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Fabrication of bottom-emitting organic light-emitting diode panels interconnected with encapsulation substrate by Au—Au flip-chip bonding and capillary-driven filling process

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ABSTRACT

We present fabrication and testing of bottom-emitting organic light-emitting diode (OLED) panels based on flip-chip assembly and non-destructive scanning. In this method, the OLED and electric circuits are fabricated on separate substrates and interconnected by low temperature assembly to create a high-performance bottom-emitting OLED including other functions such as thin-film transistor (TFT) circuits. The low temperature assembly process consists of two steps. First, an OLED substrate and encapsulation glass with circuits are bonded at 100 °C via Au—Au bond. Encapsulation glass is utilized for the functional substrate with circuits. Next, the bonded panel is sealed by capillary underfill within and by applying and curing seal materials to the panel edge. The fabricated OLED was non-destructively evaluated by scanning acoustic microscopy (SAM). The SAM image shows all φ500 μm Au bumps were bonded to Au pads, indicating that OLED and encapsulation substrates were assembled. Electroluminescence of the OLED was demonstrated by applying voltage. Stable current-luminance characteristics were obtained for the fabricated OLED with an operating voltage of 3.25 V. The results indicate that the proposed fabrication is available for bottom-emitting OLED controlled by TFT circuits. In future, the assembly process can be widely applied to other flexible organic electronic devices with roll assembly by altering OLED or circuits with other devices because this is a simple pressure method with low temperature, achieving encapsulation at same time.

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1. Introduction

Recently, organic light-emitting diodes (OLEDs) have become widely used in lighting and displays because they are thin, lightweight, and flexible, and offer a wide viewing angle and low power consumption [1]. Among display applications, active-matrix OLEDs (AMOLEDs) have attracted attention for use in next-generation flat panel displays [2]. In AMOLEDs, the drive current to each light-emitting pixel is controlled by a thin-film transistor (TFT) circuit. In addition to the advantages of OLEDs, AMOLED displays hold great promise for flat panel displays requiring a large area, high resolution, fast response, and long lifetime.

There are two main conventional methods of AMOLED fabrication. One is bottom-emitting OLEDs, and the other is top-emitting OLEDs [3–4]. In both types, the fabricated AMOLED display is hermetically sealed and filled by vacuum laminating it to encapsulation glass, because OLEDs are extremely sensitive to moisture and oxygen [5]. Although high-efficiency panels are required for commercialization, the complex structure of AMOLEDs impacts OLED performance and the light-extraction efficiency of the panel. In bottom-emitting OLEDs, external luminance efficiency inevitably decreases due to the low aperture ratio. In top-emitting OLEDs, ITO sputtering for the top cathode substantially damages the organic layers, and highly transparent fill materials are required between the OLED and encapsulation glass. There are also circuit and wiring limitations for the TFT circuits, because the OLED and TFT arrays are fabricated on the same substrate. Many previous studies aimed at overcoming these challenges have been reported on topics such as stringent pixel structures for a higher aperture ratio in bottom-emitting OLED [6], special deposition technologies for the transparent cathode in top-emitting OLEDs [7], and inverted OLEDs for easy connection to the TFT [8]. Although such conventional approaches based on element technology have gradually improved device performance, these improvements were not radical solutions regarding the complex structure of AMOLEDs.

To overcome such complex structures, efficient use of encapsulation glass is one of the solutions because it contributes to larger device areas and more simple structures. This requires OLED substrate and functional

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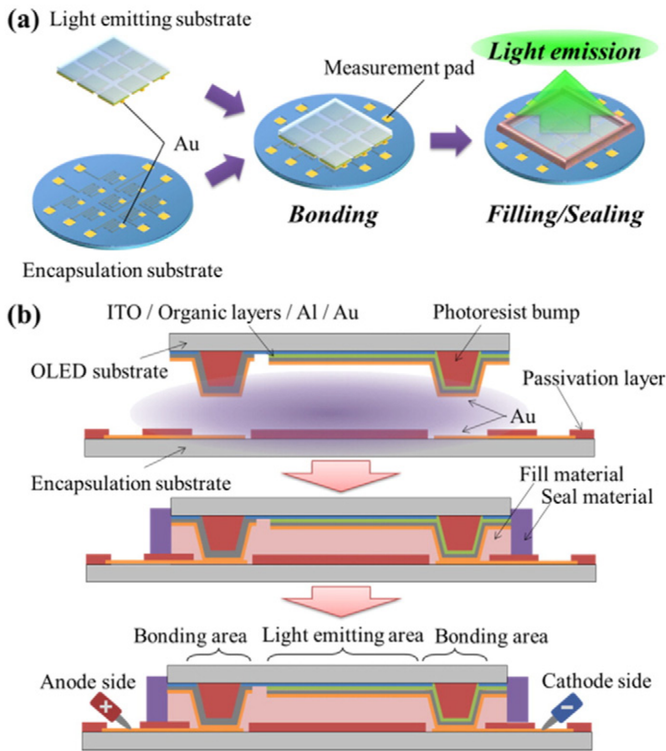

Fig. 1. (a) Concept of OLED panel fabricated by flip-chip assembling of bottom-emitting OLED substrate and functional encapsulation substrate (b) Assembly procedure: Au surfaces on OLED substrate and encapsulation substrate were cleaned by O_2 plasma. After cleaning, substrates were assembled by Au—Au flip-chip bonding and capillary-driven filling process. Fabricated panel was evaluated by applying voltage from external pads.

encapsulation substrate are electrically interconnected. Flip-chip assembly, recently reported as an integrated technology for high-density devices, is effective for direct electrical connection between two substrates [9]. By integrating bottom-emitting OLED and TFT circuits on separate substrate into a single AMOLED panel with a flip-chip assembly, sufficiently large area of OLED and circuits areas can be obtained with a simple structure. Encapsulation glass is utilized, as are other substrates including TFTs.

In this paper, we propose a novel fabrication method for bottom-emitting OLED panels based on flip-chip assembly for high-performance OLED devices. In the proposed method, the top cathode of the bottom-emitting OLED is interconnected with a circuit on encapsulation glass by Au—Au bonding and capillary-driven filling. A low-temperature process is desirable for high efficiency, considering that organic materials are thermally unstable because of their lower glass-transition temperature (T_g) [10]. For this reason, we selected Au—Au bonding, which is known as an effective method for low-temperature bonding by plasma or vacuum ultraviolet surface treatment, or by using a joint layer of porous Au alloys [11–13]. Furthermore, we selected non-cured fill materials to reduce the heat effects of curing. We also report an evaluation method for the flip-chip assembly process, involving non-destructive observation of interfacial areas by scanning acoustic microscopy (SAM).

2. Fabrication

Fig. 1(a) shows a schematic illustration of the proposed OLED panel. In the panel, a 50 mm square OLED substrate and a 4 in. glass wafer encapsulation substrate were fabricated on separate substrates and assembled. For the bonding area, six rows and eight columns of bumps were placed with a bump diameter of 0.5 mm and a pitch of 3 mm. Voltage was applied to the OLED from external evaluation pads via bumps connected to the ITO anode. One bump and one pad at each pixel connected the two substrates.

As shown in Fig. 1(b), the proposed OLED panel was fabricated by a panel-assembly process after the OLED and circuits were fabricated on separate substrates. In the OLED substrate, an OLED based on a novel emitter of thermally activated delayed fluorescence (TADF) was fabricated on ITO/glass [14]. After etching ITO around the bump area, positive photoresist bumps (CP1010-120, ZEON Corporation) were patterned by photolithography. For the OLED structure, 10 nm-thick dipyrazino [2,3-f:20,30-h]quinoxaline-2,3,6,7,10,11-hexacarbonitrile (HAT-CN)/30 nm-thick 9,9′,9″-triphenyl-9H,9′H,9″H-3,3′:6′,3″-tercarbazole (Tris-PCz)/30 nm-thick 15 wt% (4s,6s)-2,4,5,6-tetra(9H-carbazol-9-yl)isophthalonitrile (4CzIPN)-doped 3,3-di(9H-carbazol-9-yl)biphenyl (mCBP)/10 nm-thick 2,4,6-tris(biphenyl-3-yl)-1,3,5-triazine (T2T)/40 nm-thick 2,7-bis(2,20-bipyridine-5-yl)triphenylene (Bpy-TP2)/0.5 nm-thick LiF/80 nm-thick Al/200 nm-thick Au were sequentially deposited. In the encapsulation substrate, Cr/Au wiring was evaporated and patterned on the glass substrate. After patterning, metal wiring was fully covered by a passivation layer without the pad area for bonding or evaluation. For the passivation layer, a positive photoresist (CP1010-14, ZEON Corporation) with height of less than 1 μm was used. The Au film thickness was 100 nm. The separately fabricated substrates were assembled by Au—Au bonding and capillary-driven filling. In the Au—Au bonding process, both substrates were treated with O_2 plasma (PL-8, SUSS MicroTec AG) at 100 W for 1 min to remove ambient contamination such as carbon from the Au surfaces. After alignment and fixing, the OLED and encapsulation substrates were bonded via the Au—Au bonding area under the following conditions: 20 MPa pressure, 100 °C temperature, 5×10^{-3} Pa chamber pressure, and 20 min bonding time (SB6e, SUSS MicroTec AG). In the filling and sealing process, UV-curable seal material (WB90US(P), MORESCO Co.) and non-reactive liquid fill material (XF-1000, MORESCO Co.) strongly affixed the bonded OLED panel and protected it from exposure to the ambient atmosphere by the following steps. First, to physically support the bonding strength, some edge spaces of the bonded panel were adhered by applying and curing seal material before removing the fixture. Next, fill material was dropped onto the non-sealed area and filled into gaps between the two substrates by capillary action. It took a few hours to fill all the gaps. Finally, the OLED panel was packaged by again covering the non-sealed area with seal material. Fabricated OLED panels were operated by applying voltage from external pads.

We investigated the contact angle and roughness of Au surfaces before surface treatment and Au—Au bonding to investigate the effects of plasma pretreatment and Au surface conditioning. Contact angles were measured using an LCD treatment analyzer (LCD-400S, Kyowa Interface Science Co.) 1 s after a 2 μL droplet was dropped on the Au surface. Surface roughness was measured in a 2 μm square in the scan area using a scanning probe microscopy (SPM-9600, Shimadzu Corp.). To investigate the interface between the assembled substrates, we used a scanning acoustic microscopy (SAM 300, PVA TePla AG) to observe a test

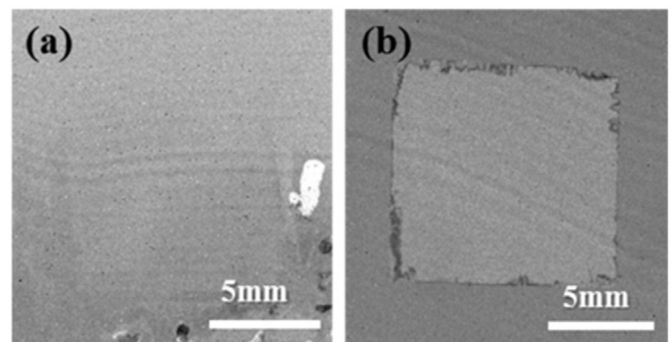

Fig. 2. SAM image of bonding interface of (a) test device bonded at RT and (b) test device successfully bonded at higher bonding temperature.

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