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Elucidations of weak microcavity effect and improved pixel contrast ratio in Si-based top-emitting organic light-emitting diode

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A B S T R A C T

Microcavity effect and pixel contrast ratio (PCR) are key issues for top-emitting organic light-emitting diode (TOLED). Si and Ag are two widely used reflective anodes for constructing effective TOLEDs. The mechanism contributing to microcavity effect and PCR has been clarified by using conventional opto-electronic theory. Consequently, the differences of microcavity effect and PCR between Si-based and Ag-based TOLEDs are discovered. Our results indicate that the Si-based TOLED possesses weak microcavity effect and improved PCR in comparison with Ag-based device. This is resulted from the low reflectivity and less reflective phase change of Si. The weak microcavity effect in Si-based TOLED also contributes to negligible variation of electroluminescent spectra with viewing angles and low device efficiency. Furthermore, Si-based TOLED shows rather high PCR which is about quintuple that of Ag-based device.

1. Introduction

Light emission from Si and Si-based devices has been attracted increasing attention for revolutionizing Si-based optoelectronics application [1,2]. In recent years, the light emission from Si-based device is predominantly focused on the combination of highly efficient organic light-emitting diode (OLED) with Si as a result of inefficient band-to-band radiative recombination in Si itself [2–4]. Many methods have been proposed to improve the performances of Si-based OLED. However, the efficiency is extremely low in Si-based OLED in the early stage [2,5,6]. Considerable improvement was demonstrated by using an ultrathin SiO_2 as buffer layer in Si-based OLED in 2004 [7]. After this, extensive studies have been investigated including inserting buffer layer of V_2O_5 [8,9] or MoO_x [4], optimizing device structures [3,8,10], and using highly efficient emitting materials [8,10,11]. It should be noted that the Si possesses low reflectivity which usually results in weak microcavity effect [3,4,8,11]. This is a shortcoming for efficiently out-coupling light from the cavity-structure device, e.g., top-emitting OLED (TOLED). Since high-reflectance bottom electrode is essentially required to obtain enhanced wide-angle and multiple-beam interferences within the cavity, the low reflectance of Si undoubtedly counteracts the improvement of device efficiency in the forward direction. On the other hand, low-reflectance bottom electrodes such as Mo [12,13], Sm [14] and Cu [15] are considered as an effective method of approaching weak microcavity effect and enhancing device pixel contrast ratio (PCR). It is well established that the weak microcavity effect and high PCR are of great importance for practical applications, because the weak microcavity effect usually corresponding to improved distribution of emission intensities at different viewing angles. While high PCR is ideal for outdoor displays under high illuminance. Consequently, Si-based OLED is a potential candidate for meeting such a requirement in practical applications.

Taking into account that Ag is the most-widely used anode in TOLED, in this study, we mainly focused on the elucidation of weak microcavity effect and improved PCR in TOLED having Si anode in comparison with the counterpart having Ag anode by using conventional optoelectronic theory. Although various methods were reported in analyzing emission characteristics resulted from microcavity effect [16,17], here we propose an intuitionistic and simple method to distinguish the differences of microcavity effect and PCR between TOLEDs with Si anode and Ag anode.

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2. Experimental details

The TOLED was grown on the substrate of p-type Si wafer. The wafer is (100) oriented and has an electrical resistivity of about 10 Ω cm. An Al ohmic contact was formed in the backside. After routine chemical cleaning, the device was fabricated on the front side of Si in a multi-source organic deposition system with a base pressure of around 1×10^{-4} Pa. Before depositing the hole-transport layer of NPB (50 nm), an ultrathin buffer layer of MoO_x (3 nm) was deposited for tuning the hole-injection characteristics [4]. Then the emitting system (25 nm) composed of 9,9′,10,10′-tetraphenyl-2,2′-bianthracene (TPBA) doped with 2 wt% 9,10-bis(*m*-tolylphenylamino)anthracene (TPA) was deposited [3]. After this, 20-nm-thick 4,7-diphenyl-1,10-phenanthroline (BPhen) and 10-nm-thick tris(8-hydroquinoline)aluminum (Alq_3) were thermally evaporated and served as hole-blocking layer and electron-transport layer, respectively. Conventional LiF (0.3 nm)/Al (3 nm)/Ag (18 nm) trilayer semitransparent cathode was deposited and patterned by a shadow mask to define the emitting area [18]. The thickness of each function layer was roughly optimized in terms of maximizing luminous efficiency. Another TOLED having the same layer structures except that the anode is replaced by 80-nm-thick Ag coated onto Si was also fabricated for comparison. We refer to the TOLED with Si as substrate and anode (or Si as *substrate* and the coated Ag as anode) as Si-based (or Ag-based) device. The light was collected from the semitransparent cathode. The general structures of these devices were shown in Fig. 1. The typical deposition rate for organic materials was ∼1 Å/s. The detailed measurements were carried out as described in our previous works [4].

3. Results and discussion

3.1. Theory calculation

In a TOLED with microcavity structure, the output electroluminescence (EL) spectrum is greatly depended on the trade-off between wide-angle and multiple-beam interferences which predominantly determined by the reflectivities and reflective phase changes of the two mirror electrodes. The resonance wavelength (λ) in the normal direction (the incident angle $\theta = 0°$) satisfies [18]:

$$\frac{4\pi}{\lambda}\sum n_m d_m + \sum \Phi_i = q\cdot 2\pi \quad (q:\text{integer}), \tag{1}$$

where q is the mode number, Φ is the phase shift at the mirror electrode, n_m and d_m are the respective refractive index and physical thickness of the m-th layer sandwiched between the two electrodes.

When the light deviates from the normal direction, i.e., the incident angle $\theta \neq 0°$, Φ shows different values for S and P polarization, which can be calculated with Eqs. (2) and (3), as follows [19]:

$$\Phi_S = \arctan\frac{2vn_0\cos\theta}{u^2+v^2-n_0^2\cos^2\theta} \quad \text{(S polarization)} \tag{2}$$

$$\Phi_P = \arctan\left[2n_0n^2\cos\theta\frac{2ku-(1-k^2)v}{n^4(1+k^2)^2\cos^2\theta-n_0^2(u^2+v^2)}\right] \quad \text{(P polarization)} \tag{3}$$

The above phase change on reflection originates from the reflectivity of the mirror electrode, showing different tracks under consideration of the polarization state. The corresponding reflectivity can be expressed by [19]:

$$R_S = \left(|r_s|e^{j\Phi_s}\right)^2 = \frac{(n_0\cos\theta-u)^2+v^2}{(n_0\cos\theta+u)^2+v^2} \quad \text{(S polarization)} \tag{4}$$

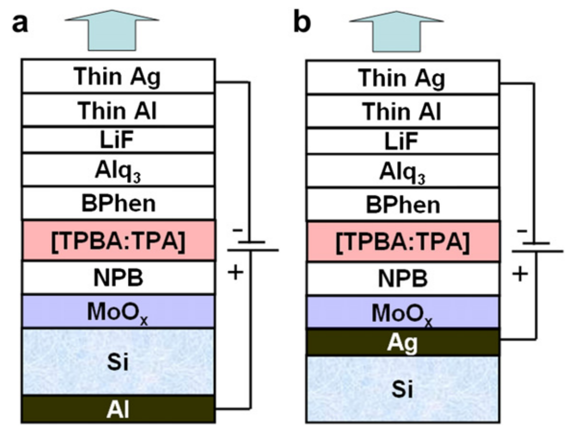

Fig. 1. Schematic structures of (a) Si-based and (b) Ag-based devices.

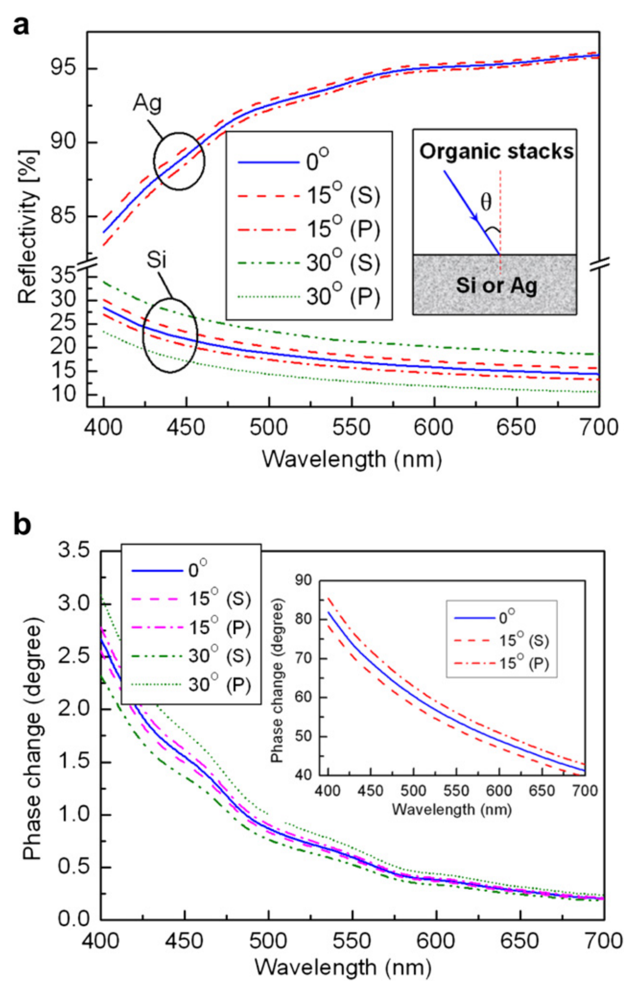

Fig. 2. (a) Calculated reflectivities of Si and Ag under different incident angles (θ) shown in the inset. (b) Calculated phase changes of Si and Ag (inset) under different incident angles. The S and P polarizations under different angles show some differences.