Abstract

Organic light emitting diodes (OLEDs) with thin-film passivation are expected to provide a means of producing next-generation flat-panel wide-area displays that are thin, lightweight, and flexible. Thick silicon nitride (SiN_x) films fabricated by a plasma-CVD method are already recognized as being a practical passivation film for OLEDs, but these are not suitable for automotive applications as cracks are generated in the films as a result of the thermal stress that is caused by the high temperatures that can arise in automobiles. To overcome this problem, we have developed plasma-CVD SiN_x/plasma-polymerized hydrogenated carbon nitride (CN_x:H) multi-layer films that increase the longevity of passivated OLEDs in automotive applications. The films exhibit a high barrier performance against moisture even at high temperatures, because the thermal stress in the films is released by the soft CN_x:H layers and no cracks are produced. Indeed, OLEDs with a multi-layer passivation film lasted over 1000 hours in driving tests at 85 °C (initial luminance = 400 cd/m²), while OLEDs with the thick SiN_x passivation film soon failed and no longer emitted light.
1. Introduction

Light-emitting diodes based on organic materials are highly attractive candidates for flat-panel displays and the backlights of liquid crystal displays. Nowadays, thanks to developments in materials, device structures, and process techniques, organic light-emitting diodes (OLEDs) with a luminous efficiency in excess of 70 lm/W\(^1\), \(^2\) and a lifetime larger than 10,000 hours\(^3\) have been demonstrated, and red, green, and blue light-emitting devices are already available.

OLED displays with thin-film passivation\(^4\) are expected to find applications in next-generation wide-area flat-panel displays that are thin, lightweight, and flexible.\(^5\), \(^6\) Inorganic thin-films created by a chemical vapor deposition (CVD) method, with a thickness of a few micrometers, have been regarded as being well suited to this application because they offer a high barrier performance and good coverage. Indeed, silicon nitride (SiN\(_x\)) films fabricated by a plasma-CVD method\(^7\), \(^8\) have already been shown to be well suited to OLED passivation. In automotive applications, however, the passivation films are required to show high reliability despite severe conditions including high temperatures and humidities. Unfortunately, under such conditions, the thick SiN\(_x\) films often crack or peel as a result of thermal stress, because they are hard and fragile. If thin SiN\(_x\) films are fabricated, their resistance to thermal stress can be improved, but their barrier and coverage performance degrades such that dark spots and dark areas appear. To achieve both qualities, researchers have assumed that a multi-layer structure consisting of hard inorganic films and soft organic films would be effective.\(^5\)

In this paper, we describe how we used plasma-polymerized films for the soft organic films to develop plasma-CVD SiN\(_x\)/plasma-polymerized hydrogenated amorphous carbon nitride (CN\(_x\):H) multi-layer passivation films specifically for automotive OLED displays. These films are expected to exhibit good stress relaxation qualities, given the soft CN\(_x\):H layer inserted between the thin SiN\(_x\) layers. The deterioration in the barrier and coverage performance resulting from the thinner SiN\(_x\) layers is handled by adopting a multi-layer structure. Thus, this passivation is expected to offer an excellent barrier to moisture, high stress relaxation, and good coverage, thus making it ideal for automobile OLED passivation.

2. Preparation

2.1 CN\(_x\): H films

The CN\(_x\): H films were fabricated by a plasma-polymerized deposition method using methane (CH\(_4\)) and nitrogen (N\(_2\)) gas. We used CN\(_x\): H in preference to C:H because it is possible to reduce the intrinsic stress and improve the adhesion to the SiN\(_x\) layer by controlling the N\(_2\) gas ratio. Figure 1 shows the N\(_2\) gas ratio dependence of the intrinsic stress in the CN\(_x\): H films. The intrinsic stress was found to be a minimum at an N\(_2\) gas ratio of 0.5, and this value was very small when compared with that for the C:H film (at an N\(_2\) gas ratio of 0). We deposited the SiN\(_x\) film as the first layer because the CN\(_x\): H film formed a granular structure on an Al electrode but not on the SiN\(_x\)/Al, as shown in Fig. 2. A granular structure, on which a deposited SiN\(_x\) film would probably form pinholes, is not appropriate for multi-layer passivation.

2.1 OLEDs and passivation

An OLED was prepared by a vacuum evaporation system (TOKKI CM369), with a multi-layer passivation film grown in-situ using a plasma-CVD multi-chamber system (SAMCO PD-3802L). The passivated OLED was fabricated without being exposed to the air by transporting the samples...
between the apparatus in a box purged with N₂ gas.

A typical OLED, as considered in this study, consists of Al/LiF/tris(8-hydroxyquinoline) aluminum (Alq₃)/N,N'-dimethylquinacridone (Me-Qd)-doped Alq₃/triphenylamine tetramer (TPTE)/phthalocyanine (H₂Pc)-doped copper phthalocyanine (CuPc)/indium tin oxide (ITO) with an emitting area of 3 × 3 mm. The thickness of each of these layers was 100 nm, 0.5 nm, 40 nm, 20 nm, 50 nm, 10 nm, and 150 nm, respectively. H₂Pc-doped CuPc⁷) and TPTE⁸) were used because of their stability at high temperatures. An ITO- and SiO₂-coated soda-lime glass plate was used as the substrate. The ITO surface was polished to prevent the formation of pinholes. Before we deposited the organic materials, the substrate was irradiated with UV light in an oxygen atmosphere, after which it was immediately placed in the preparation chamber of the vacuum evaporation system. In the preparation chamber, the substrate was then exposed to Ar/O₂ plasma to remove any surface contamination.

The structure of the multi-layer passivation film was CNₓ:H / SiNₓ / CNₓ:H / SiNₓ/OLED, and the thickness of the CNₓ:H layer was 500 nm, while that of the SiNₓ layer was 200nm. The growth conditions for the SiNₓ and CNₓ:H films are given in Table 1. The intrinsic stress in both films was low enough to allow them to be fabricated on the soft organic films without cracking. For comparison, we prepared an OLED that was passivated by an SiNₓ film of the same thickness as the multi-layer film (1.4 µm) and a can lid encapsulated OLED with BaO as its absorbent.

3. Results and discussion

3.1 Structural analysis

Figure 3 shows a cross-sectional scanning electron

![Cross sectional SEM images of the multi-layer passivation on the OLED (a) and to the cathode separator (b).](image)

**Table 1** Growth conditions of SiNₓ and CNₓ:H.

<table>
<thead>
<tr>
<th>Item</th>
<th>SiNₓ</th>
<th>CNₓ:H</th>
</tr>
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<tbody>
<tr>
<td>Gas</td>
<td>SiH₄/NH₃/N₂</td>
<td>CH₄/N₂</td>
</tr>
<tr>
<td>Flow (sccm)</td>
<td>30/30/500</td>
<td>10/10</td>
</tr>
<tr>
<td>Pressure (Pa)</td>
<td>53</td>
<td>50</td>
</tr>
<tr>
<td>RF power density (W/cm²)</td>
<td>0.03</td>
<td>0.16</td>
</tr>
<tr>
<td>Substrate temperature (°C)</td>
<td>100</td>
<td>23</td>
</tr>
<tr>
<td>Thickness (nm)</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>Film stress (MPa)</td>
<td>20-30</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>
microscope (SEM) image of the multi-layer passivation of the OLED (a). It also shows a cross-sectional SEM image of the multi-layer passivation on the cathode separator (b), which is required by a passive-matrix display, in order to observe the coverage performance. The samples were formed using a focused ion beam (FIB) technique. The passivation film on the OLED was fabricated using a continuous process with each layer being grown in order. No defects were observed in the OLED or the multi-layer passivation. All of the interfaces were smooth enough to prevent the generation of pinholes. The passivation film was also fabricated continuously on the cathode separator and each layer was grown in order, even on the sidewall. The coverage ratio was about 0.5, which can be attributed to the CNx:H films. No cracks can be observed at the corners of the cathode separator, where the stress is usually concentrated. This fact indicates that multi-layer passivation is very effective at relaxing stress.

3.2 Lifetime of OLEDs with multi-layer film passivation

Figure 4 illustrates the driving test performed on an OLED with multi-layer passivation at 85°C in the air. The results for the SiNx-passivated OLED and the can lid encapsulated OLED are also shown. The initial luminance was 400 cd/m² at 85°C and the current was held at the initial value throughout the testing. The characteristics exhibited by the multi-layer passivated OLED were similar to the can lid encapsulated OLED. Figure 5 shows charge-coupled device (CCD) images of the light-emitting area of the multi-layer passivated OLED both before and after the 1000-hour driving test. Some dark spots were observed before the test, but they didn't increase or expand, even after the test. This result indicates that the multi-layer passivation maintained its excellent moisture barrier property and caused no damage to the OLED, even at high temperatures.

In the case of the an OLED with the SiNx passivation, however, dark spots and dark areas appeared and increased at the edges of the emitting area due to cracks forming in the SiNx film, with the OLED ultimately being shortened. Given that these dark spots and dark areas did not appear when the OLED was driven at room temperature, and that the thick SiNx film was so fragile that it easily cracked under stress, we can assume that this failure was caused by thermal stress. Indeed, the stress changed by about 80 MPa between room temperature and 85°C, as calculated from the coefficients of linear thermal expansion of the SiNx film (3.9 × 10⁻⁶/°C), as measured using the Si wafer-bending method with a laser-deflection system, and that of the soda-lime glass substrate (8.5 × 10⁻⁶/°C). In addition, because the stress in the hard SiNx film fabricated on the soft organic film tends to concentrate and increase at defects or edges, the value of the thermal stress

![Fig. 4](image-url) Driving test of the OLEDs at 85°C. Initial luminance was 400 cd/m² and the driving current was kept at initial value.

![Fig. 5](image-url) CCD images of a light emitting area of the multi-layer passivated OLED before and after the driving test for 1000 hours at 85°C.
between room temperature and 85 °C is considered large enough to form cracks in the SiN_x film.

These results indicate that multi-layer passivation is much more resistant to thermal stress than the SiN_x passivation. We assume that the high durability of the multi-layer passivation derives from the CN_x:H layer acting as a stress relaxation layer. Indeed, the stress relaxation ability of the CN_x:H layer is quite high because the CN_x:H film is polymer-like, which was supported by the results of the analysis by the CNH coder, in that the composition of the CN_x:H film thus formed was C_{0.35}N_{0.08}H_{0.52}, and the Young's modulus of the CN_x:H film was less than 5 GPa, which is extremely small compared with the SiN_x film (240 GPa).

4. Conclusion

We have developed plasma-CVD SiN_x/plasma-polymerized CN_x:H multi-layer passivation films for automotive OLED displays. For the multi-layer film, we adopted a CN_x:H/SiN_x/CN_x:H/SiN_x/OLED structure, so as to reduce the intrinsic stress and produce smooth individual layers. By using this multi-layer passivation, we successfully produced a passivated OLED with the same high-temperature longevity as the can lid encapsulated OLED. We believe that the excellent characteristics of the multi-layer passivation derives from the thermal stress relaxation ability of the CN_x:H layer. Thus, we expect to see the practical application of multi-layer passivation to automotive OLEDs.

References


(Remark received on May 27, 2005)