

Twin Target Sputtering System with Ladder Type Magnet Array for Direct Al Cathode Sputtering on Organic Light Emitting Diodes

Jong-Min Moon and Han-Ki Kim***

Abstract

Twin target sputtering (TTS) system with a configuration of vertically parallel facing Al targets and a substrate holder perpendicular to the Al target plane has been designed to realize a direct Al cathode sputtering on organic light emitting diodes (OLEDs). The TTS system has a linear twin target gun with ladder type magnet array for effective and uniform confinement of high density plasma. It is shown that OLEDs with Al cathode deposited by the TTS show a relatvely lower leakage current density ($\sim 1\times10^{-5}$mA/cm^2) at reverse bias of -6V, compared to that ($1\times10^{-2}\sim10^{-3}$ mA/cm^2 at -6V) of OLEDs with Al cathodes grown by conventional DC magnetron sputtering. In addition, it was found that Al cathode films prepared by TTS were amorphous structure with nanocrystallines due to low substrate temperature. This demonstrates that there is no plasma damage caused by the bombardment of energetic particles. This indicates that the TTS system with ladder type magnet array could be useful plasma damage free deposition technique for direct Al cathode sputtering on OLEDs or flexible OLEDs.

Keywords : Twin target sputtering, Al cathode, OLEDs, Plasma damage, leakage current

1. Introduction

Organic light-emitting diodes (OLEDs) are attracting considerable attention because of its potential applications in flat panel displays and flexible displays [1-3]. In the fabrication of the OLEDs and flexible OLEDs, deposition of the metal cathode layer such as Al, Ag, Al-Li, and Mg-Ag on organic layer is essential for electron injection [4-7]. In preparing a metal cathode layer, resistive heating-induced thermal evaporation have been mainly employed for depositing the metal cathode layers because the organic layer is extremely sensitive to radiation during sputtering or electron-beam evaporation. However, thermal evaporation method has critical drawbacks, such as serious undesirable reactions of Al with the ceramic crucible, creeping up of Al on the ceramic crucible wall, and difficulty of achieving a large area deposition due to point-type Al source geometry. In addition, low efficiency of Al material usage with scale up the size of glass substrate is a critical disadvantage of point-type Al source. For these reasons, sputtering method has been considered as an alternative deposition technique for the metal cathode preparation in the fabrication process of the OLEDs. Sputtering is one of the commonly used deposition techniques in the fabrication of the liquid crystal displays and thin film transistors due to its simplicity, high throughput and easy scale-up of glass size. However, bombardment of energetic particles ejected from the plasma region during the sputtering process results in undesirable damage to the underlying organic layers. Liao *et al.*, reported that high-energy ion irradiation result in a change in the band structure of the Alq_3, specially highest occupied molecular orbital (HOMO), and have a severe influence on the characteristics of OLEDs [8]. Despite many efforts to prevent plasma damage effect in the sputtering process, the development of direct cathode metal sputtering technique is still under way [9-11]. Therefore, the development of a direct Al cathode sputtering method is very important in solving the problems of point-type Al source in the thermal evaporation method.

In this paper, we report on the plasma damage free Al cathode sputtering technique using specially designed twin

Manuscript received August 12, 2007; accepted for publication September 15, 2007.
This work was supported by a Korea Research Foundation Grant funded by the Korea Government (MOEHRD: Basic Research Promotion Fund) (KRF-2006-331-D00243)
* Member, KIDS; ** Student Member, KIDS
Corresponding author : Han-Ki Kim
Department of Information and Nano Materials Engineering, Kumoh National Institute of Technology (KIT)
Address: 1 Yangho, Gumi, Gyeongbuk, 730-701
E-mail : hkkim@kumoh.ac.kr **Tel** : +54-478-7746 **Fax** : +54-478-7769

target sputtering (TTS) system for large area OLEDs. The specially designed TTS system not only has several advantages such as low working pressure, low substrate temperature, high efficiency of target materials, and easy scale-up but also obviates the bombardment of energetic particles due to effective confinement of high density plasma. It is shown that the OLEDs made with the Al cathode grown by the TTS system exhibit much lower leakage current density than that of OLEDs with the Al cathodes grown by conventional DC magnetron sputtering. Based on the results of structural and surface analysis of the Al films, we suggest possible mechanism to explain plasma damage-free sputtering of the TTS.

2. Experiment

To realize direct Al cathode sputtering on the organic layers, we developed a specially designed TTS system with linear gun consisting of ladder type magnet array. Originally it was developed to deposit transparent top cathode layer in top-emitting OLEDs using sputtering technique without plasma damage effect on organic layer [11]. Prior to designing the TTS system, magnetic field simulation with different magnet array was carried out using Maxwell software, a finite element solver, to obtain efficient and uniform confinement of high density plasma between Al targets. A schematic diagram of the TTS system is shown in Fig. 1. Two Al targets (250 × 100 mm in size) were placed face-to-face as a distance ranged from 50 mm and 100 mm generating high magnetic field whose line ideally enter and leave the targets perpendicularly. During the TTS process, electrons tightly held by the Lorenz force spiralling with the helix pitch and oscillate between two targets due to the negative voltage of both targets as shown in Fig. 1(a). Thus, the energetic particles can be confined within the magnetic field. To optimize Al cathode deposition condition, Al cathode layer were deposited on glass substrate as a function of power, target to substrate distance, and working pressure. Structural and surface properties of Al films were examined by synchrotron x-ray scattering and field-emission scanning electron microscopy (FESEM). Substrate temperature during the TTS process was measured by thermo couple and thermal tape at the center of glass substrate. To confirm plasma damage free sputtering of the TTS system, fluorescent OLEDs were prepared. All organic layers with a structure of hole injection layer/hole transporting layer/electron transporting layer (HIL/HTL/ETL) and emission layer (EL) were deposited by thermal evaporation on glass substrates coated with ITO anode layers. 4,4',4"-Tris(*N*-(2-naphthyl)-*N*-phenyl-amino)-triphenylamine (2-TNATA) was used as HIL. α-napthylphenlylbiphenyl (NPB) and tris-(8-hydroxyquinoline) aluminum (Alq_3) were used as HTL and ETL (EL) layer, respectively. Subsequently, a 15 Å-thick LiF was grown on the Alq_3 layer by the thermal evaporation. After deposition of thin LiF layer, 1000 Å-thick Al cathode layer was then sputtered on LiF layer using the TTS system. For comparison, OLEDs with Al cathode layer deposited by DC magnetron sputter system was prepared. After sputtering the Al cathode layer, all of the OLEDs samples were glass-encapsulated for protection against moisture and oxygen in the air. The current density-voltage (*J-V*) characteristics of the OLEDs with the Al cathode layer were examined using a Photo Research PR-650 spectrophotometer driven by a programmable dc source.

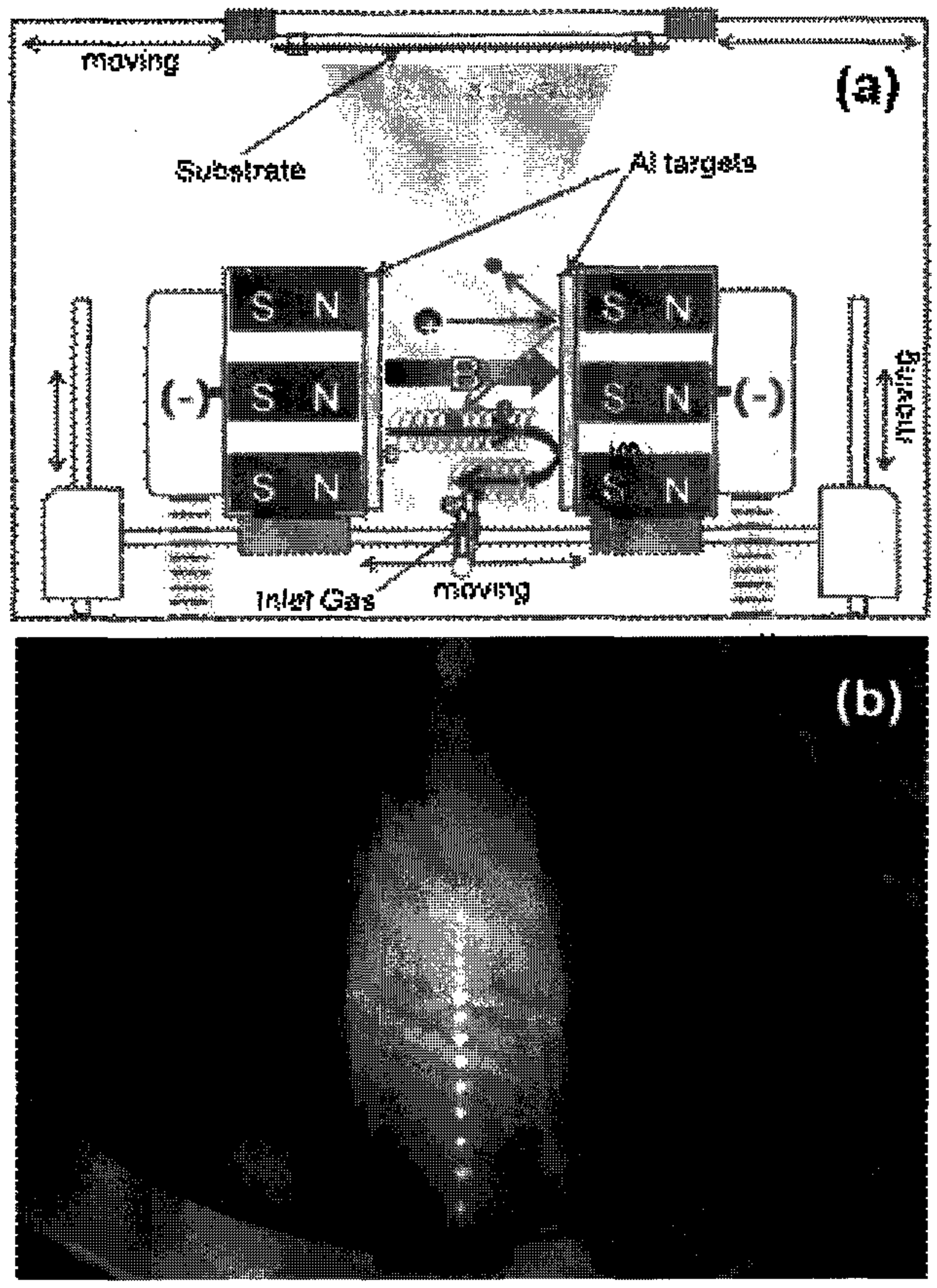

Fig. 1. (a) Schematic diagram of specially designed twin target sputter (TTS) system and (b) picture of effectively confined plasma between Al targets.

3. Results and Discussion

Fig. 1 shows a schematic diagram of the TTS system and picture of the plasma uniformly confined between two Al targets. The Al cathode films could be deposited on the substrate moving horizontally in vacuum chamber. The TTS system was characterized by ladder type magnet array and position of facing Al target planes generating closed magnet flux from the N-pole to the S-pole as shown in Fig. 1(a). Therefore, most the energetic particles, such as charged ions and γ-electrons resulting in the optical and electrical degradation of organic films, could be effectively confined between the Al targets. Effectively confined plasma between Al targets was shown in Fig. 1(b). It was shown that the substrate was not directly affected by irradiation of plasma due to geometry of twin Al targets and confined plasma. In addition, symmetrically arranged two Al target planes could form high-density plasma between Al targets. Thus, compared with the conventional DC sputtering technique, TTS has higher deposition efficiency and wider operating pressure range due to high density of plasma [12].

To confine high-density plasma effectively between Al targets, it is imperative to simulate the magnet fields as a shape of magnet arrays. Fig. 2 exhibits a magnet field simulation results according to different types of magnet arrays. In case of conventional facing target array in Fig. 2(a), it was found that high density magnetic fields were formed at the side region of the gun due to existent of magnet at edge of the twin target gun. In case of conventional facing magnet array, the formation of uniformly confined plasma between the Al targets was difficult due to relatively low magnet field density at the region of gun center. However, it was observed that inserting additional magnets at the center region of twin target gun like a ladder lead to uniform magnet fields between Al targets in Fig. 2(b). Due to the existence of additional ladder type magnets, more efficient and uniform confinement of high-density plasma could be possible during Al sputtering process. From the viewpoint of target efficiency and sputtering yield, the TTS gun with ladder type magnet array is more beneficial than conventional edge type magnet array. Furthermore, decrease in target-to-target distance at optimized magnet array from 100 mm to 62 mm could improve the uniformity of magnet fields between Al targets as shown in Fig. 2(c).

Fig. 3 shows the dependence of discharging voltages

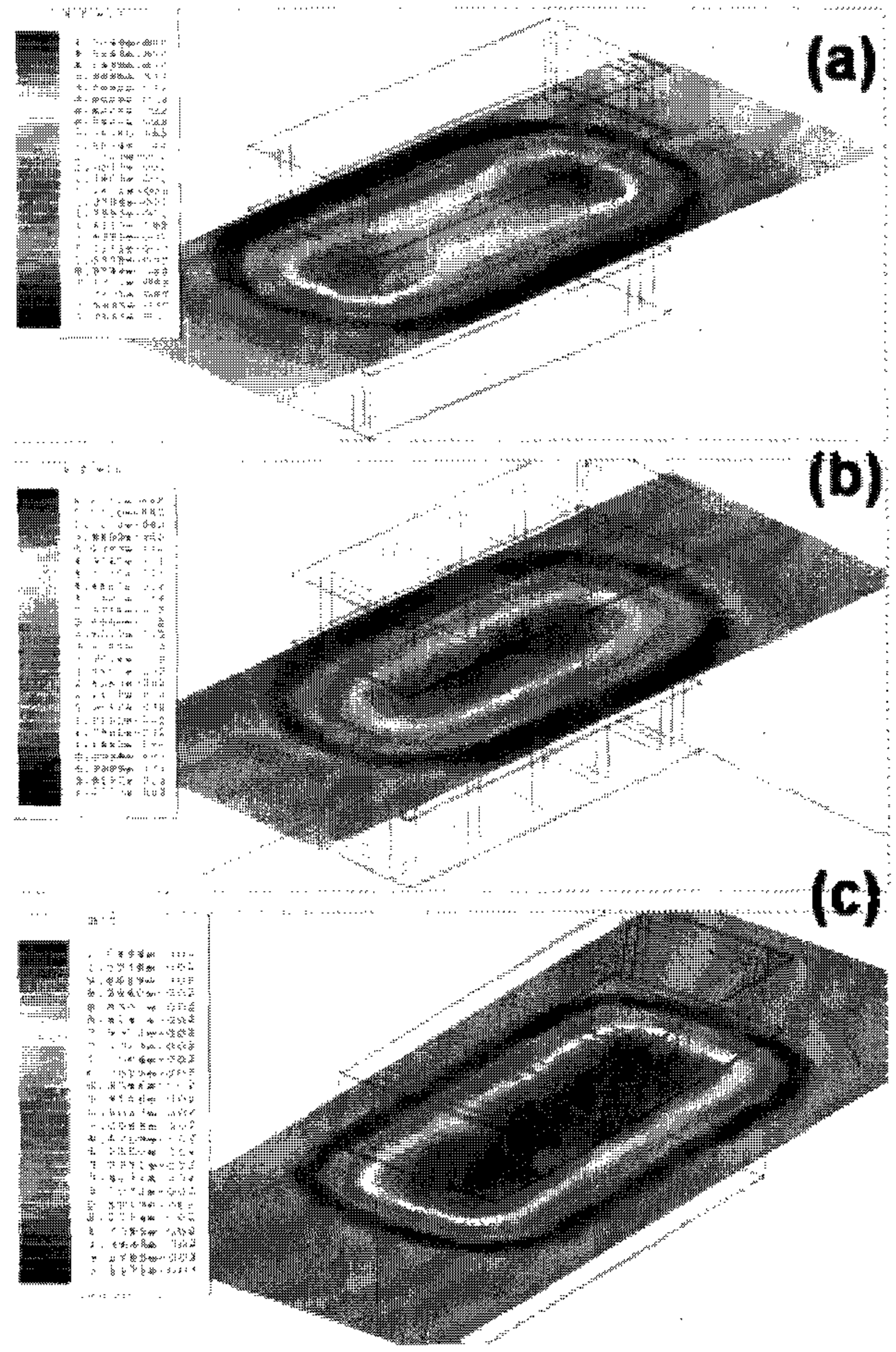

Fig. 2. Magnetic field simulation results. (a) Conventional facing target magnet array, (b) ladder type magnet array employed in the TTS system (100 mm) and (c) ladder type magnet array with short target-to-target distance (62 mm)

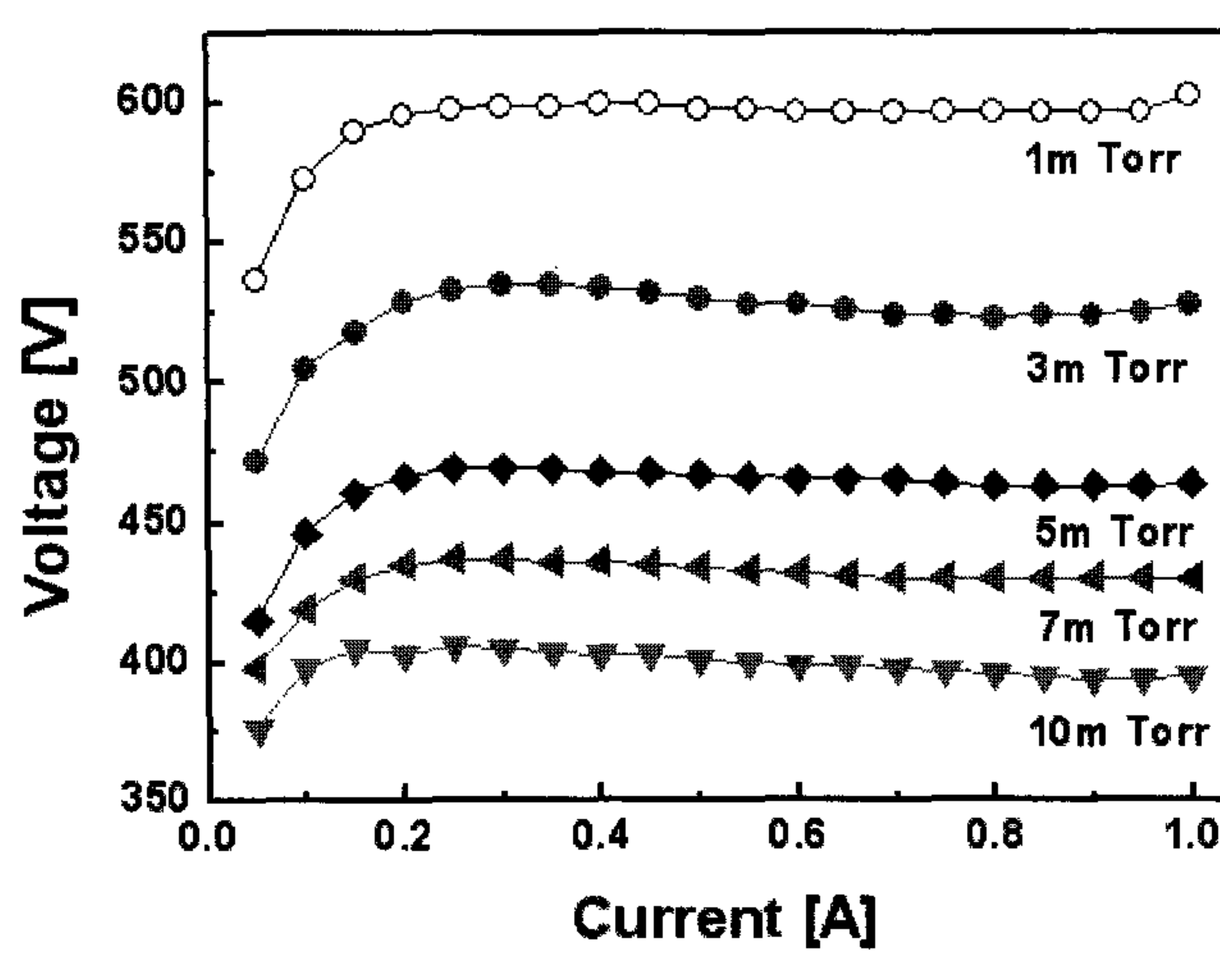

Fig. 3. Discharge voltage and current characteristics depending on the working pressure.

on the working pressure. It shows that as the working pressure increases, the discharge voltage decreases. By increasing working pressure from 1 to 10 mTorr, we can simply decrease the discharge voltage from 600 to 400 V, which is one of the key parameters in a plasma damage free sputtering. The decrease in the discharge voltage could be attributed to the increased amount of ionized ions and high energy γ-electrons. However, the discharge voltage was kept constant at working pressure with increasing input powers. The stable discharge voltage indicates that the TTS technique is a stable sputtering process for direct Al cathode sputtering on organic layers.

Fig. 4 shows temperature variation of the glass substrate during the TTS process with increasing sputtering time. The substrate temperature was measured by thermo couple at the center region of the glass substrate during TTS process for 2 hours. It is noteworthy that substrate temperature during the TTS process could be kept below 53.6℃ even though sputtering process is carried out for 2 hours without any intentional cooling system. This indicates that bombardment of the energetic particles is effectively restricted by confinement of plasma between the Al targets.

Fig. 5 shows surface FESEM images of the Al film grown on the bare glass substrates by the TTS system at different DC power of 400 and 1200 W. The working pressure and Ar flow rate was kept constant at 1 mTorr and 10 sccm. It was shown that the Al film grown by the TTS at DC power of 400 W have very smooth surface with very fine grains (Fig. 5(a)). This indicates that the mobility of the deposited Al atoms is very low due to the low substrate temperature. However, as for the Al film grown at DC

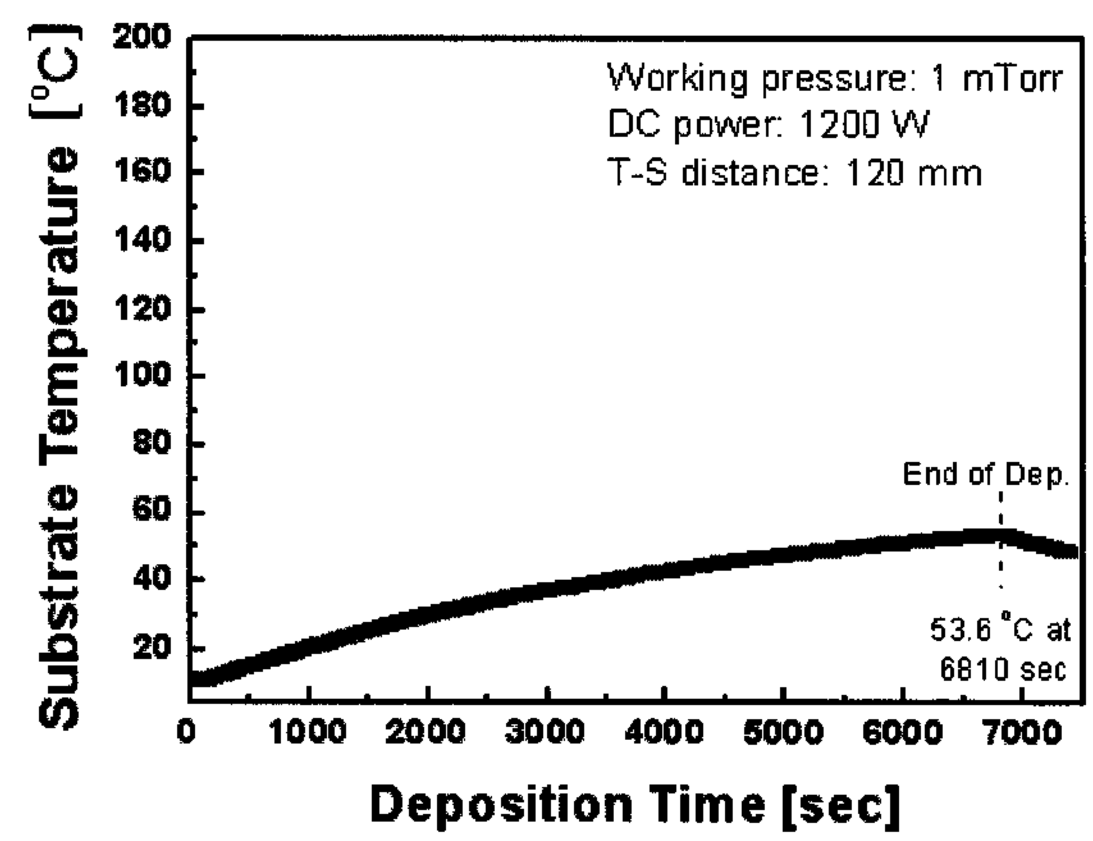

Fig. 4. Variation of substrate temperature at the center region of the glass substrate as a function of deposition time during Al deposition

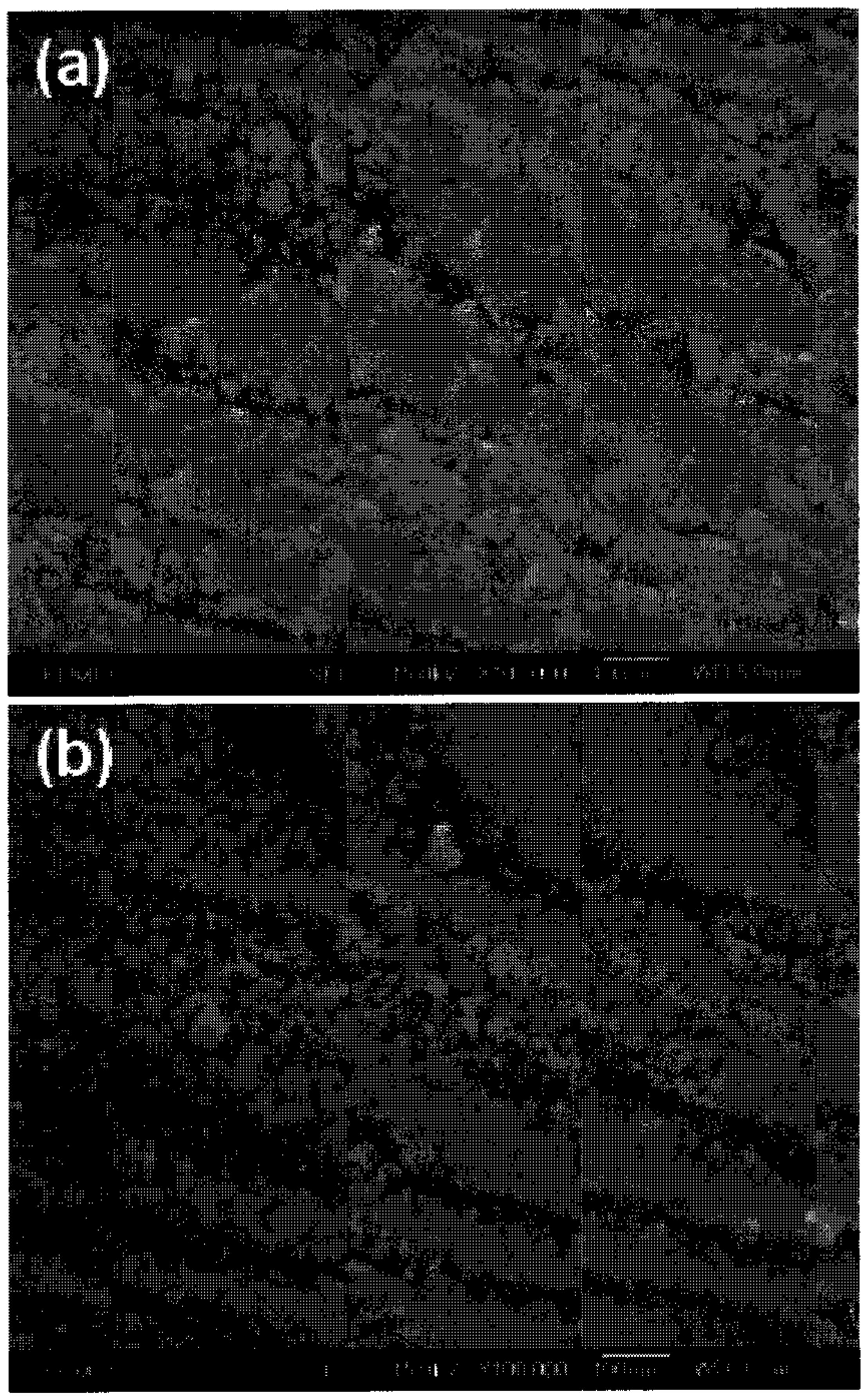

Fig. 5. FESEM surface images of Al films deposited by the TTS system at DC power of (a) 400 W and (b) 1200 W.

power of 1200 W in Fig. 5(b), the surface is relatively denser than that of Al film grown at 400 W.

Fig. 6 shows synchrotron x-ray scattering result of Al film deposited on glass substrate by TTS system at DC power of 400 W. Very weak x-ray diffraction peaks of (111) and (222) direction indicated that the TTS grown Al film was prepared at low substrate temperature due to effective confinement of high-density plasma between Al targets. This is consistent with measured substrate temperature shown in Fig. 4 and smooth surface of the Al film in Fig. 5. From the synchrotron x-ray scattering result, it was thought that TTS grown Al film have amorphous structure with embedded nanocrystallines.

Fig. 7 shows the current density-voltage (*J*-*V*) characteristics of the OLEDs with the Al cathode layers grown by the DC magnetron sputter and the TTS, respectively. The Al films were grown at DC power of 400 W and working pressure of 1 mTorr by TTS. The *J*-*V* curve of the OLEDs with the Al cathode grown by the DC

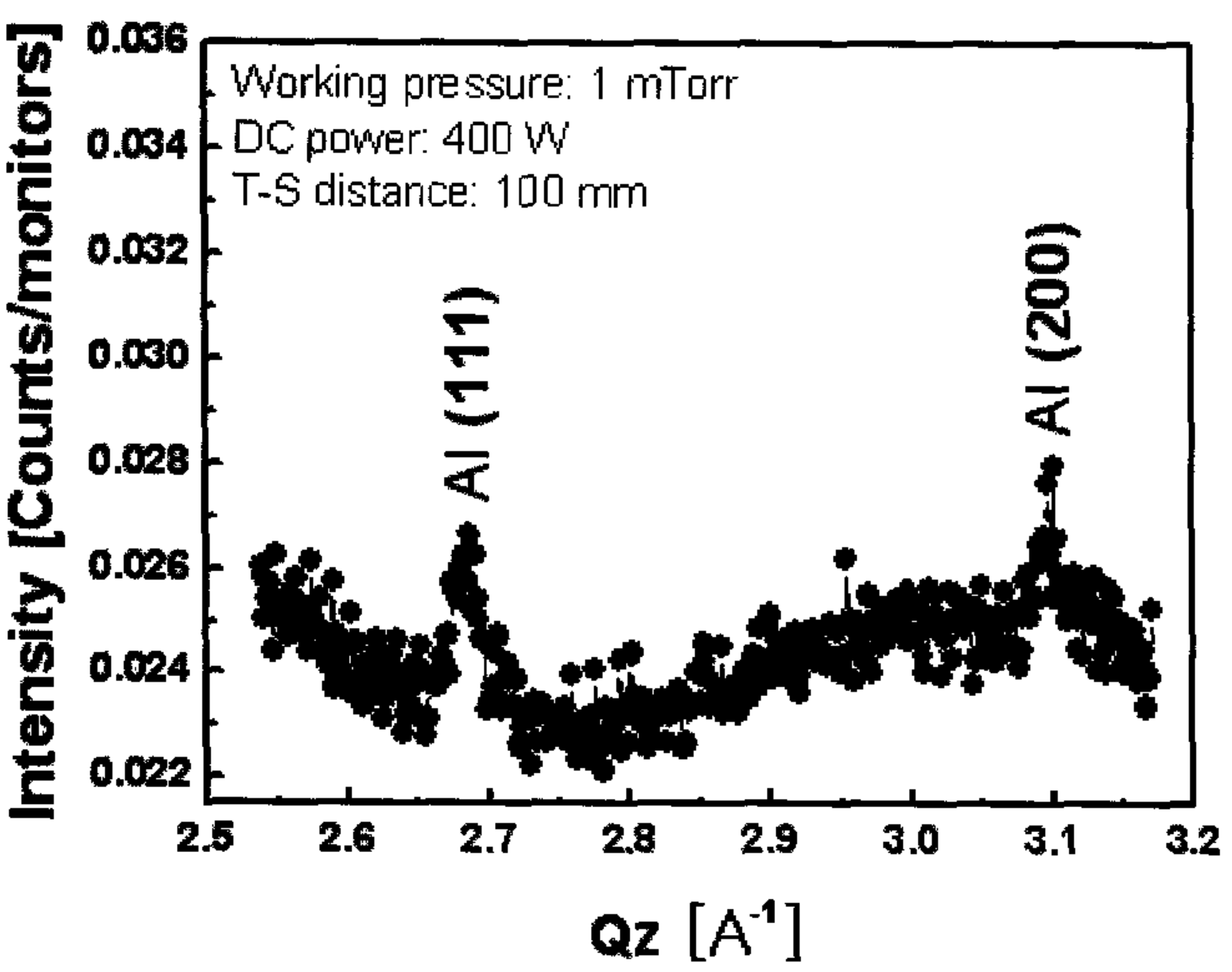

Fig. 6. Synchrotron x-ray scattering results of Al film grown on glass substrate by TTS system.

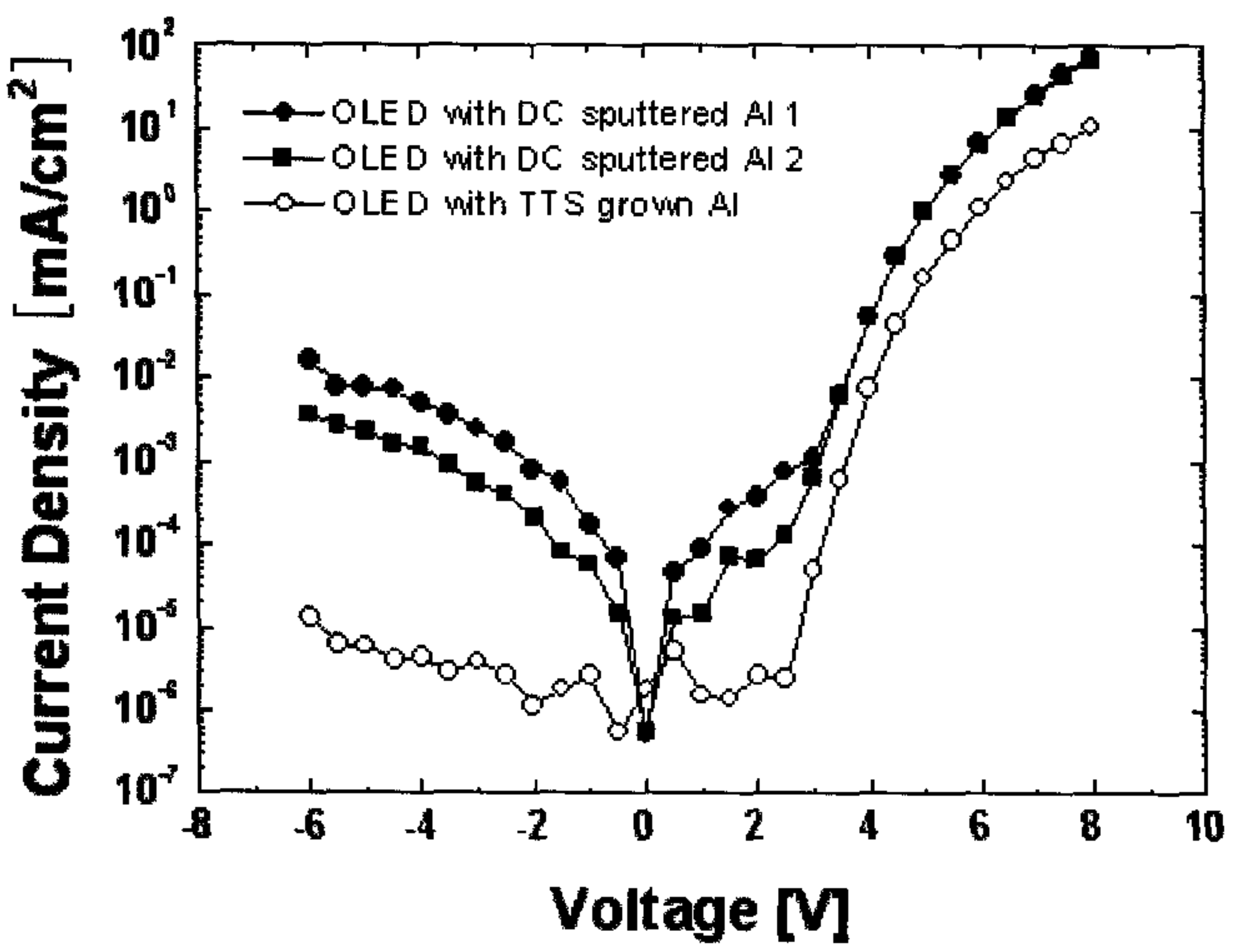

Fig. 7. Current density-voltage characteristics of the OLEDs with the Al cathode grown by conventional DC sputter and TTS system respectively.

magnetron sputter shows a large leakage current density at reverse bias. The sample shows a similar leakage current density between 10^{-2} and 10^{-3} mA/cm^2 at -6V. It is believed that a large leakage current density of the OLEDs is related to the conducting paths resulting from the formation of plasma-induced local damages. However, the OLEDs with the Al cathode layers prepared by the TTS shows a very low leakage current density at reverse bias. The leakage current density is between 10^{-5} and 10^{-6} mA/cm^2 at -6V. Therefore, these results show that the TTS is a promising technique for realizing the Al cathode direct sputtering on organic layers.

Based on the *J-V*, FESEM, X-ray scattering examination results, the plasma damage-free deposition of the Al cathode layer on the OLEDs by the TTS could be explained as follows. First, it can be related to the confinement of the energetic particles in the strong magnetic field. The X-ray scattering examination and FESEM results showed that the Al films prepared by the TTS were amorphous structure due to the low substrate temperature, indicating the absence of the bombardments of the energetic particles. Since most of the energetic particles could be confined in the strong magnetic field between the facing targets, the substrates located outside the plasma region cannot be affected directly by the bombardments of the energetic particles and so maintain low temperatures. Therefore, there is no plasma damage effect caused by the bombardment of the energetic particles during sputtering process of the TTS. Second, it can be attributed to the position of the OLED samples maintained vertical to the targets, which prevent the direct bombardments of the energetic particles as shown in Fig. 1. Consequently, the combined effects of the confinement of the energetic particles and the sample position could result in the plasma damage free deposition of the Al cathode layers on organic layers.

4. Conclusions

We demonstrated that the plasma damage-free deposition of the Al cathode layers on OLEDs was successfully realized by the TTS technique. Specially designed TTS system with ladder type magnet array has two facing targets generating high magnetic fields ideally entering and leaving the targets, perpendicularly. This target geometry allows the formation of high-density plasma between targets and enables us to realize plasma damage free sputtering on organic layer without protection layer against plasma. It was found that OLED with Al cathode layer prepared by TTS has much lower leakage current density (1×10^{-5} mA/cm^2 at -6V) than that (1×10^{-2}~10^{-3} mA/cm^2 at -6V) of OLED prepared by conventional DC sputtering system. This indicates that TTS technique is a promising Al cathode direct sputtering method for substituting conventional point source type Al thermal evaporation.

References

[1] J. H. Burroughes, D. D. C. Bradley, A. R. Brown, R. N. Marks, K. Mackay, R. H. Friend, P. L. Burns, and A. B. Holmes, *Nature* **347**, 539 (1990).

[2] C. W. Tang and S. A. VanSlyke, *Appl. Phys. Lett.* **51**, 913 (1987).
[3] N. C. Greenham, S. C. Moratti, D. D. C. Bradley, R. H. Friend, and A. B. Homes, *Nature* **365**, 628 (1993).
[4] P. E. Burrows, G. Gu, V. Bulovic, S. R. Forrest, and M. E. Thompson, *IEEE Trans. Electron Devices* **44**, 1188 (1997).
[5] M. Stößel, J. Staudigel, F. Steuber, J. Blassing, J. Simmerer, A. Winnacker, H. Neuner, D. Metzdorf, H.-H. Johannes, and W. Kowalsky, *Synthetic Metals* **111**, 19 (2000).
[6] E. I. Haskai, A. Curioni, P. F. Seidler, and W. Andreoni, *Appl. Phys. Lett.* **71**, 1151 (1997).
[7] L. S. Hung, C. W. Tang, M. G. Mason, *Appl. Phys. Lett.* **70**, 152 (1997).
[8] L. S. Liao, L. S. Hung, W. C. Chan, X. M. Ding, T. K. Sham, I. Bello, C. S. Lee, and S. T. Lee, *Appl. Phys. Lett.* **75**, 1619 (1999).
[9] Han-Ki Kim, D.-G. Kim, K.-S. Lee, M.-S. Huh, S. H. Jeong, K. I. Kim, H. Kim, D. W. Han, and J.H. Kwon, *Appl. Phys. Lett.* **85**, 4295 (2004).
[10] Han-Ki Kim, Sang-Woo Kim, Kyu-Sung Lee, and K. H. Kim, *Appl. Phys. Lett.* **88**, 083513 (2006).
[11] Han-Ki Kim, D.-G. Kim, K.-S. Lee, M.-S. Huh, S. H. Jeong, K. I. Kim, and Tae-Yeon Seong, *Appl. Phys. Lett.* **86**, 183503 (2005).
[12] P. F. Carcia, R. S. McLean, M. H. Reilly, L. J. Pillione, and R. F. Messier, *J. Vac. Sci. Technol. A* **21**, 745 (2003).