Organic Electronics 15 (2014) 3137–3143

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Improved performance and low cost OLED microdisplay with titanium nitride anode

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ARTICLE INFO

Article history:
Received 14 January 2014
Received in revised form 30 July 2014
Accepted 5 September 2014
Available online 18 September 2014

Keywords:
Top-Emitting Organic Light-Emitting Diode (TEOLED)
Microdisplay
Titanium nitride (TiN)
Anode
Complementary Metal–Oxide–Semiconductor (CMOS)
Low cost

ABSTRACT

This work experimented on the TEOLED (Top-emitting Organic Light-Emitting Diode) using the TiN (titanium nitride) as the anode for the microdisplays based on the CMOS (Complementary Metal–Oxide–Semiconductor) integrated circuit substrate. TiN is a hard, dense, and refractory material with steady physical and chemical characteristics. It is proved in this work to be a good candidate for the anode of the TEOLED due to its good electrical and optical characteristics. A SXGA resolution OLED microdisplay is designed and developed with TiN anodes. The luminance reaches beyond 2700 cd/m^2 when the operating voltage is below 5 V. The power efficiency reaches 13 lm/W at the luminance of 1000 cd/m^2. As a conclusion, TiN can be used to solve the incompatibility problem between the CMOS process and the OLED process. By fabricating the top metal coated with TiN as the TEOLED anodes in the standard CMOS process, it is not necessary to build a new separate post-process line for the anodes in the mass manufacture. Hence, the process step for the CMOS-based OLED microdisplay will be simplified, huge cost will be saved and the production yield will also be improved.

1. Introduction

The OLED (Organic Light-Emitting Diode) is challenging the LC (Liquid Crystal) to be an alternative flat-panel display technology because of its self-emitting property, solid-state nature, wider viewing angle, faster switching speed and easier manufacturing process [1]. Among the OLED products, the OLED microdisplay [2] has attracted intensive attentions due to its potential applications in military and commercial products such as the wearable electronic devices [3,4]. It solves the contradiction between the large view size demand and the small physical device size [5]. Most OLED displays use the amorphous silicon or the polycrystalline silicon as their substrates. However, the larger feature size of the amorphous silicon TFTs (Thin Film Transistor) does not match the tiny pixel pitch of the microdisplays (usually less than 15 µm). For polycrystalline silicon substrate OLEDs, although the TFT feature size is not a vital problem, the display resolution is still limited and the cost is extremely high [6]. As an alternative solution, the OLED based on the single crystalline silicon with CMOS (Complementary Metal–Oxide–Semiconductor) circuits is found to be advantageous for the microdisplay in terms of the size, power, frequency, circuit diversity and cost [7,8].

Since the single crystalline silicon substrate is opaque, people begin to use the TEOLED (top-emitting OLED)

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http://dx.doi.org/10.1016/j.orgel.2014.09.001
1566-1199/© 2014 Published by Elsevier B.V.

structure rather than the traditional BEOLED (bottom-emitting OLED) structure [9]. To obtain a high performance for TEOLEDs, the materials of the anodes has to be chosen elaborately. They usually conform to such criteria: high work function, low electrical resistivity, high reflectivity and good chemical stability. There were many previous works on the anode for TEOLEDs. Ag [10] was considered as one of the most promising TEOLED anode materials due to its high reflectivity of 94% at the wavelength 520 nm and its low electrical resistivity of 1.47 $\mu\Omega$ cm at the temperature 298 K. Ag/ITO [11] composite bi-layer structure shows combining advantages on both of the high reflectivity of Ag and the high work function of ITO. Other groups have investigated on the materials such as Al/ITO, [12], Ag/Al [13], Au [14], Pt [15], V [16] and Mo [17] as the anodes of TEOLEDs. Unfortunately, in spite of their good electrical and optical characteristics, none of the materials mentioned above is supported by the current standard CMOS foundry. To be used as the anodes of the CMOS-based OLED microdisplays, those materials have to be fabricated under certain special post-process other than the CMOS process. Since the pixel pitch is very small for microdisplays, the investments for the anode post-process are considerable, including the equipment, workshop, mask, software, labor, etc. Furthermore, when the silicon wafers are transferred from the CMOS foundry to the post-process line, it tends to incur the anode surface defects due to the physical or chemical instability of these materials, resulting in the low yield and extra cost. So the question is whether there exist some materials that are both compatible with the technologies of CMOS and OLED?

In the CMOS engineering, TiN (titanium nitride) [18] is one of the most commonly used barrier materials. It is a hard, dense, and refractory material with an extremely high melting point ($\sim$2900 °C) and the high electrical conductivity ($\rho = \sim 22\ \mu\Omega$ cm). It is also used in bio-electrode applications due to its chemical stability and CMOS compatibility [19]. Meanwhile, the technology for TiN depositing and structuring has been well-established for mass productions in the CMOS industry for many years [20]. So it can be inferred that TiN is a potential candidate to solve the anode incompatible problem for the CMOS-based OLED devices. In late 1990s', Thompson's group [21] experimented on the thin conductive semi-transparent TiN film applied as the anode for BEOLEDs. The anode was made by the chemical vapor deposition process, achieving a high quantum efficiency which even surpassed that of the OLEDs with the ITO anodes in certain situations. Recently, Ventsch et al. [22] demonstrated the properties of the TEOLED fabricated with TiN anodes on the CMOS dummy substrate. The luminance reached 1000 cd/m^2 at the voltage of 7 V for all colors. In this paper, we report the TEOLED using TiN as the anode based on the single crystalline silicon substrate with CMOS ICs (Integrated Circuit). The SXGA resolution (1280 $\times$ 1024) mono-color AMOLED (Active Matrix OLED) microdisplay is designed with the mini pixel pitch of 5 μm $\times$ 15 μm. The EL (electroluminescent) characteristics are improved compared with previous works while fewer anode process steps are required.

2. Experimental

The substrate for the test OLED microdisplay is a well-designed CMOS IC. It integrates a 1280 $\times$ 3 $\times$ 1024 display pixel array, control circuits and two test pixel arrays. Each pixel contains a seven-transistor voltage PWM (Pulse Width Modulation) driving circuit. The IC was taped out under the SMIC (Semiconductor Manufacturing International Corporation, China) 0.35 μm, 3.3–6 V dual voltage, 1P4 M (with the custom top metal) CMOS process.

For the test purpose, the wafers were diced into micro-display pieces before fabricating OLEDs. For mass productions, the wafers could be processed in the OLED process flow before dicing. The OLED microdisplays were made by evaporating the small molecular OLED layers and electrodes on the surface of the silicon substrate in the high vacuum (base pressure 10^{-5} pa), and then encapsulated in the N_2 atmosphere (H_2O, O_2 < 1 ppm). The constituent organic layers for the OLED were deposited next to the anode by the thermal vacuum evaporation with the commercial grade HIL:HILD, HTL, GH:GD and ETL powder sources. The deposition rates of the organic thin films were 0.2–2.0 Å/s. The cathode was implemented with the composite layer of 10 Å LiF (lithium fluoride) topped with 250 nm Al. The deposition rates of LiF and Al were 0.3 Å/s and 3 Å/s, respectively.

The thickness of the films was determined *in situ* by the crystal monitor. The optic-electrical characteristics of the microdisplays were measured by the Keithley 2400 and 6485 source/measure units. The surface morphologies of the gate dielectrics were characterized by the tapping mode AFM (Atomic Force Microscopy) and the Olympus BX51 M model optical microscope equipped with a CCD camera.

3. Results and discussion

The structure of the TiN anode TEOLED microdisplay is shown in Fig. 1. The OLED is fabricated on a silicon wafer substrate which integrates CMOS circuits and a customized top metal layer. The patterned top metals are used for pixel anodes. They are connected with the CMOS circuits through the metal vias and metal layer. The top metal is a five-layer sandwich structure – Ti/TiN/Al/Ti/TiN from bottom, which is fully compatible with typical CMOS process. The bottom Ti liner layer helps the metal Al adhere to the insulator layer. The bottom TiN layer is a barrier to prevent Al from diffusing into the insulator layer and also reduce the roughness of Al layer. The upper Ti layer is not necessary but can reduce the sheet resistance of the top metal. The upper TiN is also a barrier in the typical CMOS process, but it is customized in this work for OLED anodes. The transparent cathode is covered on the organic material layers. The thin film encapsulation layers protect organic materials against moistures and atmospheres.

The surface morphology of the anode has a great impact on the performance of the OLED, for example, the electrical characteristics and the lifetime [23]. The harsh topographic feature or any protrude metal spikes on the anode surface may induce pin-holes in the adjacent organic material