Highly Bendable TFT Arrays Withstanding Over One Million Bending Cycles

Manabu Ito, Noriaki Ikeda, Chihiro Miyazaki, Yukikazu Tanaka, Kaoru Hatta and Mamoru Ishizaki

manabu.ito@toppan.co.jp
Technical Research Institute, Toppan Inc. 4-2-3, Takanodai-Minami, Sugito, Saitama, 345-8508, Japan
Keywords: oxide TFT, bendability, bending radius, island structure

ABSTRACT

In order to realize highly bendable oxide TFT, we have developed novel organic / inorganic dielectric layer. Our IGZO TFT can withstand one million bending test at bending radius of 1mm without employing neutral plane concept. We see a big potential for the application of wearable sensors.

1 Introduction

Flexible thin film transistors (TFT) have been attracting a lot of attention due to the applicability to foldable smarphone, IoT sensors, and photodetectors [1-3]. In order to realize flexible TFT, various methods have been proposed as follows.

1) Employing soft organic materials
2) Patterning stiff inorganic layers into islands
3) Thinning total thickness of the device
4) Utilizing neutral plane concept

1) Using organic materials, including organic semiconductor layer, is one of the promising ways to realize flexible TFTs because of its softness of the organic materials [4]. However, due to its low mobility, poor stability and immature process, organic TFT has not yet mass-produced.

2) Hsu *et.al.,* demonstrated that, by patterning device materials into isolated islands, ''hard'' device islands can remain crack free [5]. In this way, inorganic hard materials can be used for flexible TFT.

3) Thinning total thickness of the device is the most common way to make flexible TFT [6]. Normally, thickness of the substrate governs the total thickness of the TFT, therefore thinning substrate thickness is widely used in flexible TFT.

4) When multilayered structure device is bent, at a given position in the cross section, there is a plane where strain does not apply, which is called neutral plane [7]. Therefore, fragile TFT layer is normally placed at the neutral plane. Utilizing neutral plane is quite powerful tool to realize highly flexible TFT. However, in neutral plane concept, entire device structure is extremely restricted.

In this article, we report highly bendable TFT using transparent amorphous oxide semiconductor (TAOS) without employing neutral plane concept. TAOS TFT is regarded as one of the most promising candidates for flexible device due to its high performance at relatively low processing temperature [8-10]. Nevertheless, conventional oxide TFT suffers from relatively poor flexibility because inorganic dielectric, such as SiO_2 or Si_3N_4 are vulnerable to bending. Therefore, hybridization of inorganic and organic dielectric have been proposed for bottom gate oxide TFT [11-13]. In this structure, very thin inorganic layer serves as a plasma resistant layer for beneath organic dielectric layer during sputtering process of TAOS. While rather thick organic dielectric layer guarantees the insulation resistance and flexibility.

However, reported results were not flexible enough to be used for wearable sensor applications [11-13]. We attribute this inadequate flexibility as the fragility of the thin inorganic dielectric.

Here, we adopt inorganic / organic bilayer dielectric, whose inorganic layer is patterned to isolate each device. Moreover, less than 10 nm - thick inorganic layer are employed to realize highly bendable IGZO TFT. We see a big potential for the application of this highly bendable TFT for wearable sensors.

2 Experiment

We employ bottom-gate top-contact etch stopper structure IGZO TFT. As a substrate material, polyimide-based liquid materials was coated onto glass carrier substrate subsequently baked. We sputtered Al-based alloy metal onto the polyimide films and patterned it as a gate electrode. Onto gate electrode, acrylic based resin was coated and baked, which serves as a first gate dielectric layer. Subsequently, SiO_2 layer with 7nm thickness was deposited by chemical vapor deposition (CVD) technique, using SiH_4, N_2O, H_2 as source gases. This SiO_2 layer works as a second gate dielectric layer. For comparison, we also prepared TFT without SiO_2 layer. Onto this SiO_2 layer, IGZO semiconductor layer with the thickness of 35 nm was sputtered using DC sputtering technique. We employ composition of In:Ga:Zn=1:1:1 target. After fabrication of IGZO layer, IGZO and SiO_2 layer was patterned one after the other using same photomask. For passivation layer, we choose acrylic based polymer, which is identical material to the first dielectric layer. After patterning passivation layer, Al-based source and drain layer was sputtered and patterned. After completion of the TFT process, flexible TFT on polyimide substrate is peeled off from the carrier glass. In this manner flexible IGZO TFT was fabricated. Cross-section schematic view of our flexible IGZO TFT is shown in Fig. 1.

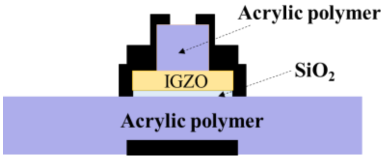

Fig. 1 Cross-section schematic view of flexible IGZO TFT

After fabrication of the flexible IGZO TFT, the device was bent for one million times under compressive stress at a curvature radius of 1 mm (R=1mm) using Yuasa system's clamshell-type enduring test machines. Bending direction is parallel to the flow of current and bending cycle is 1 cycle/second.

In order to demonstrate the application to motion sensor, 8×8 flexible TFT array was fabricated. On to this IGZO TFT array, P(VDF-TrFE) ferroelectric polymer film was laminated electrically and mechanically.

3 Results

In order to investigate the effect of thin SiO_2 layer, we evaluated the transfer characteristics of the TFT with and without SiO_2 layer. Surprisingly, TFT with thin SiO_2 layer shows reasonable characteristics of $\mu = 8.85$ cm^2/Vs, $V_{th} = 1.2$ V, and ss = 0.33 (V/decade), although TFT without SiO_2 layer exhibits poor characteristics of $\mu = 0.74$ cm^2/Vs, $V_{th} = 11.5$ V, and ss = 2.23 (V/decade).

Photograph of flexible IGZO TFT is shown in Fig. 2. As shown in Fig 2, our flexible IGZO TFT can be bent considerably.

Fig. 2 Photograph of flexible IGZO TFT

In order to quantify the bendability of the TFT, we conducted bending test by enduring test machine described in the Experiment section. Before and after bending test, we do not observe any noticeable change in the TFT characteristics.

Moreover, motion sensor, which consists of flexible TFT array and ferroelectric polymer film are attached onto the skin around the throat. In this way, muscle motion around the throat can be monitored to access the swallowing ability. Photograph of the motion sensor are shown in Fig.3 (a). The obtained results of the motion of the throat during swallowing tea is depicted in Fig.3 (b). As is clearly shown in Fig.3 (b), muscle motion of the throat is clearly detected.

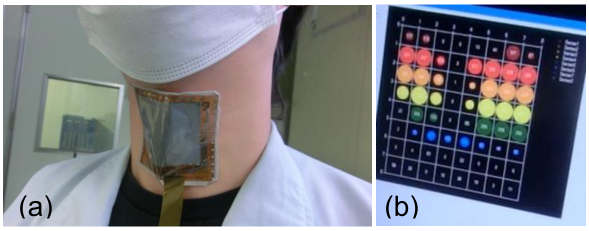

Fig. 3 (a) Motion sensor using flexible IGZO TFT array attached onto the throat, (b) Motion of the throat during swallowing tea

4 Discussion

As described in Results section, 7nm-SiO_2 layer between IGZO and acrylic polymer dielectric layer plays a critical role in realizing reasonable TFT characteristics. Without SiO_2 layer, the first dielectric layer made of polymer material degrades severely during the sputter deposition of IGZO. Polymer dielectric layer is vulnerable to the ions or radicals in the plasma, therefore good interface between semiconductor and gate dielectric layer cannot be implemented. Thin 7nm-SiO_2 interfacial layer serves as the protection layer for polymer dielectric layer against the plasma environment.

Moreover, patterning hard inorganic layer is of great importance. Without patterning 7nm-SiO_2 layer, we observe a lot of tiny cracks in the device after bending test at R=1mm. TFT with cracking does not show any modulation anymore. On the contrary, any cracks are not observed in the patterned SiO_2 TFT. This is attributed that TFT with patterned inorganic layer becomes more resilient against bending, because deformation takes place mostly in the compliant interisland region in island structure device [5].

Thickness of the inorganic dielectric layer also matters a lot. The TFT with 30nm SiO_2 layer suffers from cracking after bending at R=1mm. Even if the inorganic layers are patterned, strain concentrates at thicker inorganic layers. That leads to yield or cracking of the inorganic layers. We do not evaluate TFT with thinner than 7nm-SiO_2 layer. However we predict that even thinner SiO_2 layer leads to island growth of the films, which cannot cover the whole channel area of polymer gate insulator and results in deterioration of the TFT characteristics. Anyhow, further study should be done.

We compare our bendability result with the reported values as shown in Fig. 4. In this graph, X axis is the bending times and the Y axis is the reciprocal of bending radius (=R/1). As is clear from this graph, the TFT in this study is far more durable than the reported values. It should also be noted that the channel of our TFT is not placed at the neutral plane of the device.

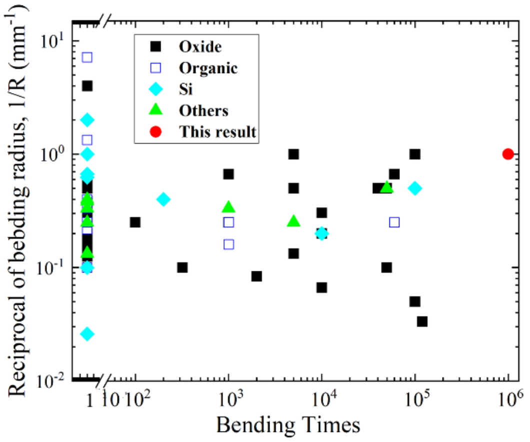

Fig. 4 Reported value of the relationship between bending times and reciprocal of bending radius

As for sensor application, we have successfully monitor the movement of the throat. In all over the world, aging of the population progresses rapidly. One of the problems for aged people are swallowing disorders, which is called dysphagia. Proper assessment of the swallowing ability is required to enhance the quality of the life. We believe that our highly bendable motion sensor would be one of the promising candidates to solve the issues of the aging society.

5 Conclusions

In order to realize highly bendable IGZO TFT array, we have developed novel organic / inorganic dielectric layer, where inorganic dielectric layer is patterned like an island shape. Our IGZO TFT can withstand one million bending test at r = 1 mm without employing neutral plane concept. As far as we know, this is the first report that can demonstrate one million times bending at r = 1 mm. We see a big potential for the application of our highly bendable TFT for wearable sensors.

References

[1] J.-S. Park, T. -W. Kim, D. Stryakhilev, J.-S. Lee, S.-G. An, Y. -S. Pyo, D. -B. Lee, Y. G. Mo, D. -U. Jin, and H. K. Chung, "Flexible full color organic light-emitting diode display on polyimide plastic substrate driven by amorphous indium gallium zinc oxide thin-film transistors", Appl. Phys. Lett. 95, 013503 (2009).

[2] A. T. Yokota, Y. Inoue, Y. Terakawa, J. Reeder, M. Kaltenbrunner, T. Ware, K. Yang, K. Mabuchi, T. Murakawag M. Sekino, W. Voitc, T. Sekitani and T. Someya, "Ultraflexible, large-area, physiological temperature sensors for multipoint measurements" Proc. Natl. Acad. Sci.112, 14533 (2015).

[3] H. Oh, G. -C. Yi, M. Yip, S. A. Dayeh, "Scalable tactile sensor arrays on flexible substrates with high spatiotemporal resolution enabling slip and grip for closed-loop robotics" Sci. Adv. 5 eabd7795 (2020).

[4] T. Sekitani, U. Zschieschang, H. Klauk and T. Someya, "Flexible organic transistors and circuits with extreme bending stability" Nature Mater. 9, 1015 (2010).

[5] P. I. Hsu, M. Huang, Z. Xi, S. Wagner, Z. Suo, and J. C. Sturm, "Spherical deformation of compliant substrates with semiconductor device islands" J. Appl. Phys. 95, 705 (2004)

[6] M. Kaltenbrunner, T. Sekitani, J. Reeder, T. Yokota, K. Kuribara, T. Tokuhara, M. Drack, R. Schwödiauer, I. Graz, S. Bauer-Gogonea, S. Bauer and T. Someya "An ultra-lightweight design for imperceptible plastic electronics" Nature 499, 458 (2013)

[7] G. Crawford (ed.), Flexible Flat Panel Displays (Wiley,West Sussex, 2005) Chapter 14

[8] K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano and H. Hosono, "Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors" Nature 432, 488 (2004).

[9] M. Ito, C. Miyazaki, M. Ishizaki, M. Kon, N. Ikeda, T. Okubo, R. Matsubara, K. Hatta, Y. Ugajin, and N. Sekine, "Application of amorphous oxide TFT to electrophoretic display" J. Non-Cryst. Solids. 354, 2777 (2008).

[10] M. Ito, M. Kon, C. Miyazaki, N. Ikeda, M. Ishizaki, R. Matsubara, Y. Ugajin, and N. Sekine, "Amorphous oxide TFT and their applications in electrophoretic displayss" phys. stat. sol.(a) 205, 1885 (2008).

[11] B. -U. Hwang, D. -I Kim, S. -W. Cho, M. -G. Yun, H. J. Kim, Y. J. Kim, H. –K. Cho, N. –E. Lee, "Role of ultrathin Al_2O_3 layer in organic/inorganic hybrid gate dielectrics for flexibility improvement of InGaZnO thin film transistors" Org. Electron, 15, 1458 (2014).

[12] Y. Kumaresan, Y. Pak, N. Lim, Y. Kim, M. -J. Park, S. -M. Yoon, H. -M. Youn, H. Lee, B. H. Lee and G. Y. Jung, "Highly Bendable In-Ga-ZnO Thin Film Transistors by Using a Thermally Stable Organic Dielectric Layer" Sci. Rep. 6, 37764 (2016).

[13] J. Y. Choi, S. Kim, B. –U. Hwang, N. –E. Lee, and S. Y. Lee, "Flexible SiInZnO thin film transistor with organic/inorganic hybrid gate dielectric processed at 150 °C" Semicond. Sci. Technol. 31, 125007 (2006).