such as high-resolution and large-screen displays, flexible display technologies for adjusting the display form-factor that can be folded or slid into a roll shape have attracted considerable attention. Following that, as of the ultimate peak of flexible display technologies, stretchable displays (also known as displays with a free form-factor) are considered to be the ideal next-generation technologies.[1] This is owing to the countless future applications that only stretchable displays are capable of, as surrounding environments in real-life are mostly composed of curvilinear surfaces, including human skin. For example, wearable devices that are attached to the body or clothing, a size-variable screen display that can function as a phone, a tablet, and a TV as needed, or healthcare monitoring systems where heavy and rigid devices are no longer qualified.

However, the stretchable displays must satisfy stricter requirements in order to maintain electrical and optical properties under mechanical stretching conditions than existing flexible or foldable displays. All components of the stretchable display, including the light-emitting diodes, thin-film transistors (TFTs), electrodes, and interconnects, should all be designed to withstand extreme strain. As a result, numerous approaches to realizing stretchable displays have been developed that go beyond the typical materials and fabrication techniques used in conventional rigid electronics.[2] The introduction of an elastic interconnect with a buckling or serpentine shape that can form rigid-island structures could be one of the representative examples for the strategic approaches to efficiently consuming the external strain stress for the stretchable displays.

Although these approaches can produce acceptable results in a wide variety of stretchable display applications, the stretchable displays exhibit a critical drawback related to the deterioration of image quality during mechanical deformation. The degradation of image quality occurs as the resolution (the number of pixels per unit area) and the luminance (the brightness per unit area) decrease significantly as the space between each pixel increases during mechanical stretching, resulting in image blurring.

To maintain the display's resolution and luminance before and after stretching, some researchers have employed a novel design concept called "hidden pixel" structures. That is, the pixels were divided up into subgroups, with some pixel groups (referred to as hidden-pixels) being activated only when the distance between adjacent other pixels (referred to as normal-pixels) increased under the tensile strain to sustain the initial pixel density. As illustrated in **Fig. 1**, the empty space between the normal-pixels is filled with the activated hidden-pixels, preventing loss of resolution and luminance during stretching. Such concept was demonstrated conceptually in a simple passive-matrix (PM) light-emitting diode (LED) pixel array by adjusting the power supply to the hidden-pixels in response to their stretching state via a metal interconnect with a negative gauge-factor resistance or a deformable three-dimensional structure fabricated through complex processes. Taking this further, some key technologies compatible with a pixel circuit containing multiple TFTs are essentially required to apply this design to commercially available active-matrix (AM) displays.

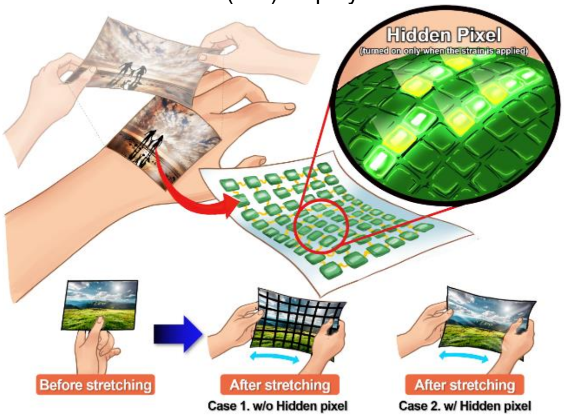

Fig. 1. Schematic illustration of example stretchable displays with and without hidden pixel structure.

Here, we have developed a strain-sensor-in-pixel (S-SIP) system capable of recognizing the tensile of each hidden pixel and determining whether the hidden pixels are activated by integrating the strain-sensor into the TFT pixel circuits on the AM-based stretchable display backplanes. This system was implemented by introducing interconnects and stain sensors between the gate and source electrodes of a driving TFT in pixel circuits, allowing the TFT operation to be adjusted depending on the applied strain. Specifically, for the strain-sensors, additive manufacturing technology using electrohydrodynamic (EHD) jet printing is applied. Not only does this printing method have the advantages of conventional ink jet printing, such as low cost, simplicity of processing, and no material waste, but it also has the capability of producing extremely fine line widths (less than 1μm) via input voltage control. By extending these printing techniques, we have devised a method to allow the sensor-regions and interconnect-regions to be selectively deposited within the oxide TFT-based pixel circuits, which could be used as a vital element in the hidden-pixel operation mechanism for resolution-sustainable AM-based stretchable displays.

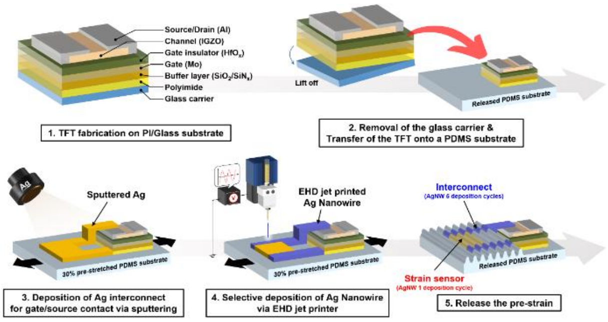

Fig. 2. Fabrication process of the strain-sensor integrated oxide TFTs.

2 Experiment

A fabrication process of the strain-sensor integrated oxide TFTs for implementing hidden pixel structures is shown schematically in **Fig. 2**. To improve the mechanical durability of the oxide TFTs and strain-sensors, we used rigid-island structures involving the transfer of oxide TFT-based flexible electronics onto a polydimethylsiloxane (PDMS) elastomer substrate. For the flexible substrates, we used a flexible polyimide (PI) substrate (20 μm) on the glass carrier deposited with a buffer layer of SiO_2 (40 nm)/SiN_x (200 nm), a bottom gate electrode of molybdenum (Mo, 60 nm), and a gate insulator of hafnium oxide (HfO_2, 150 nm). For their channel layer, a 40 nm-thick amorphous InGaZnO (a-IGZO) semiconductor was deposited on them via radio-frequency (RF) magnetron sputtering at room temperature. Sequentially, a post-annealing process was carried out at 300 °C for an hour under an air ambient. After the channel layer was formed, 200 nm-thick of Al electrodes as a source and a drain electrode were deposited by RF sputtering. Using a shadow mask, the channel length and width were defined as 150 and 1000 μm, respectively.

The fabricated IGZO TFTs on the PI/glass substrate were mechanically detached from the glass substrate and then transferred to the 100 μm thick PDMS-based stretchable substrate. The stretchable substrate was prepared by spin-coating on a glass carrier with a PDMS solution composed of a silicone gel and a cross-linker with a weight ratio of 10:1 (Sylgard 184; Dow Corning). Then, the PDMS film was thermally cured at 100 °C for 60 min, and then peeled-off from the glass carrier.

Following that, the sputtering and EHD jet printing processes are used sequentially to form an interconnect connecting the gate electrode and source electrode of the TFT, as well as a strain-sensor capable of controlling the contact resistance between them. Prior to selectively depositing the sensor-regions and interconnect-regions, Ag thin-films connecting the gate electrode and source electrode of the TFT were deposited on the 30% pre-stretched PDMS substrate by RF sputtering. Then, using an EHD jet printer, a solution of Ag-nanowires (AgNWs) dispersed in isopropyl alcohol (0.5 wt.%; Sigma-Aldrich) was printed onto the sputtered Ag film and heated on a hot plate at 60 °C for 10 min to remove any remaining solvent from the coated layer. By finely controlling this processing cycle, AgNWs were selectively deposited in 1 cycle for the sensor-regions and 5 cycles for the interconnect-regions, thereby adjusting the Ag crack density and resistance changes by mechanical stress. Finally, after the pre-stretched PDMS substrate was released, the wrinkled structures of Ag thin-films with high mechanical durability were formed on the substrate.

To measure the electrical resistance changes and transfer characteristics during stretching of the strain-sensor integrated IGZO TFTs, a custom-made equipment that combines the probe-station (model APX-8C; WIT) with a parameter analyzer (model 4200A; Keithley Instruments) and 4-axis automatic stretching stages (Sciencetown, ST1) was used.

3 Results & discussion

Various interesting research about strain-sensors based on structural or morphological change of the materials have been conducted. Among the strain-sensors, an induced crack-based piezo-resistive strain-sensor is one of the most popular sensor design technologies in stretchable electronics. In general, the mechanical properties of the materials and the induced strain on the substrate are the main factors that contribute to the crack formation. At this point, increasing the size or density of cracks increases the sensor's sensitivity to tensile stress, but at the expense of its endurance or repeatability, so it is critical to carefully control their trade-off relationship.

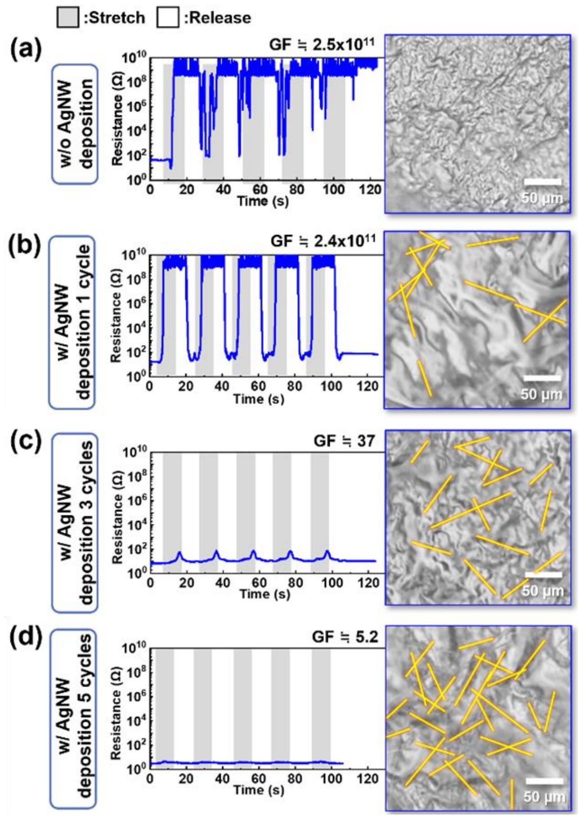

Fig. 3. Resistance measurement results for 5 tensile repetitions up to 30% strain of Ag thin-film based strain-sensors (a) without AgNW depositon, (b) with AgNW deposition 1 cycle, (c) with AgNW deposition 3 cycles, and (d) with AgNW deposition 5 cycles. The insets are optical microscope images for comparison of each thin-film's deposited AgNW density.

Sputtered Ag thin-films on stretchable elastomer substrates are well known to be fragile even at low external tensile strain, leading to entire rupture or cracking due to their intrinsically poor ductility under tensile strain. Thus, by appropriately adjusting the above-mentioned trade-off relationship for these sputtered Ag thin-films, we introduced two crack-inducing process techniques on the films to selectively form sensor-regions with high sensitivity and a large resistance change and interconnect-regions with low sensitivity and no resistance change in response to the tensile strain. The first one is to construct a wrinkled structure by performing all the metal deposition processes onto the 30% pre-stretched substrate. This helps dissipate the strain stress and reduces the occurrence of abrupt thin-film fractures. Nevertheless, as illustrated in **Fig. 3(a)**, it has poor durability against even after 5 strain loading repetitions, with an initial resistance of less than 10^2 Ω, which eventually increased up to 10^{10} Ω. All resistance change measurements are performed at both ends of the thin films (5 cm × 1 cm), and all their stretching tests are carried out at tensile strains of up to 30% and a speed of 5 mm/s.

As a second complementary method, we used the EHD jet printing process to delicately deposit AgNWs along the fine line of Ag thin-films sputtered on the 30% pre-stretched substrate. The measurement results of resistance changes and its gauge factor (GF) in the thin-films depending on the number of AgNW deposition cycles during 5 strain loading repetitions are shown in **Fig. 3(b–d)**, and the density of AgNWs can be confirmed in conjunction with the inset optical microscope images. The GF expresses the sensitivity of strain-sensors, which defined as $\Delta R/R_0$ = (GF)ε, where $\Delta R/R_0$ is the fractional resistance change in response to an applied strain, ε. As a result of the device measurement, it was confirmed that as the deposition cycle increased, the resistance changes according to the tensile decreased. Especially, in cases where the GF was approximately 2.4×10^{11} after 1 deposition cycle, the GF was significantly reduced to 5.2 after 5 deposition cycles.

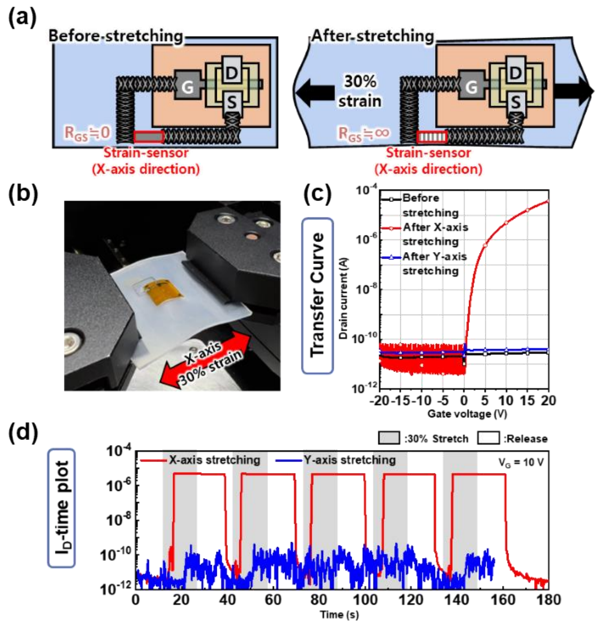

Fig. 4. (a) A schematic of the strain-sensor integrated oxide TFTs before and after X-axis direction stretching. (b) An image of the fabricated device that operates only after stretching along the X-axis. (c) Transfer characteristics of the X-axis strain-sensor integrated oxide TFTs before and after stretching. (d) Drain current measurement results of the X-axis strain-sensor integrated oxide TFTs during 5 repeated stretching tests at V_G=10 V.

As the first step to integrate the manufactured devices into the oxide TFT-based pixel-circuits, the fabricated interconnect was used to connect the gate electrode and source electrode of the TFT, and the fabricated strain-sensor was deposited in the middle of the interconnect as shown in **Fig. 4(a)**. The strain-sensor inserted between the interconnect could act as a variable resistance with a low resistance of less than 100 Ω to a high resistance of more than 10^{10} Ω depending on its stretching states. **Fig. 4(b)** is an image of the fabricated TFT that operates only after stretching along the X-axis. As shown in **Fig. 4(c)**, examining the device's transfer characteristics before and after X-axis 30% stretching confirms that only little current (less than 10^{-9} A) flows through the TFT before stretching but that it operates normally after stretching regardless of the gate voltage (V_G). This strain-sensor integrated TFT, in which strain acts as another gate, exhibited a field-effect mobility of 10.37 cm^2/Vs, an on/off current ratio of 4.45×10^9, and a subthreshold swing of 0.40 V/dec. The reason for this is that the TFT's gate and source electrodes are short-circuited due to the connected interconnects before stretching, making no voltage difference between the gate and the source electrode. After X-axis direction 30% stretching, however, the gate and source electrodes become open-circuited, allowing the TFT to operate normally, turning on when the $V_G > 0$ V. In contrast, because AgNWs were deposited five times except for the X-axis direction sensor area using EHD jet printer, the TFT does not function when stretched in the Y-axis direction. Additionally, as shown in **Fig. 4(d)**, 5 repeated stretching tests were conducted using our customized equipment, which is capable of simultaneously measuring the electrical characteristics of TFTs and substrate stretching. Consequently, when the V_G is set to 10 V, it is obvious that the TFT operates reliably only under X-axis tensile.

Thus, we could say that the direction-selective TFT-type strain-sensor was successfully manufactured with the high-sensitivity that operate normally only in the stretched state. Furthermore, the device is expected to be suitable for various stretchable electronics applications beyond stretchable displays, such as long-term standby mode healthcare monitoring systems with low power consumption that actually function only when the device is stretched.

4 Conclusions

In this research, we have proposed a strain-sensor embedded pixel circuit system, or S-SIP system, that automatically activates hidden pixels only when the display is in the stretched mode. It has been found that by converting the gate and source electrodes to a shorted-circuit or opened-circuit, depending on the stretching state, it is possible to determine whether or not the driving TFT in the hidden pixels operates. This could be accomplished by embedding both strain-variable resistance (GF≈2.4×10^{11}) and strain-invariant interconnect (GF≈5.2) based on selectively induced cracks in Ag thin-film with AgNWs via sputtering and EHD jet printing processes. Based on this, we have designed a 2T1C-based S-SIP circuit system that can provide valuable insights into developing an effective solution to prevent image blurring caused by the deformation of stretchable displays.

Acknowledgments

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