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Study of Low Power Deposition of ITO for Top Emission OLED with Facing Target and RF sputtering Systems

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Abstract. Deposition of ITO as top transparent electrode was studied using two deposition systems with and without direct contact to working plasma; namely with conventional RF-magnetron planar (RSS) and pulsed-DC facing target sputtering systems (FTS). Test devices were made on glass substrates and consisted of (from bottom up) ITO/4 Organic Layers/ITO. Depositions were performed at low deposition powers; 30 and 60 watts, to reduce damages by energetic sputtered particles to underlying organic layers. Test devices from both sputtering systems were found to function well. Leakage current density at -5 V reverse bias were relatively constant from 0.3 and 0.4 mA/cm² at 30 W and 60 W in FTS, while the values were found to increase from 0.001 to 0.2 mA/cm² at 30 W and 60 W in RSS.

1. Introduction
Since its introduction in 1987 [1], organic light emitting devices (OLED) have been of growing interest. Its importance as a competitive choice for flat panel display has been realized. OLED has already been commercialized in mobile phones and small size TVs. Active research and development in flat panel display is ongoing to launch a larger size OLED TVs to match those available in plasma panel display and LCD. To fully realize the potential of OLED with existing silicon-chip based technology, OLED active matrix display or top emission on silicon wafer is preferable to conventional bottom emission. Currently, various variants of top emission OLED are found such as n-i-p [2], inverted OLED [3] or simply top emitting OLED [4]. This development does enhance a more efficient configuration such as stack OLED [4, 5]

Top emitting OLED requires transparent anode such as ITO to be deposited on top of delicate emission layers. These organic emissive layers are generally easily damaged by energetic ion-bombarding, radiation and heating. It has been known that direct coating of the top electrode does unavoidably cause damage to a certain degree. Kim et al [6] have coated aluminum directly on LiF/Alq3 organic layers and claimed to achieve very low damage OLED but have afterwards reported a difficulty to accomplish such deposition without insertion Mg-Ag layer [7]. A semi-transparent with e.g. Au or Mg/Ag [5] has also been applied but at the expense of lower transparency. Therefore, damage-suppressed or low-damage electrode coating of onto the delicate emission layers is still of utmost interested.
Deposition of ITO as top electrode with argon as sputtering gas, besides sputtered atoms (indium, oxygen and tin in case of ITO), there also includes reflected argon neutral. Due to their electrically neutral, argon neutron feel no Coulomb force and can hence travel in a longer distance. They can possibly cause damage further deep into the organic stacks. Small mixture of heavier gas such as Xe and Kr in Ar [8] has been introduced to kinetically reduce energy of reflected neutral argon. In a reactive sputtering, i.e., inclusion of small oxygen partial pressure, there are also additional reflected neutral oxygen and negative oxygen ions. Carcia et al [9] have used a RSS system at 100 W with the target potential of -110V and have estimated the mean initial energy 

\[ E_{In,O}, E_{Ar}, E_{O}, E_{O} \]

are 10, 21, 55, and 110 eV, respectively. The final energy at organic stacks on a substrate is reduced due to collisions in plasma along the path. Negative oxygen ions are still the most destructive to a substrate. To reduce energy of negative oxygen ions in a conventional RSS is necessary to deposit at low power. As such, only low plasma density and subsequently low deposition rate can be performed.

An alternative concept to effectively suppress negative oxygen ions is implemented in a so-called facing target sputtering system (FTS). This system has first appeared around 1980 [10]. In the system, two sputtering targets are facing each other with a substrate placed at a midway of the two targets and at a relative distance away from the axis. With such configuration the plasma is confined between the targets which help to achieve significantly denser plasma and hence higher deposition rate which could well be above 100 nm/min [11]. This would help to have short exposure time to reduce detrimental effects of ITO deposition [3].

Yamamoto et al. [12] have demonstrated another concept of RF-magnetron sputtering system with a cylindrical target and placing their substrate at a distance above the target cylinder. They have achieved lower damage and higher quantum efficiency with this new variant compared to the conventional RSS. However, deposition rate is very slow, e.g., 1.6 nm/min at 50 W.

In this paper we demonstrate a sputtered deposition of top ITO cathode onto a stack of organic layers by using two deposition systems; a facing target sputtering system (FTS) and a conventional non-reactive RF-sputtering system (RSS). This study is focused on the investigation of effects this coating on the top emitting OLEDs.

2. Experimental details

All testing devices were prepared on commercial oxygen-plasma treated ITO-coated glasses with standard configuration (5×5 mm²). PEDOT-PSS (thickness 70 nm) was first spin-coated. NPB(30 nm), Alq₃ (40nm) and BCP (10nm) were then coated in an evaporation chamber under the background pressure < 6×10⁻⁶ Torr. The device was finally sputter-deposited of ITO as the top electrode using either FTS or RSS system.

The pulsed-DC facing target sputtering system is shown in figure 1(a). The base pressure in the sputtering is kept below 6×10⁻⁶ Torr. A gas mixture of argon:oxygen (9:1) was first introduced into the chamber and pure argon was then fed. The integral flow rate was kept constant at 15.0 sccm. The partial oxygen flow rate is approximately 0.6%. The working pressure in the chamber was then controlled to 7.6×10⁻³ Torr by adjusting a gate valve. An active area of each ITO target is about 9.6 cm in diameter. Pre-sputtering of ITO facing-targets was carried out for 5 minutes before starting the actual cathode deposition. Pulsed DC power supply was then delivered to the chamber at 30 and 60 W. Deposition time was controlled to achieve about 200 nm thick ITO layer. At each power, depositions of ITO with identical parameter were carried separately on bare glass substrates for measurements of (i) crystal structure with XRD (Rigaku, RINT 2500), (ii) thickness with Dektak ST Veeco Surface Profiler.

For a comparison, we have also fabricated devices with the identical structure by using a conventional RF-planar magnetron sputtering system at the same powers. The sputtering target is 7.6 cm in diameter. In this case, sputtering gas is pure argon and sample was located at the offset position 40 mm from the center of target for avoiding damage from plasma. Schematic of the conventional setup is shown in figure 1(b).
3. Results and discussion

3.1. Film Thickness measurements
For FTS deposition, thicknesses of the ITO film were measured to be 168 and 203 nm for 30 and 60 W, respectively. For RSS deposition, thicknesses were 278 and 200 nm for 30 and 60 W deposition, respectively.

3.2. Crystal structure
In the FTS, ITO films deposited at 30 W were found in an amorphous phase, while at 60 W a high degree of preferential orientation in the plane (222) at 30.5° was observed. Planes (211), (400), and (622) were also observed at 22°, 52°, and 61° with much weaker intensity. Figure 2 shows XRD patterns of the ITO films obtained from FTS. The particles become more energetic at higher power, consequently become higher mobile adatom and thus promote better crystallinity. In the RSS, similar trend is also observed. For the sake of comparison, we have also performed the deposition at higher power i.e., 90, 188, and 400 W. Except at 60 W, all other deposition powers have revealed their amorphous phase. It has been expressed [9] that an increment in partial oxygen pressure $pO_2$, also increase in oxygen ion and atomic flux, help target surface to become more fully oxidized and promote crystallinity. This can also be observed at 90W with amorphous at low $pO_2$ and a more pronounce (222) plane at higher $pO_2$. An optimum $pO_2$ is directly proportional to deposition power [11].
3.3. Current density at reverse bias

The leakage current density-voltage measurements were done by applying with reverse negative voltage to the bottom ITO electrode and positive voltage to the top ITO electrode. Results of J-V with reverse bias from these measurements are shown in figure 3. Devices fabricated in the FTS exhibit higher leakage current than those fabricated with RSS. At 30 W, the FTS deposition of ITO film has a leakage current of about 3 order of magnitude higher than its counter part RSS-deposited film. At 60 W the leakage current are in the same order. One of possible explanations could be a negative effect of oxygen during the FTS deposition of the ITO film, while the RSS deposition was made in a non-reactive environment of Ar gas. The deviation between 30 W and 60 W in FTS devices is, however, generally much lesser than those in RSS. Results with higher deposition power (90, 188 and 400W) with FTS exhibit similar leakage current density. A relatively constant leakage current in FTS indicates that damages to underlying organic layers depend very little on the deposition power. This trend holds even when increasing power by an order of magnitude (30 to 400 W).

This dependency is very sensitive in the conventional sputtering or RSS system because negative oxygen ions in the plasma could reach the substrate directly. Negative oxygen ions in the plasma gain higher kinetic energy with increasing RF power in the RSS. They can, therefore, dissipate higher energy and possibly damage the organic layer to the higher degree. Deposition of ITO with RSS system with relatively low level of damage has to be done at low deposition power with which advantages for high rate deposition is inevitably diminish.
3.4. Current-voltage characteristics and luminance efficiency.

Figure 4 shows $J-V$ characteristic of the devices. Electrode deposited with FTS exhibit similar behaviour and has relatively constant turn-on-voltage (TOV). The trend is unchanged when deposited with higher powers, e.g., 90 W. Those fabricated with RSS show similar $J-V$ character. However, the TOV at 30 W is lower than at 60 W, indicating lower damage with decreasing power. In term of luminance efficiency devices, as shown in figure 5 from both FTS and RSS show similar efficiency. Although it has been reported [12] that their cylindrical system, which the substrate has been placed outside plasma, offered higher quantum efficiency of devices than the conventional RSS planar type; we have found the different is not significant.
4. Conclusion
We have presented experimental results of coating ITO on active organic layer as the top electrode at low deposition powers (30 and 60 W) using facing target and RF sputtering systems. Deposition of ITO films using FTS has been performed in argon atmosphere with 0.6% partial oxygen flow rate, compared with pure argon atmosphere in the RSS deposition. Leakage current densities at -5V of the OLED devices were relatively unchanged in the FTS system but were found to increase with increasing deposition power in RSS system. At 30 W, leakage current densities in devices from the FTS system are higher than those from the RSS system; while at 60 W, they are in the same order. One of possible explanations may due to negative effect of inclusion of oxygen in the FTS system.

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