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Highly Bendable Transparent Electrode Using Mesh Patterned Indium Tin Oxide for Flexible Electronic Devices

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***Abstract*— We developed a highly bendable transparent indium tin oxide (ITO) electrode with mesh pattern for flexible electronic devices. Mesh pattern reduces an effect of tensile stress and propagation of cracks when the electrode is bent. The proposed ITO electrode was fabricated on a polyethylene terephthalate by means of photolithography and wet etching. The bendability was investigated through cyclic bending test. Resistance increase rate of the mesh patterned ITO electrode after 1000 times bending was approximately 9.18 × 10^2 times as low as that on a plane ITO electrode. In addition, the distinct cracks were not observed on the mesh patterned ITO electrode after cyclic bending. Mesh patterned ITO electrode was applied to a liquid-based organic light-emitting diode (OLED). Even the use of the mesh patterned ITO after 100 times bending, electroluminescence emission was confirmed without obvious damages. These results indicate that the mesh patterned ITO electrode gives an impact in flexible electronic devices.**

Keywords—Indium Tin Oxide, Flexible electronic device, Flexible transparent conductive electrode, Mesh patterned electrode, Liquid-based organic light-emitting diode

I. Introduction

Flexible electronic devices, such as organic light-emitting diodes (OLEDs), touch panels and organic solar cells have attracted attentions owing to their mechanical stability and high bendability. These devices are expected to enrich people's lives. These devices require not only flexibility but also transparency in visible light range to take advantage of its feature. Recently, there has been an extensive effort to develop flexible transparent electrodes as one of the key elements for flexible electronics, for example, Ag nanowires [1,2], Al nanowire networks [3] Au nano-square mesh [4], poly-(3,4-ethylenedioxythiophene):poly(styrenesulfonic acid) (PEDOT:PSS) films [5], and carbon nanotubes [6,7]. On the other hand, indium tin oxide (ITO) is widely used as transparent conductive electrodes in the field of optoelectronics, because ITO exhibits excellent optical transparency [8], electrical conductivity [8], and appropriate work function for hole-injection [9]. Moreover, ITO is one of the metal oxide materials, hence, ITO shows high chemical and physical durability [10], and high workability [11]. However, since ITO forms cracks easily due to its rigidity, conventional ITO electrodes are not suitable for flexible device [12,13]. These cracks are considered to cause electrical failure of devices [14,15]. To prevent ITO from cracking, novel ITO-based flexible electrodes, including ITO nanowires [10], ITO nanoparticle [12], and ITO/CuS nanosheet network composite film [13] have been reported. Still, almost all of ITO-based flexible electrodes need complex structures and process so far. Consequently, simple structure and process for a highly bendable ITO have been required.

In this study, we propose a highly bendable transparent ITO electrode structuralized a simple mesh pattern. The proposed electrode was fabricated with just 2-steps process: photolithography and wet etching. Figure 1 shows the concept of a highly bendable ITO electrode with the mesh pattern. Mesh patterned ITO is fabricated on a flexible film. The mesh pattern is effective to avoid ITO from cracking by suppressing tensile stress. Furthermore, even if cracks occur, the mesh pattern stops propagation of cracks, thereby, conductivity can be maintained. In addition, liquid-based OLED using the mesh patterned ITO electrode is fabricated to investigate the feature of the mesh patterned ITO electrode in applications. Liquid organic semiconductors (LOSs) were selected as an emitter, because LOSs have high potential for flexible electronic devices [16,17].

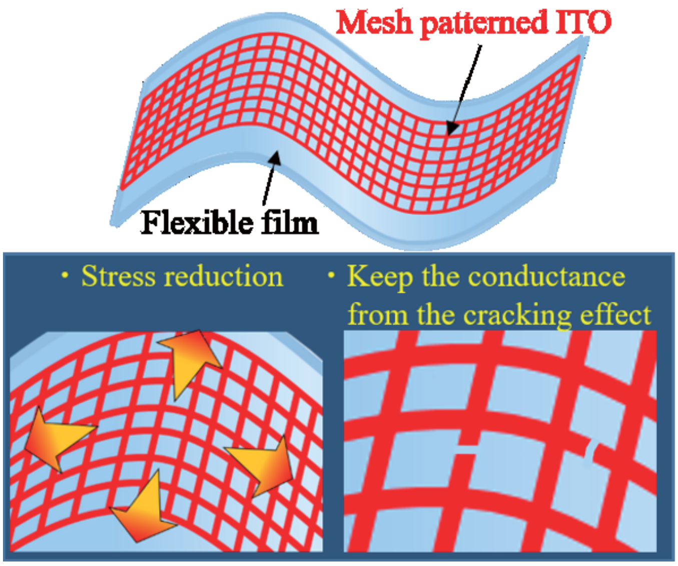

Fig. 1. Concept of a highly bendable transparent mesh patterned ITO electrode. Mesh pattern improves the flexibility of the electrode by suppressing tensile stress and stopping propagation of cracks.

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II. EXPERIMENTAL

A. Design

The design of a mesh patterned ITO electrode is shown in Figure 2. ITO with thickness of 130 nm on 125-µm-thick polyethylene terephthalate (PET) film with sheet resistance of 30 Ω sq^{-1} (Kyoei Denshi Co., Ltd.) was used. Line width and space of mesh pattern were designed to 50 µm. The size of mesh pattern was determined to be smaller than the size of one pixel in common displays [18]. The film was 30 mm in length and 40 mm in width.

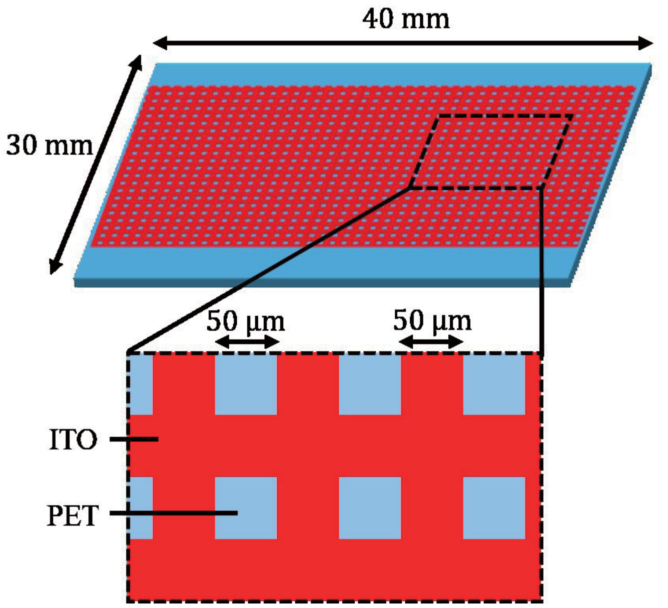

Fig. 2. Design of mesh patterned ITO on PET film. Line width and space were determined to be smaller than the size of one pixel in common displays.

B. Fabrication process

Mesh patterned ITO electrode was fabricated by a simple 2-step fabrication: photolithography and wet etching. Firstly, ITO/PET film was cleaned in Acetone, isopropyl alcohol with ultra-sonication sequentially, and deionized water to remove contaminations. A 7-µm-thick resist layer (AZ4620, MicroChem Co.) was spin-coated on the film, and then ultra violet (UV) light was irradiated on the resist for patterning the resist. ITO was etched by diluted aqua regia, which was diluted to reduce etching rate. Finally, mesh patterned resist was removed.

C. Evaluation

The bendability of the mesh patterned ITO electrode was investigated by a cyclic bending test as shown in Figure 3. Curvature radius was fixed to 6.85 mm by using a cylinder. Distance of contact probe pads were kept to 30 mm, and bending was repeated 1000 times. In addition, plane ITO electrode, was also evaluated as a reference. The change of resistance was measured using digital resistance meter (HOZAN TOOL INDUSTRIAL CO. LTD., DT-117). The surface of ITO electrodes before and after cyclic bending were evaluated by scanning electron microscope (SEM) (Hitachi High-Technologies Co., SU-8240). Moreover, a liquid-based OLED using the mesh patterned ITO electrode was fabricated to evaluate its optical-characteristics. The mesh patterned ITO electrodes before and after 100 times bending were applied as a cathode.

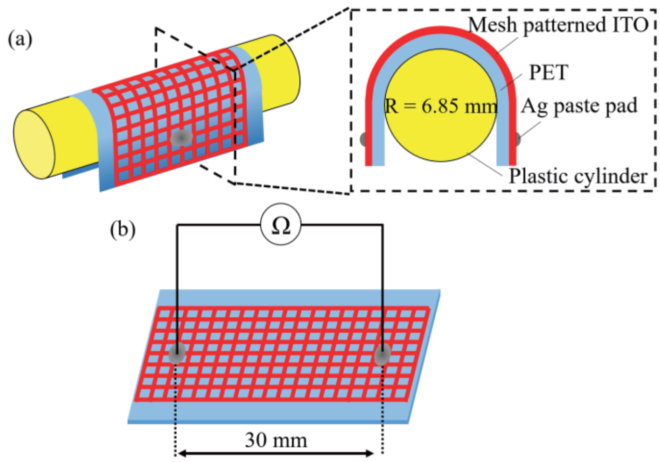

Fig. 3. Experimental setup of fabricated mesh patterned ITO electrode. (a) Cyclic bending test using plastic cylinder, with bending radius being kept at 6.85 mm and (b) evaluation of the resistance.

III. RESULTS AND DISCUSSION

Optical microscope image of the fabricated mesh patterned ITO electrode is shown in Figure 4. ITO was patterned successfully via the simple 2-step fabrication. Figure 5 shows the change of resistance versus the times of bending through the cyclic bending test, and the resistance values before and after the test were summarized in Table 1. The resistance of the plane ITO electrode is 55.7 Ω, and it increased to approximately 1700-fold after the test (9.14×10^4 Ω). On the other hand, with mesh pattern, the initial resistance (171.2 Ω) is higher than the resistance of plane ITO electrode due to its pattern. However, increasing rate of the resistance was no more than 1.8 times after the bending test (314.2 Ω). This means the resistance value of the mesh patterned ITO electrode after the 1000 times bending was 99.6 % reduced compared to the plane one. Figure 6 shows surface SEM images of the ITO electrodes: (a) initial ITO before bending, ITO (b) with and (c) without mesh pattern after bending repeated 1000 times. As shown in Figure 6(a), there are no cracks on the initial plane ITO surface. After the bending test, obvious cracks were not observed on the mesh patterned ITO electrode, while many cracks were formed on the plane ITO electrode. These results indicate that the mesh pattern increases the flexibility of ITO electrode by suppression of the tensile stress and propagation of cracks. Finally, liquid-based OLEDs using the plane or mesh patterned ITO electrode were fabricated. Figure 7 shows electroluminescence (EL) operation results of the OLEDs at 70 V. Uniform EL emissions were successfully observed from the devices, indicating that the pattern size was fine enough not to be observed the mesh pattern. In addition, the intensity of the OLEDs using the electrodes before or after 100 times bending achieved comparable level by introducing the mesh pattern. These results indicate that proposed mesh patterned ITO electrode has a high potential for other flexible electronic devices.

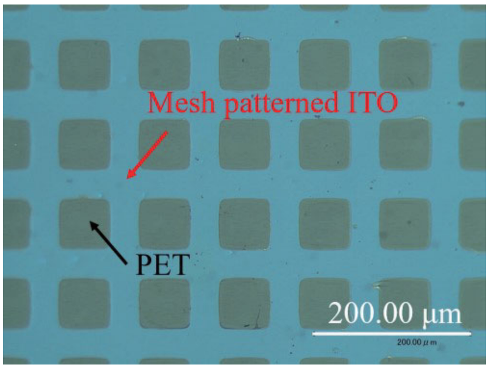

Fig. 4. Optical microscope image of fabricated mesh patterned ITO on PET film

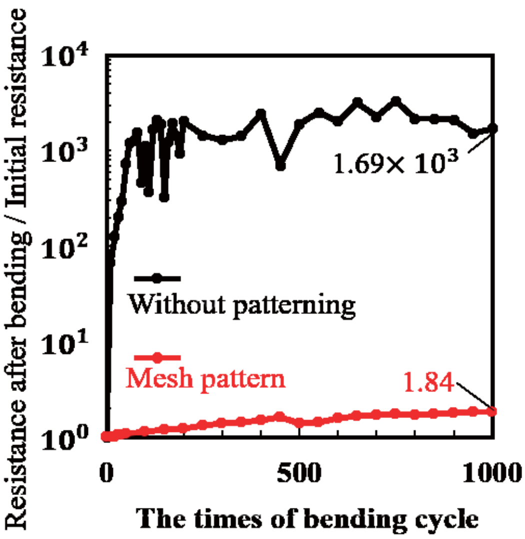

Fig. 5. The change of electrical resistance versus the times of bending cycle for ITO electrodes with mesh pattern and without the patterning.

Table 1. The electrical resistance of ITO electrodes with mesh pattern and without the patterning, before bending and after bending 1000 times.

	Before bending	After 1000 times bending
Without patterning	55.7 [Ω]	9.41×10^4 [Ω]
Mesh pattern	171.2 [Ω]	314.2 [Ω]

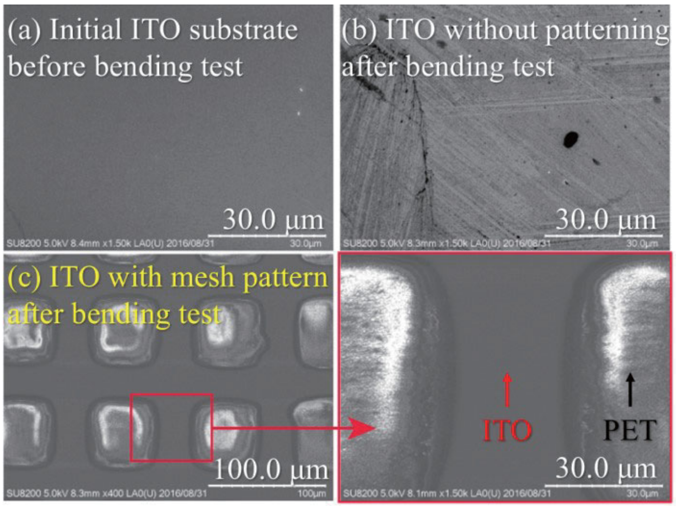

Fig. 6. SEM images of ITO electrode surface. (a) Initial ITO substrate before bending test. (b) ITO electrode without the patterning after 1000 times bending. (c) Mesh patterned ITO electrode after 1000 times bending and an enlarged picture of (c).

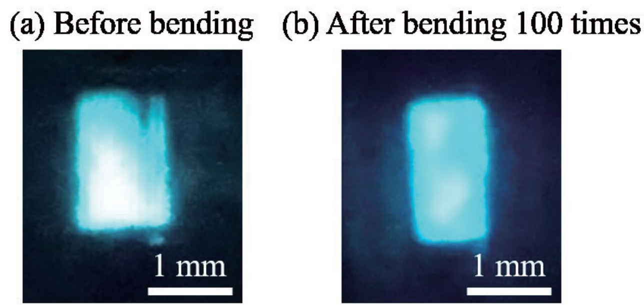

Fig. 7. Electroluminescence emission from fabricated liquid-based OLED device consists of an cathode, which uses (a) mesh patterned ITO electrode before bending or (b) mesh patterned ITO electrode after 100 times bending. Both devices were applied 70 V.

IV. CONCLUSION

We proposed highly bendable transparent ITO electrode structuralized a simple mesh pattern. Mesh patterned ITO electrode was successfully fabricated via simple 2-step processes: photolithography and wet etching. Since the obvious cracks were not formed on ITO surface, the mesh patterned ITO electrode shows an excellent flexibility compared with the plane ITO electrode through the cyclic bending test. The resistance value after 1000 times bending of the mesh patterned ITO electrode was less than 0.334 % of that of the plane ITO electrode. Moreover, the use of fine mesh patterned ITO electrode obtains uniform EL emission. The proposed mesh patterned ITO electrode is applicable for future practical flexible electronic devices.

ACKNOWLEDGMENT

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