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A method for undercut formation of integrated shadow mask used in passive matrix displays

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Abstract

This paper reports a method for making integrated shadow masks used in fabrication of passive matrix organic light emitting diode (OLED) displays. Common positive and negative photoresist were employed to produce retrograded strip pillars with large overhang and undercut by a special photolithography procedure. The pillar strips serve as an effective shadow mask for patterning the organic layers and the metal cathodes in passive OLED display devices. Such an integrated shadow mask is viable for large deposition angle up to 70°. The method is also expected to be usable for fabricating more complicated structures for other applications.

Keywords: Photolithography; Integrated shadow mask

1. Introduction

Organic light emitting diodes (OLEDs) are electroluminescent (EL) devices that emit light generated by radiative recombination of injected electrons and holes within one or more layers of organic EL materials. Compared with the other technologies used for flat panel display (FPD), OLED display offers some unique device advantages, such as low-power consumption, wide viewing angle, good contrast, video rate operation, low-voltage operation, and lightweight. OLED display devices are also thermally stable with adequate operating lifetime.

An FPD panel consists of an array of picture elements, or pixels, on a substrate, which is typically arranged into a matrix of rows and columns. In passive-matrix OLED displays, the individual pixels are defined by the overlap of indium tin oxide (ITO) column strips (anodes) and metal row strips (cathodes). To illuminate a particular pixel, a sufficient positive voltage is applied between the column and the row lines crossing at that particular pixel. The anode strips can be easily formed by using conventional photolithography and wet etching processes before the organic layers are deposited. However, the cathode cannot be patterned in the same way because the developer and the etching solutions would cause damage to the underlying organic compounds. Because of this, a separate shadow mask is normally used to form the cathode patterns during the vacuum evaporation of the cathode metal [1]. This method is simple but difficult to achieve fine-definition patterns with line spacing of 100 μm or less because of the limitations in the precision achievable in making the masks and the strength of the mask materials. In addition, the alignment of the separate shadow mask with substrate in a vacuum system is always difficult. It is not possible to achieve a high quality cathode with sharp edges because of the gap existing between the mask and the substrate.

To overcome these problems, various integrated shadow mask approaches have been proposed [2–6]. Such an integrated shadow mask usually consists of a series of pillars with retrograde wall profile that are fabricated on the substrate and will remain as part of the final device. The pillars serve as the separators by which the organic layers and cathode are automatically patterned. An insulating base layer is required to prevent shorting between the cathode and anode layers in the regions where the organic layers are absent (or very thin) as a consequence of more scattering property of metal. The typical structure of such integrated shadow mask pillars is shown in

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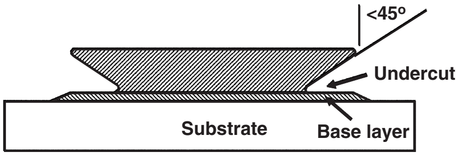

Fig. 1. Schematic pillar profile made by conventional process in an integrated shadow mask.

Fig. 1. The retrograde angle of the pillar must be large enough to ensure that the sidewalls of the pillars will not be coated with the cathode metal thus preventing the adjacent rows from electrically shortening. For this reason, off-axis deposition of metal should be avoided with might and main. It was reported that such resist-pillars with sloped edges could be formed using a multi-layer photoresist system [2].

To allow large angle deposition, pillars with large undercut and longer overhang are desired in the integrated shadow mask. Weaver et al. [3] disclosed a single layer integrated mask with clear features of undercut and overhang by using special photoresist materials (such as NR7-6000-PY). The mask has a large aspect ratio of 1.5, defined as the ratio of depth to height of the undercut. However, the process appears to be difficult to control and the special photoresist used is expensive. Alternatively, multilayer systems with large overhang and undercut were developed by using vapor deposition and chemical etching process [4–6]. The materials used include SiO_2, SiO_x, TiO_2, SiN_x, Si_3N_4 and polyimide. To work with these materials sophisticated physical or chemical vapor deposition processes are required, resulting in high fabrication cost. In addition, the acidic solution in chemical etching process used for the undercut formation may also attack the transparent anode layer, which is normally ITO.

In this paper we report a new method for the fabrication of integrated shadow mask by conventional photolithographic process using common photoresist materials. We demonstrate that large undercut and overhang can be obtained by the simple and cheap process. The mechanism of undercut formation is also discussed.

2. Experimental procedures

The substrates were 4-inch silicon wafers with 300 nm thick thermal oxide. Commercially available positive and negative photoresist were used to produce strip pillars with large overhang and undercut on the dummy silicon wafers. The fabrication process developed is schematically illustrated in Fig. 2.

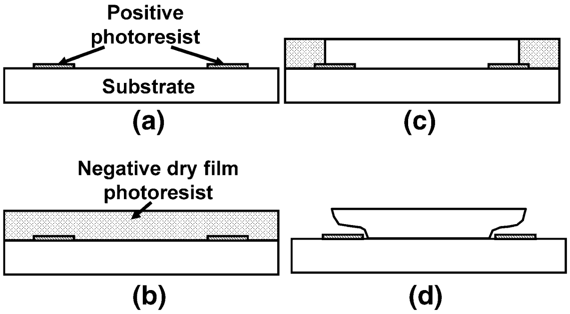

Fig. 2. Schematic illustration of fabricating integrated shadow mask with steps of (a) formation of positive photoresist lines, (b) lamination of negative photoresist (dry film), (c) UV exposure of negative photoresist layer, and (d) developing the negative photoresist to form the pillar with undercut and overhang.

A positive photoresist (AZ2100-40, manufactured by Clariant GmbH) was spin coated onto a wafer substrate at 1500 rpm for 40 s. The photoresist was baked at 373 K for 150 s on hot plate and then exposed to a 12.5 mW/cm^2 broad band ultra-violet (UV) radiation for 10 s through a photo-mask, such that only the portions of photoresist that were to be removed after developing were exposed. The desired strips, as shown in Fig. 2a are obtained after developing the photoresist in a developer ($AZ^{®}$400K, manufactured by Clariant Corporation) at room temperature for about 30 s. The resultant positive photoresist lines have a thickness of about 2 μm and are referred to as undercut controller. The wafer substrate with the positive photoresist lines was then coated with a 25 μm thick negative dry film photoresist (HP-3410, manufactured by Eternal Chemical Co. Ltd.), as shown in Fig. 2b, by a hot lamination process at a temperature of 383 K and a film feeding speed of 1.5 cm/s. The dry film photoresist layer was exposed to a 12.5 mW/cm^2 broad band UV radiation for 25 s through a photo-mask, such that only the portions of photoresist that were to be remained after developing were exposed, as shown in Fig. 2c. The dry film photoresist layer was patterned into the desired pillar, as shown in Fig. 2d, after developing in an aqueous solution containing 1% sodium carbonate at room temperature for about 120 s, followed by rinsing and drying. A further flood UV exposed under the same conditions as the first UV exposure for at least 5 min can be applied for further strengthening.

In order to investigate the mechanism of the pillar formation, silicon wafer samples with only dry film photoresist layer were also prepared using the similar procedure as above mentioned. The cross-section profile of the pillars was observed under an optical microscope after hand broken the wafer samples with a glass cutter.

3. Results and discussion

A typical microscopic view of the as fractured cross-section of a pillar strip made by the method described above is shown in Fig. 3. Large undercut and long overhang with an aspect

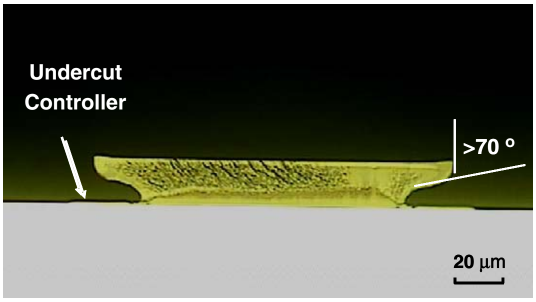

Fig. 3. Micrographic image of pillar cross-section with large undercut and overhang made by the new fabrication method.

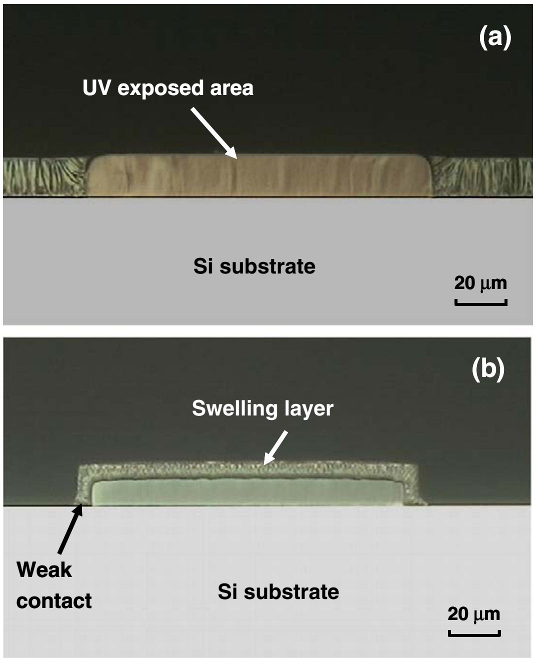

Fig. 4. Microscopic cross-section of dry film on a Si substrate after selective UV exposure (a) and developing (b).

ratio of about 2∼2.5 can be easily achieved. The high aspect ratio is beneficial to release the limitation of deposition angle in conventional integrated shadow masks. In this case, the available deposition angle was significantly increased from about 45° of the conventional integrated shadow mask (Fig. 1) to about 70° (as shown in Fig. 3). The significant increase of available deposition angle is meaningful for enhancing production yield of display devices.

From Fig. 3, it can also be seen that the positive photoresist undercut controller still remains on the substrate. This remaining thin photoresist layer is desired for avoiding electrical shorts between bottom and top electrodes due to the limited coverage of the deposited organic material, which has the same function as the insulating base layer described in literature [2].

Additional experiments were carried out to understand the mechanism behind the formation of the undercut and overhang of the pillar made by the fabrication process. Fist, a single layer negative dry film photoresist was laminated on a silicon wafer. After selective UV exposure through a photo mask, the negative photoresist was sufficiently cross-linked, which can be seen from the clear visual difference between the exposed and unexposed areas, as shown in Fig. 4a. After developing, only a strip with rectangle cross-section was obtained without any undercut, as shown in Fig. 4b. This shows that the existence of the positive photoresist is necessary for the formation of the overhang and undercut. Second, a sample with both spin-coated positive photoresist and a laminated negative dry film photoresist was prepared and UV exposed without using photo mask. The cross-section of the sample before developing is as shown in Fig. 5a. It is noticed that a new layer with thickness of about 10 μm, which is different from both the positive and negative photoresists, has formed in between the two photoresists. Since the original thicknesses of positive and negative photoresist layers are 2 and 25 μm, respectively, it is obvious that the new layer locates mainly inside the negative photoresist. With reference to the experimental result in Fig. 4, it is reasonable to conclude that the formation of the new layer is attributed to the influence of the underlying positive photoresist. During the lamination process, the negative dry film photoresist layer is applied to the sample under high pressure and relatively high temperature (383 K). The surface layer of the positive photoresist is likely soften and diffused into or mixed with the negative photoresist material. As a result, a mixing layer that contains both of the negative and positive photoresist is formed.

Although no chemical analysis to the mixing layer is available yet, the existence of mixing zone can be further verified indirectly as below. Normally, with enough dosage of UV radiation the negative photoresist will be sufficiently cross-linked and thus remained, and the positive photoresist will be chain-scissored and thus removed, during the respective developing processes. However, the mixture of the two types of photoresist in the mixing layer could not be effectively cross-linked even with UV radiation due to the separation effect of the diffused positive photoresist. Fig. 5b shows the edge portion of the sample shown in Fig. 5a after emerged in the negative photoresist developer for 5 s. It can be seen that portion of the mixing layer was selectively removed and the unaffected negative photoresist remained. It is also noted that, although having been chain-scissored under UV radiation, the positive photoresist was also not affected after developing. This is because the developer (1% sodium carbonate solution) used in this test is for negative dry film photoresist and does not attack the positive photoresist significantly.

Based on the above experimental results, the mechanism of undercut formation in the present process for integrated

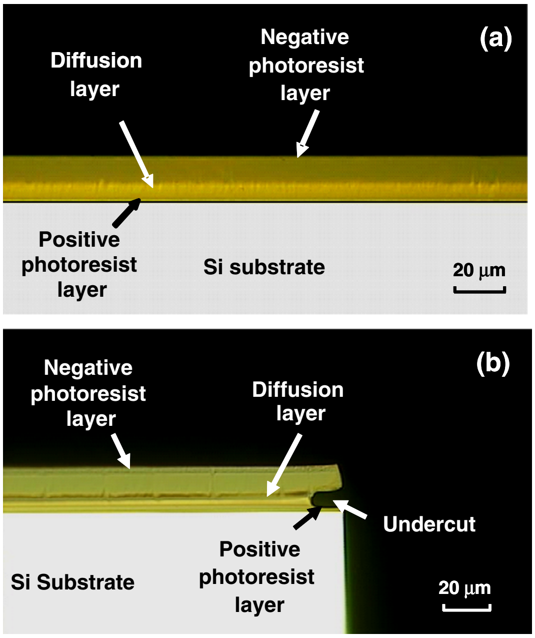

Fig. 5. Microscopic cross-section of dry film on positive photoresist layer (undercut controller) after flood UV exposure (a) and developing (b).

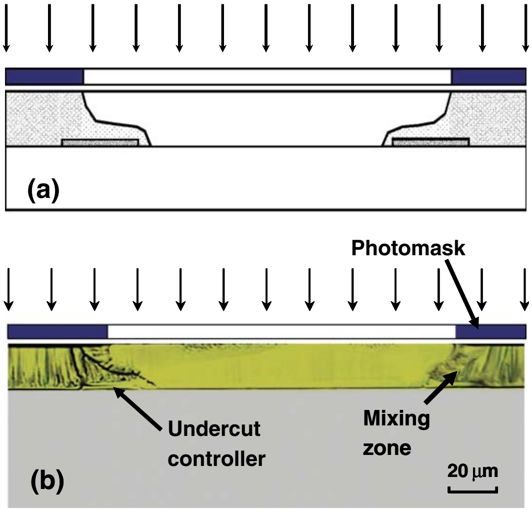

Fig. 6. Schematic (a) and microscopic (b) illustrations of insufficient crosslink of the negative photoresist in the mixing zone after selective UV exposure, which defines the pillar profile in the integrated shadow mask.

shadow mask is schematically illustrated in Fig. 6a. A mixing layer (zone) is formed in between the negative photoresist and the undercut controller (positive photoresist). In the subsequent developing process, the mixture zone is removed together with the unexposed negative photoresist, resulting in the desired undercuts and overhangs, as shown in Fig. 3. A microscopic cross-section of a sample after UV exposure without being developed is shown in Fig. 6b, which is an experimental support to the illustration in Fig. 6a.

From the above understanding, it is believed that the dimensions of the undercut and overhang can be easily ‘regulated’ by the shape of the positive photoresist strip and the lamination conditions of the negative dry film photoresist. Our results (not shown here) demonstrated that both lamination temperature and film feeding speed have influences on the size of undercut: higher temperature and slower feeding speed result in wider mixing zones (or diffusion layer). However, since the process window for the lamination temperature is usually rather narrow (as in the present case, the recommended range is from 368 to 383 K), undercut regulation with temperature is not a good option in practical applications. Instead, change of feeding speed based on a fixed lamination temperature is more viable. It should be also noted that developing process also has influence on the quality of the formed pillar. For example, over developing may result in delamination of the pillar due to the swelling effect, which can clearly be observed in Fig. 4b. The swelling layer formed in developing process may reduce the stiffness of the pillar, specifically for the mask design with narrow pillar base and large overhang.

Based on the new mask fabrication process, prototypes of passive matrix (132 × 64) OLED device have successfully been produced and operating well by far. The high reproducibility of the OLED device demonstrates that the mask fabrication process is quite robust and stable.

4. Conclusions

We have developed a new process to fabricate an integrated shadow mask used for making passive matrix OLEDs. The results showed that retrograded strip pillars with large overhang and undercut can be formed by common positive and negative photoresists. The formation of overhang and undercut is mainly due to a mixing zone of positive and negative photoresist. Based on the postulation, methods for regulating shape and size of undercuts were proposed. The pillar strips can serve as effective shadow mask for patterning the organic layers and the metal cathodes in fabrication of OLED display panels and other micromechanical and electronic devices.

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