Near infra-red transparent Mo-doped In$_2$O$_3$ by hetero targets sputtering for phosphorescent organic light emitting diodes

Yong-Hee Shin$^{a}$, Sin-Bi Kang$^{a}$, Sunghun Lee$^{b}$, Jang-Joo Kim$^{b}$, Han-Ki Kim$^{a,*}$

$^{a}$Department of Advanced Materials Engineering for Information and Electronics, Kyung Hee University, 1 Seocheon-dong, Yongin, Gyeonggi-do 446-701, Republic of Korea
$^{b}$Department of Materials Science and Engineering and the Center for Organic Light Emitting Diode, Seoul National University, Seoul 151-744, Republic of Korea

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We report a highly near infrared (NIR) transparent MoO$_3$-doped In$_2$O$_3$ (IMO) film prepared by hetero target sputtering for use as a transparent anode in phosphorescent organic light emitting diodes (OLEDs). Effective activation of Mo dopant in the In$_2$O$_3$ matrix and good crystallinity with the (222) preferred orientation from by rapid thermal annealing (RTA) led to the lowest resistivity of $4.25 \times 10^{-4}$ Ohm cm and sheet resistance of 16.9 Ohm/ square, comparable to a conventional ITO anode without lose of transparency in the NIR region. Due to high carrier mobility in the IMO matrix, IMO film exhibited higher transmittance in the visible and NIR regions compared to ITO film even though it has a similar resistivity. Both synchrotron X-ray scattering and high resolution transmission electron microscope examinations showed that the optimized IMO film annealed at $600^\circ$C had a rectangular shaped columnar structure with a strongly preferred (222) orientation. Identical current density–voltage–luminance and quantum efficiency of the phosphorescent OLED fabricated on an IMO anode were comparable to those of the OLED on a reference ITO anode due to the high transparency and low resistivity of the IMO anode.

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**1. Introduction**

Transparent conducting oxide (TCO) anodes with excellent transmittance and low resistivity are one of the key components for organic light emitting diodes (OLEDs) because effective hole injection and light emission occur through the TCO anodes [1–5]. Until now, Sn-doped In$_2$O$_3$ (ITO) films prepared by DC sputtering have been commonly used in industry and academic research as a transparent anode for phosphorescent or fluorescent OLEDs, due to their low resistivity ($2–3 \times 10^{-4}$ Ohm cm) and high transmittance in the visible range (80–83%) [2,6]. However, conventional ITO anodes exhibit low near infrared (NIR) transparency due to the effect of plasma wavelength ($\lambda_p$), which is critically dependent on the free carrier concentration in the ITO films [7]. Because low resistivity of the ITO film could be obtained from a high carrier concentration ($\sim 10^{21}$ cm$^{-3}$), conventional ITO film with a high carrier concentration showed abruptly decreased transmittance in the NIR region [7,8]. To address this problem of ITO films, refractive metal (Mo, W, Ta, Zr) doped In$_2$O$_3$ films have been extensively investigated as a high mobility TCO (HMTCO) with high NIR transparency. Calnan et al. have reviewed the characteristics of HMTCOs with different dopants and defined HMTCO as a TCO film possessing high mobility (HMTCO) with high NIR transparency. Calnan et al. have reviewed the characteristics of HMTCOs with different dopants and defined HMTCO as a TCO film possessing high mobility above $\sim 62.5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ with high NIR transparency while maintaining a low resistivity of $\sim 10^{-4}$ Ohm cm [8]. Among refractive metal-doped In$_2$O$_3$ films, MoO$_3$-doped In$_2$O$_3$ (IMO) films have been extensively investigated because the MoO$_3$ dopant has a higher valence (+3) electrons than Sn$^4+$ dopant (+1) and a higher Lewis acid strength (LAS:3.667) than SnO$_2$ (LAS:0.228) [8–17]. In addition, high NIR transparency caused by a low carrier concentration and high mobility allows IMO films to function as an alternative to conven-
tional ITO films. As reported by Meng et al., substitution of Mo$^{6+}$ into In$^{3+}$ sites lead to low resistivity ($1.7 \times 10^{-4}$ Ohm cm) and high mobility ($\sim 100 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) of the IMO film as well as high NIR transparency due to higher valence electrons of the Mo dopant [14,15]. Even though IMO film was prepared from the IMO target with a low Mo doping concentration, it exhibited similar resistivity due to its high carrier mobility [9]. Yoshida et al reported that the high mobility of IMO film was closely related to decreased scattering time rather than a decreased effective mass [16]. Moreover, Yamada et al. reported that IMO film prepared by RF magnetron sputtering had a low resistivity of $1.5 \times 10^{-4}$ Ohm cm, which is comparable to conventional ITO film [17]. Recently, Fortunato et al. also reported that IMO films prepared by spray pyrolysis have a high mobility of $\sim 149 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ [10]. In our previous work, we suggested that appropriate Mo doped In$_2$O$_3$ film is a promising transparent anode to substitute conventional ITO anode for organic solar cells, due to its low sheet resistance and high NIR transmittance [18]. In spite of the merits of IMO films as transparent electrodes, application of NIR-transparent IMO anodes in phosphorescent OLEDs and a comparison of IMO and ITO films for OLEDs have not yet been reported in detail. Furthermore, a detailed investigation of the rapid thermal annealing (RTA) effect on the electrical, optical, and structural properties of IMOs film is still lacking.

In this work, we investigated the characteristics of rapid thermally annealed IMO films prepared by hetero target sputtering as an alternative to conventional ITO anodes for phosphorescent OLEDs. The improved electrical and optical properties of IMO films with increasing RTA temperature were correlated with carrier mobility and improved crystallinity. Using synchrotron X-ray scattering and high-resolution transmittance microscopy analysis, the microstructures of optimized IMO films were examined in detail. Furthermore, the feasibility of IMO film as a transparent anode for phosphorescent OLEDs was investigated. Identical performances of phosphorescent OLEDs with IMO anode to those of the OLEDs with ITO anode implies that IMO is a promising anode to replace the conventional ITO anode.

2. Experimental

A hetero target sputtering process using MoO$_3$ and In$_2$O$_3$ ceramic targets was carried out to deposit a 250 nm-thick IMO film on glass substrates at room temperature. The hetero target sputtering technique is a well-known co-sputtering method for preparing compound thin films or TCO films. Prior to hetero target sputtering, the MoO$_3$ and In$_2$O$_3$ targets were pre-sputtered for 10 min under pure Ar ambient to remove contamination from the surface of the targets. After pre-sputtering, IMO film was sputtered on the glass substrate with dimensions of $25 \times 25 \text{ mm}^2$ at a constant DC power of 100 W applied to the In$_2$O$_3$ target, a RF power of 30 W applied to the MoO$_3$ target, a pure Ar flow ratio of 10 sccm, and a working pressure of 3 m Torr without intentional substrate heating. Rotating the substrate holder at a speed of 20 rpm gave uniformly coated IMO films. After hetero target sputtering of MoO$_3$ and In$_2$O$_3$, the 250 nm thick IMO films were rapidly thermal-annealed with increasing temperature up to 600 °C under vacuum ($\sim 10^{-3}$ Torr). The temperature gradient rate and annealing time were maintained at 20 °C/s and 10 min, respectively. The thickness of hetero-sputtered IMO films was measured with a surface profiler (Nanomap-LS). The electrical and optical properties of IMO films were examined by using Hall measurement (HL5500PC, Accent Optical Technology) and a UV/visible spectrometer (JASCO V-570) as a function of the annealing temperature. In addition, the dependence of resistivity of the IMO film was investigated using a physical property measurement system (Quantum Design) in the temperature range from 350 K to 2 K to study the conduction mechanisms of the optimized IMO film. The dependence of IMO film microstructures on annealing temperature was evaluated by synchrotron X-ray scattering at the GI-WAXS beam line of the Pohang Light Source (PLS). The wavelength of incident X-rays was set to 1.243 Å by a double bounce Si (111) monochromator. High-resolution transmission electron microscopy (HRTEM) was also employed to investigate the microstructure of the optimized IMO film. For HRTEM analysis, the optimized IMO sample was prepared via focus ion beam milling. The surface morphology of the IMO films were analyzed by field emission scanning electron microscope (FESEM: LEO SUPRA 55) and atomic force microscopy (AFM: Park Systems XE-70).

To evaluate the feasibility of IMO film as an alternative anode to ITO films for OLEDs, phosphorescent OLEDs were fabricated on patterned-IMO and ITO anodes. For the reference ITO anode, commercial ITO coated glass (Samsung Corning precision materials) was used. Due to the absence of an IMO wet etchant, the patterned IMO anode was prepared using a thin metal shadow mask. After conventional wet cleaning and UV–ozone treatment for 10 min, the IMO/glass and reference ITO/glass samples were simultaneously transferred into an organic-metal evaporation system. After evaporation of all of the organic layers, a 1 nm thick LiF layer was then deposited as the electron injection layer (EL), followed by a 100 nm-thick Al cathode layer that was patterned using a shadow mask. The current density–voltage–luminescence (J–V–L) characteristics of phosphorescent OLED fabricated on the different anode materials were measured with a Keithely 2400 and a Si photodiode mounted below the phosphorescent OLEDs.

3. Results and discussion

Fig. 1a shows the Hall measurement results of 250 nm-thick IMO films as a function of RTA temperature. The resistivity of the IMO film decreased with an increase in RTA temperature. As-deposited IMO film showed a fairly high resistivity of $3.07 \times 10^{-3}$ Ohm cm, while the 600 °C annealed IMO film showed the lowest resistivity of $4.25 \times 10^{-4}$ Ohm cm. This reduction in resistivity could be attributed to effective activation of the Mo$^{6+}$ (Mo$_{6+}$) or Mo$^{4+}$ (Mo$_{4+}$) dopants in the In$_2$O$_3$ matrix [15,16,18,19]. Meng et al. have suggested that Mo$^{6+}$ substitutes for In$^{3+}$ sites and yields three excess electrons in IMO films [15].
that of In\textsuperscript{3+} in an In\textsubscript{2}O\textsubscript{3}-based TCO, since the dopant with a high Lewis acid strength (LAS) value could also be responsible for the high mobility of the IMO film. However, considering the previously reported mobility of the IMO films, the mobility of the hetero-sputtered IMO film was low since the activation and crystallization of the IMO films by RTA were less efficient than in situ high temperature substrate growth. To investigate the conduction mechanism in the IMO film, the resistivity was measured with decreasing and increasing sample temperatures. Temperature dependence for the resistivity for the optimized IMO film (600 °C annealed IMO) from 350 K to 2 K is shown in Fig. 1b. Regardless of IMO sample cooling or heating, the IMO film showed a positive dependence on temperature \((dp/dT > 0)\) implying that the IMO film possesses typical metallic characteristics due to its degenerate semiconductor properties similar to conventional ITO films \([21]\). The positive temperature dependence of IMO film resistivity could be explained by an electron–phonon scattering mechanism \([22]\). As the temperature was increased, conduction electron–phonon scattering increased, resulting in an increase in the resistivity of the IMO film. Gupta et al. have reported a similar metallic conduction mechanism for 100 nm thick IMO films fabricated by pulsed laser deposition \([23]\). They also explained that delocalization of electrons led to metallic conduction of the IMO film, which is a characteristic of degenerate semiconductors.

Fig. 2a shows the optical transmittance of IMO films as a function of RTA temperature. Regardless of the RTA temperature.

However, Yoshida et al. found that activated Mo dopant was not Mo\textsuperscript{6+} but rather Mo\textsuperscript{4+} based on X-ray photoelectron spectroscopy analysis \([16]\). In our previous work, we also reported that the content of Mo\textsuperscript{6+} dopant in the In\textsubscript{2}O\textsubscript{3} film critically affected on the electrical and optical properties of IMO film \([18]\). While there remains controversy over the exact activation mechanism of the Mo dopant, the activation of Mo\textsuperscript{6+} or Mo\textsuperscript{4+} dopant plays an important role in the reduction of resistivity of IMO films. Due to an effective activation of the Mo dopant, the carrier concentration of the IMO also increased with increasing RTA temperature as shown in Fig. 1a. For the IMO film, the large valence difference between Mo\textsuperscript{6+} and In\textsuperscript{3+} indicates that the IMO required less Mo dopant to achieve low resistivity \([15]\). Consequently, the IMO film exhibited a higher mobility than other TCO films due to the significant reduction of ionized impurity scattering, which is the main scattering mechanism of highly degenerated TCO films. In addition, high carrier mobility can be explained in terms of higher Lewis acid strength (LAS) of Mo dopant (3.667) compared with In\textsuperscript{3+} (1.026) \([8]\). As discussed by Wen et al., the ionized impurity scattering could be reduced if the LAS value of the dopant was higher than that of In\textsuperscript{3+} in an In\textsubscript{2}O\textsubscript{3}-based TCO, since the dopant with a higher LAS value would more strongly polarize the electronic charge from the valence band, resulting in screening of charges and reduced the scattering at the scattering center \([20]\). Therefore, the charge screening effect of the Mo\textsuperscript{6+} dopant with a high LAS value could also be responsible for the high mobility of the IMO film. However, considering the previously reported mobility of the IMO films, the mobility of the hetero-sputtered IMO film was low since the activation and crystallization of the IMO films by RTA were less efficient than in situ high temperature substrate growth. To investigate the conduction mechanism in the IMO film, the resistivity was measured with decreasing and increasing sample temperatures. Temperature dependence for the resistivity for the optimized IMO film (600 °C annealed IMO) from 350 K to 2 K is shown in Fig. 1b. Regardless of IMO sample cooling or heating, the IMO film showed a positive dependence on temperature \((dp/dT > 0)\) implying that the IMO film possesses typical metallic characteristics due to its degenerate semiconductor properties similar to conventional ITO films \([21]\). The positive temperature dependence of IMO film resistivity could be explained by an electron–phonon scattering mechanism \([22]\). As the temperature was increased, conduction electron–phonon scattering increased, resulting in an increase in the resistivity of the IMO film. Gupta et al. have reported a similar metallic conduction mechanism for 100 nm thick IMO films fabricated by pulsed laser deposition \([23]\). They also explained that delocalization of electrons led to metallic conduction of the IMO film, which is a characteristic of degenerate semiconductors.

Fig. 2a shows the optical transmittance of IMO films as a function of RTA temperature. Regardless of the RTA tem-
temperature, all of the IMO films showed a similar high transmittance in the visible wavelength region and a drop of the transmittance in the 600–800 nm wavelength regions. It was found that an average transmittance between 400 and 800 nm increased slightly with increasing RTA temperature. The 600 °C annealed IMO film showed a transmittance of 93.68% at 550 nm and an average transmittance of 84.86% in the 400–800 nm wavelength regions. In particular, IMO films showed much higher transmittance than conventional ITO films in the NIR region. For ITO films, a high carrier concentration led to a decrease in the NIR transmittance as shown in Fig. 2a. However, the IMO film showed fairly high NIR transmittance even though it had similar resistivity to the ITO film. This indicates that the IMO films contained a lower free carrier concentration than ITO films. The inset picture shows the transparency of the shadow mask patterned IMO anode after 600 °C annealing used to fabricate phosphorescent OLEDs. After 600 °C annealing, the patterned IMO film had a slight green color. To determine the optimal RTA temperature for IMO films to prepare phosphorescent OLEDs, the figure of merit value \( \frac{(T^{MAX}/R_{sh})}{n} \) was calculated using the average optical transmittance \( (T) \) and the sheet resistance \( (R_{sh}) \), as shown in Fig. 2b [24]. For IMO films, the figure of merit values were mainly affected by sheet resistance since all of the IMO film showed a similar transmittance regardless of RTA temperature as shown in Fig. 2a. The IMO film annealed at 600 °C showed the highest figure of merit value (11.46 × 10^{-2} Ohm^{-1}) as well as the lowest sheet resistance (16.9 Ohm/square, comparable to conventional ITO films (5–10 × 10^{-2} Ohm^{-1})). Based on the calculated figure of merit value of the IMO films, the optimum RTA temperature was determined to be 600 °C.

Fig. 3 shows the mean free path \( (l) \) of IMO films as a function of RTA temperature. Because the carrier mobility of the IMO film is closely related to the mean free path of the carrier, the mean free path \( (l) \) was calculated based on a sufficiently degenerate gas model as follows [25]:

\[
l = \left(3\pi^2\right)^{1/3} \times \left(\frac{h}{2\epsilon}\right) \times \frac{1}{\rho} \times n^{-2/3}
\]

where \( h = h/2 \), \( h' \) is Planck’s constant, \( \rho \) is the resistivity, \( n \) is the carrier concentration and \( 'e' \) is the electron charge. The calculated values are summarized in Table 1. With increasing RTA temperature, the \( l \) in IMO films increased. The 600 °C annealed IMO film provided the longest \( l \) of 5.80 nm, which is much smaller than the grain size of IMO film (50–70 nm) as measured by TEM analysis in Fig. 5a. This result indicates that the effect of scattering at the grain boundaries and dislocations can be ignored. Therefore, it is evident that scattering of the conduction electrons is mainly affected by neutral and ionized impurity scattering in the IMO films as discussed by Parthiban et al. [25].

Fig. 4 exhibits the synchrotron X-ray scattering results obtained from IMO films as a function of RTA temperature. For the as-deposited IMO film, in addition to a broad glass peak, there were weak (211), (222), (400), (440), and (622) peaks. The diffraction peaks of as-deposited IMO film were well matched with those of the standard cubic bixbyite \( \text{In}_2\text{O}_3 \) structure [26]. In addition, the as-deposited IMO films show similar intensities for the (222) and (400) peaks. However, it is noteworthy that the rapid thermal annealed IMO samples revealed a strong intensity of (222) peak, indicating that the annealed IMO films contained grains with (222) preferred orientation. On the basis of the synchrotron X-ray scattering results, it was proposed that the IMO films also have a tendency to grow with (222) texture when annealed in a vacuum. To investigate the detailed microstructure of the optimized IMO film with the preferred (222) orientation, HRTEM examination was performed. Fig. 5a shows a cross-sectional view of the optimized IMO film.

![Fig. 3](image-url)  
**Fig. 3.** Calculated mean free path \( (l) \) of an electron in IMO films with increasing RTA temperature as calculated from the resistivity and carrier concentration.

![Fig. 4](image-url)  
**Fig. 4.** Synchrotron X-ray scattering results of crystalline IMO film as a function of RTA temperature.

| Table 1 Calculated mean free path \( (l) \) of the electron in IMO film from the resistivity \( (\rho) \) and carrier concentration \( (n) \). |
|----------------------------------|------------------|------------------|------------------|
| Annealed temperature \( (°C) \) | Resistivity \( (\times 10^{12} \text{cm}^{-2} \text{cmVs}^{-1}) \) | Carrier concentration \( (n) \times 10^{20} \text{cm}^{-3} \) | Mean free path \( (l) \) \( (\text{nm}) \) |
| As-deposited | 30.7 | 1.29 | 1.62 |
| 400 °C | 43.2 | 6.02 | 1.92 |
| 500 °C | 7.21 | 3.24 | 3.74 |
| 600 °C | 4.25 | 3.71 | 5.8 |

HRTEM image of the optimized IMO film. As expected from the synchrotron X-ray scattering results, the IMO film showed a well-developed columnar structure with a very smooth surface morphology. Vertical columnar growth in the [001]/[002] direction normal to the interface was apparent in the HRTEM image. Compared to previously reported IMO films, grown at an in situ high substrate temperature [15–19], the post-annealed IMO film showed a very smooth surface morphology with a rectangular shaped columnar structure, unlike conventional DC sputtered ITO film with a long V-shaped columnar structure. The cross sectional HRTEM image in Fig. 5a shows that the rectangular grain size of the IMO film was 50–70 nm. The enlarged HRTEM images in Fig. 5b were obtained from the A’, B’, C’ and D’ strata of the IMO film shown in Fig. 5a. From the substrate region to the top region of the IMO film, the 600 °C annealed IMO film has a bixbyite structure. Regardless of the position (A’–D’), the enlarged HRTEM images show better crystallinity than conventional ITO films. In the cases of the C’ and D’, various oriented IMO can be seen. Strong spots in the Fourier transformation patterns obtained from the A’, B’, C’ and D’ regions confirm the better crystallinity of IMO films compared to conventional ITO films [27].

Fig. 6a shows surface FESEM images of the IMO films with increasing RTA temperature. Regardless of RTA temperature, all IMO films showed fairly smooth surface morphology as expected from the cross-sectional TEM image. The subgrain with (222) preferred orientation in the IMO films showed a fairly constant size with increasing RTA temperature. Fig. 6b shows the root mean square (RMS) roughness of the IMO films with increasing RTA temperature. The inset showed the surface AFM images of the IMO films as a function RTA temperature. With increasing RTA temperature, the IMO films slightly decreased RMS roughness from 1.285 to 1.209 nm.

To investigate the feasibility of IMO film as a highly transparent anode substitution of conventional ITO anode, phosphorescent OLEDs were fabricated on the optimized IMO film with a transparency of 84.86% and a sheet resistance of 16.9 Ohm/square. Fig. 7a is a schematic diagram showing the fabrication procedure for phosphorescent OLEDs on a patterned-IMO electrode. To minimize leakage of the IMO anode, a pinwheel-shape patterned anode was employed. 175 nm-thick multi-charge generation and recombination hole transport layers (HTLs) 1,1-bis-(4-bis(4-methyl-phenyl)-amino-phenyl)-cyclohexane (TAPC) (40 nm)/1,4,5,8,9,11-hexaazatriphenylene hexacarbonitrile (HATCN) (5 nm)/TAPC (40 nm)/HATCN (5 nm)/TAPC.

Fig. 5. (a) Cross-sectional HRTEM image of IMO film and (b) enlarged images denoted by A’, B’, C’ and D’ which were obtained from the HRTEM images. The inset shows Fourier transformation pattern obtained from the A’, B’, C’, and D’ regions of the IMO film.

Fig. 6. (a) Surface FESEM images of as-deposited, 400, 500, and 600 °C annealed IMO films. (b) RMS roughness of the IMO films with increasing RTA temperature with inset showing the surface AFM images.
(40 nm)/HATCN (5 nm)/TAPC (40 nm) were employed to simultaneously reduce the driving voltage and leakage current [28]. Next, a 15 nm thick 8 wt% tris(2-phenylpyridine) iridium (Ir(ppy)_3) doped 4,4',N,N'-dicarbazolebiphenyl (CBP) layer was deposited as a green emission layer (G-EML). 50 nm of bis-4,6-(3,5-di-3-pyridylphenyl)-2-methylpyrimidine (B3PYMPM) was used as the electron transport layer (ETL). The picture on the right side of Fig. 7a shows the green emission from the phosphorescent OLED with the IMO anode. Fig. 7b exhibits an energy level band diagram of the phosphorescent OLEDs, incorporating the optimized IMO anode. The work functions of the IMO anode and reference ITO anode were simultaneously determined with a Kelvin probe (Scanning Kelvin Probe 5050, KP Technology). The Kelvin probe measurement showed that the optimized IMO anode had a work function of 5.15 eV, which was higher than the conventional ITO anode (4.9 eV). In addition, the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) energy levels of TAPC, CBP and Ir(ppy)_3 were measured using cyclic voltammetry and UV/visible absorption spectroscopy, while the HOMO and LUMO energy levels of HATCN and B3PYMPM were determined by UPS and UV/visible absorption spectroscopy [29,30]. From the energy level band diagram, it would be expected that hole injection into the TAPC from the IMO anode would be more efficient than from ITO anode due to its higher work function.

Fig. 7a shows the J–V–L characteristics of phosphorescent OLEDs fabricated on IMO and reference ITO anodes. In spite of the slightly higher sheet resistance of the IMO anode compared to the reference ITO anode (15 Ohm/square), the J–V curves of the phosphorescent OLED with either the IMO anode or the reference ITO anode had similar forward bias current densities. However, the OLED with the IMO anode had a slightly higher leakage current density at the initial forward bias region below 2 V because the IMO anode was patterned with a metal shadow mask, as shown in the inset of Fig. 2a. It was thought that the initial leakage current density of the OLED with the IMO anode was caused by the shadow effect during the hetero target sputtering with a tilted cathode gun. Therefore, it was necessary to develop an appropriate etchant for the IMO film to avoid leakage current in the initial voltage region. However, phosphorescent OLEDs with IMO and ITO anodes showed similar turn-on voltages at 2.70 and 2.71 V, respectively. In spite of the difference in work function, shown in Fig. 7b, the OLEDs showed similar turn-on...
voltage due to good ohmic contact properties between the anode and TAPC layer. The $L-V$ curves of the phosphorescent OLED with either IMO or ITO anodes also showed a similar steep increase after onset. As expected in the $J-V$ curve, the phosphorescent OLED with the IMO anode had a similar high luminance to that of the OLED with the ITO anode. Fig. 8b shows the external quantum efficacy of the phosphorescent OLEDs with IMO and reference ITO anodes. Similar to the $J-V-L$ curve, both OLEDs showed the same high external quantum efficacy (~18.2%). However, the OLEDs with IMO anode shows slightly lower quantum efficiency due to lower optical transmittance in the green wavelength region as shown in Fig. 2a.

Fig. 9 shows the EL spectra obtained from phosphorescent OLED with IMO and reference ITO anodes. As expected from $J-V-L$ results, EL spectra of the OLED with IMO anode similar to that with reference ITO anode. Because the all organic and cathode layers on the anode layer were identical, similar EL spectra of the OLED with different IMO and ITO anode indicated that the IMO anode could substitute conventional ITO anode. As a result, the overall performance of phosphorescent OLEDs with a green emission layer (G-EML) together with the IMO anode was comparable to that of phosphorescent OLEDs with the ITO anode. However, if a red or NIR emitting EML were employed, we would expect an improvement in phosphorescent OLED performance due to the IMO film’s high transmittance in the NIR region.

4. Conclusions

We have demonstrated that a high NIR transparent IMO anode can substitute for conventional ITO anodes in conjunction with phosphorescent OLEDs. At an optimized RTA temperature of 600 °C, the IMO had a comparable sheet resistance of 16.9 Ohm/square and higher optical transmittance of 84.86% to conventional ITO electrodes. Due to the low Mo dopant concentration and high LAS value of the Mo dopant, the IMO film showed fairly high mobility and high transmittance in the NIR region. In addition, improved crystallinity of the IMO film after RTA played an important role in reducing the resistivity by increasing carrier mobility. Phosphorescent OLEDs with the IMO anode showed almost identical $J-V-L$ curves, external quantum efficiency, and EL spectra to phosphorescent OLEDs with an ITO anode due to the high transmittance and low sheet resistance. Identical performance of the phosphorescent OLEDs with the IMO anode indicates that IMO film is a viable alternative to conventional ITO electrodes in phosphorescent OLEDs.

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