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Effects of surface treatment of ITO anode layer patterned with shadow mask technology on characteristics of organic light-emitting diodes

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ABSTRACT

We investigated the effects of various surface treatments of indium tin oxide (ITO) on the electrical and optical characteristics of organic light-emitting diodes (OLEDs). A 150-nm-thick ITO anode layer was patterned directly with a shadow mask during the sputtering process without the use of a conventional photolithography patterning method. The sputtered ITO layer was subjected to thermal and oxygen plasma treatments to reduce the sheet resistance and improve surface roughness. The thermal treatment was performed for 1 h at temperatures of 250 and 380 °C, which were chosen so that the glass substrates would not deform from thermal damage. The measured sheet resistance decreased from 30.86 Ω/sq for the as-sputtered samples to 8.76 Ω/sq for the samples thermally treated at 380 °C for 1 h followed by oxygen plasma treatment. The root-mean-square surface roughness measured by atomic force microscopy considerably decreased to 3.88 nm with oxygen plasma treatment. The thermal treatment considerably decreased the sheet resistance of the ITO anode layer patterned with the shadow mask. The spike-like structures that are often formed and observed in shadow mask-patterned ITO anode layers were almost all removed by the oxygen plasma treatment. Therefore, a smooth surface for shadow mask-patterned ITO layers with low sheet resistance can be obtained by combining thermal and oxygen plasma treatments. A smooth surface and low sheet resistance improves the electrical and optical characteristics of OLEDs. The surface-treated ITO layer was used to fabricate and characterize green phosphorescent OLED devices. The typical characteristics of OLED devices based on surface-treated shadow mask-patterned ITO layers were compared with those fabricated on untreated and photolithography-patterned ITO layers to investigate the surface treatment effects. The OLED devices fabricated by thermal treatment at 380 °C for 1 h followed by oxygen plasma treatment for 180 s showed the highest luminance and current density. Furthermore, the leakage current that might be induced by the rough ITO surface was dramatically reduced to 0.112 mA/cm^2. Our study showed that the shadow mask-patterned ITO anode layer treated by heat and plasma and having a low sheet resistance and surface roughness yielded excellent electrical and optical properties for OLEDs compared to those based on an untreated ITO layer. The fabricated OLED devices using the surface-treated shadow mask-patterned ITO layer exhibited comparable characteristics to those obtained from a conventional photolithography-patterned ITO anode.

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1. Introduction

Organic light-emitting diodes (OLEDs) have attracted much attention for their use in flat-panel displays and solid-state lighting owing to their unique properties such as vivid full color, low power consumption, fast response time, and potential use as flexible displays [1–6]. In the solid-state lighting industry, OLED lighting can potentially lead to a paradigm shift by virtue of salient characteristics such as surface emission, transparency, and flexible lighting [7–15].

In recent decades, the typical characteristics of OLEDs have been improved considerably with regard to long lifetimes and high efficiency [16–18]. Although OLEDs have the potential to be used as next-generation solid-state lighting, they still suffer from price competition. To overcome this issue, mass production costs should be reduced by considering new process concepts. Recently, Park et al. proposed and implemented a shadow mask patterning method as an alternative to conventional photolithography patterning processes [19].

However, when ITO anode layers are patterned by the shadow mask method during the sputtering step to reduce fabrication costs, the electrical and optical characteristics of the OLEDs are inevitably degraded compared with OLEDs fabricated on ITO anode layers patterned using conventional photolithography [20]. This is primarily caused by the relatively large surface roughness, high sheet resistance, and shadow effect [21,22]. To achieve comparable electrical and optical characteristics for OLEDs fabricated by shadow mask patterning, the surface of the shadow mask-patterned ITO layer should be thoroughly examined.

In terms of OLED performance, an ITO layer patterned using a shadow mask during the sputtering step should have a smooth surface and low sheet resistance without spike-like structures as in those sputtered without a shadow mask and patterned by conventional photolithography. Although a shadow mask-patterned ITO anode layer has the advantage of low production costs, the surface condition of the ITO anode layer is not adequate for comparable performance with OLEDs fabricated by photolithography [19]. Shadow mask-patterned ITO layers have a high sheet resistance owing to the rough surface and spike-like structures [20]. In particular, the spike-like structures in shadow mask-patterned ITO anode layers give rise to high leakage currents and short-circuit problems. Therefore, the surface morphology of shadow mask-patterned ITO anode layers should be modified after the sputtering patterning step by post-treatment to obtain a low sheet resistance and smooth surface without spike-like structures. Oxygen plasma treatment is known to lower the energy barrier for hole injection from the ITO anode to the organic hole transport layer [23–30] and to modify the surface state of the ITO layer. Oxygen and chlorine plasma treatment were employed to modify the physical and chemical properties of the ITO surface to change the work function by reducing the hole injection energy barrier [23,25]. Plasma and heat treatment of ITO anode layer can improve physical properties such as the surface roughness and sheet resistance. Therefore, modifying the surface state and typical characteristics of a shadow mask-patterned ITO layer is essential for its use in high-quality OLED devices.

In this study, we investigated the effects of surface treatments of shadow mask-patterned ITO anode layers on the OLED performance. First, 150-nm-thick ITO patterns were formed on the glass substrate during the sputtering step using a shadow mask, not conventional photolithography. Thermal treatment, plasma treatment, and their combination were performed to reduce the sheet resistance, obtain smooth surfaces, and remove spike-like structures in the ITO layers patterned by the shadow mask method. To investigate the effects of the surface treatments on the electrical and optical characteristics of OLEDs, green phosphorescent OLEDs were fabricated and characterized. OLED devices were also fabricated on a photolithography-patterned ITO anode using ITO-coated glass substrates purchased from Geomatech Co., Ltd. and non-surface-treated shadow mask-patterned ITO, and their characteristics were compared to those fabricated on a surface-treated shadow mask-patterned ITO anode layer.

2. Experiments

ITO anode layers were prepared using an RF magnetron sputtering system on glass substrates (Eagle 2000). The thickness of the ITO anode layers was fixed at 150 nm to obtain high transmittance in the visible light spectrum and low sheet resistance in the as-prepared state. ITO anode patterns were formed directly using a shadow mask during the sputtering step without conventional photolithography. For ITO sputtering, an 8-in sintered disc-type target with 99.99% purity was used. For comparison, commercially available ITO-coated glass substrates purchased from Geomatech Co., Ltd. were used as a reference. The ITO layers on the reference glass substrates were patterned using a conventional photolithography system.

For patterns formed using the metal shadow mask, the gap between the shadow mask and substrates should be minimized to reduce the shadow effect [ref:fuck paper]. Otherwise, an unexpected shadow tail may occur that can cause a high leakage current and affect the electrical and optical characteristics of the OLEDs. In our case, the gap was maintained at less than 5 mm during the sputtering steps to minimize the shadow effect.

The base pressure was 5.5×10^{-7} Torr. During the sputtering step, the working pressure was maintained at 2 mTorr with an Ar flow rate of 200 sccm and 300 W of RF power. To obtain a low sheet resistance for the as-sputtered ITO layers, the temperature of the substrate was fixed at 250 °C during sputtering.

After sputtering, the sputtered ITO-coated substrates were subjected to thermal and oxygen plasma treatments. The thermal treatment was performed using a rapid thermal annealing system for 1 h at temperatures of 250 and 380 °C. The thermal treatment temperatures were chosen to be in a range that does not induce thermal damage to the ITO-coated glass substrates. The oxygen plasma treatment was performed after sputtering was completed; the shadow mask was removed for direct patterning using