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Investigation of voltage reduction in nanostructure-embedded organic light-emitting diodes

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ABSTRACT

We investigated the reduction of the operating voltage in organic light-emitting diodes containing WO_3 nanoislands. The thickness of the organic layer and the periodicity of the nanoislands were varied in order to quantitatively analyze the electrical changes. The thickness of the N,N′-bis(naphthalen-1-yl)-N,N′-bis(phenyl)-benzidine (NPB) layer was varied from 150 nm to 600 nm, and various periodic nanoislands of 300 nm, 330 nm, and 370 nm were fabricated. Two geometric factors, which are the effective length and effective area, influence the operating voltage. The effective length is determined by the relative thickness of the nanoislands compared with the organic thickness, and the reduction of the operating voltage is linearly proportional to the relative thickness. The effective area is a nonlinear function of periodicity, and the voltage is reduced as the periodicity decreases.

1. Introduction

The power efficiency of organic light-emitting diodes (OLEDs) is a crucial issue in its use in various applications and it is limited due to low out-coupling efficiency, which is approximately 20% in conventional situations [1]. The out-coupling efficiency is limited due to various light loss channels, which include the substrate mode, waveguide mode and surface plasmon (SP) mode [2]. The substrate mode is light loss that occurs due to differences in the refractive indices between glass and air; microlens arrays and textured substrates have been reported to reduce the substrate mode [3,4]. The waveguide mode is light loss trapped in the thick transparent conductive oxide (TCO) layer, which has a higher refractive index than its comprising layers. Surface plasmon is a type of charge oscillation, and the light loss in the SP mode occurs at the interface between the organic layer and the metal cathode [5]. Photonic crystals and periodic nanostructures have been suggested for the extraction of the light losses from the SP mode and waveguide mode [6–8]. While these methods significantly improve the out-coupling efficiency, their uneven structure causes changes in the electrical properties of the OLEDs [9]. A simulated result has reported that the reduction of the operating voltage in nano-patterned OLEDs arises from the partial reduction in the thickness of the organic layer, and the locally stronger electric fields introduce shorter charge transport paths, as shown in Fig. 1 [10]. However, the quantitative relationship between the geometry of the nanostructure and the change in the electrical properties remains under investigation.

In our previous study [11], we proposed Tungsten trioxide (WO_3) nanoislands with self-aggregated Ag masks in order to extract the waveguide mode and SP mode in OLEDs, and the power efficiency was improved through two mechanisms: the light extraction through Bragg scattering and the reduction of the operating voltage through the proper hole injection property of WO_3. While Bragg scattering has been proven through optical calculations of the theoretical condition in nanoislands-embedded OLEDs, the reduction mechanism of the operating voltage has not yet been clearly established.

In this study, we investigate the reduction of the operating voltage in WO_3 nanoislands-embedded devices. Various geometric nanoislands were fabricated in order to evaluate

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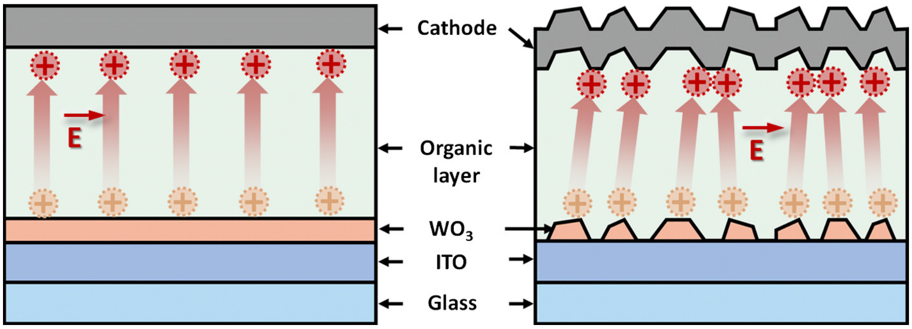

Fig. 1. Schematic cross section of devices without (left) and with (right) the WO_3 nanoislands considered in this study.

the effect of the nanoislands on operating voltages. Two factors that influence the operating voltage are examined: the effective length and the effective area. First, the effective length, which is the charge path considering the partial reduction of organic layer, is investigated through varying the thickness ratio of the nanoislands and organic layer. Second, the effective area is determined by the periodicity of nanoislands using various periodicities, relation between the operating voltage and the effective area is evaluated by various periodic nanoislands which can be tuned simply by adjusting the Ag thickness.

2. Experimental

2.1. Size-tunable WO_3 nanoislands fabrication

WO_3 nanoislands were fabricated using the same procedure as used in Ref. [9]; the substrate was glass (2.5 cm × 2.5 cm) coated with 150 nm thick indium tin oxides (ITO) and it was cleaned with isopropyl alcohol and deionized water in an ultrasonic bath. After evaporating the 30 nm thick WO_3 on the prepared ITO glass, Ag with thicknesses of 15 nm, 17 nm, and 20 nm were evaporated in order to achieve various periodicities and coverage ratios for the nanoislands. The samples were heated to 300° for 30 min in an N_2 environment in order to achieve the self-aggregated Ag mask. Then, the WO_3 film was dipped in a 1 mM potassium hydroxide (KOH) solution for 90 s at room temperature in order to selectively etch the WO_3 [12,13]. The Ag mask was removed using a nitric and sulfuric acid mixture (MA-S02; Dongwoo Fine-Chem Co. Ltd., Korea) for 90 s at room temperature.

2.2. Evaluation of WO_3 nanoislands

We calculated the power spectrum in the frequency domain in order to achieve the periodicity of nanoislands. The WO_3 nanoislands fabricated in this study did not have directionality in the spatial domain. Thus, the power spectrum as a function of the radial frequency was achieved by averaging it over the polar angles. The Image J program was used to achieve the coverage ratio of the WO_3 nanoislands. A Thermo VG Scientific X-ray photoelectron spectroscopy (Sigma Probe, USA) was used to investigate the electronic changes of the WO_3 film during the nanoislands fabrication.

2.3. Device fabrication and measurement

In order to evaluate the electrical properties of the WO_3 nanoislands, hole-only devices with an N,N'-bis(naphthalen-1-yl)-N,N'-bis(phenyl)-benzidine (NPB) hole transport layer and 100 nm aluminum (Al) metallic cathode, were fabricated via thermal evaporation. The devices were encapsulated with a UV curable resin in an N_2 environment. The thickness of the NPB layer was varied to create 150, 300, 450, and 600 nm thick layers. A Keithley 2400 sourcemeter was used to measure the voltage and current.

2.4. MATLAB calculation

A cross-sectional static-electric field in the 2-dimensional model is calculated by solving the Laplace equation. Constant permittivity in the organic layer, and no electric field in the metal electrodes are assumed for simple calculation. The electric field inside the device is achieved by calculating the gradient of the potential.

3. Results and discussion

In the previous research, we introduced WO_3 nanostructures in order to extract the waveguide mode and the surface plasmon mode to improve the out-coupling efficiency of OLEDs [5,11]. WO_3 is generally used as hole injection layer due to its good charge injection properties [12,13], and the current characteristics of WO_3 nanoislands-embedded hole-only devices were governed by the WO_3 properties [11]. However, more current flows were found in the WO_3 nanoislands-embedded devices compared with the WO_3 film-embedded devices. In this study, we fabricated various geometric hole-only devices, and experimentally investigated the factors that influence the operating voltages in the nanostructure-embedded OLEDs.

Fig. 2a shows the evolution of the XPS spectra of the WO_3 thin film after the thermal annealing and wet-etching fabrication. The 100 nm thick WO_3 film was annealed and dipped into an etchant using the same conditions for the WO_3 nanoislands fabrication in order to verify the electronic changes during the nanoislands fabrication. Fig. 2b