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Short communication

Effect of charge carrier behaviours in LiF-doped bathophenanthroline (LiF:Bphen) on the performance of organic light-emitting diodes

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ABSTRACT

Charge carrier behaviours of LiF-doped bathophenanthroline (LiF:Bphen) were investigated by single carrier devices: electron-only and hole-only devices. The results indicate that LiF doped with Bphen has dual roles: increasing current density due to enhanced electron injection and transport; decreasing current density owing to capture of holes. In electroluminescent (EL) devices, all doped devices show higher luminance and efficiency than the undoped device. Current density and luminance of doped devices are decreased because hole leakage current decreases with LiF doping level. Compared with the undoped device, 5:100 LiF:Bphen-based EL device exhibits an improved current density. For 10:100 LiF:Bphen-based EL device, current density is smaller at lower electrical field but larger at higher electrical field than that of the undoped device. At higher doping level (15:100 LiF:Bphen), smaller current density than the undoped device is observed. The operation voltage can be lowered by optimizing LiF doping level in electron transport layers.

Organic light-emitting diodes (OLEDs) have become one of candidates for flat panel displays and been of great interest for next-generation lighting sources because of their promising features[1-3]. As double charge carrier injection devices, carrier behaviours play an important role of device performance. A mass of investigations of carrier behaviours in organic semiconductors have been demonstrated that efficient carrier injection and transport are critically beneficial for high-performance OLEDs. It is well-known that organic semiconductors have lower carrier concentration and mobility compared to inorganic semiconductors[4-6], leading to higher operation voltage of OLEDs than that of inorganic counterparts. In order to reduce operation voltage, one can decrease the thickness of films and/or improve electrical conductivity of materials.

Electrical doping (*p*-type and *n*-type) has been proved to effectively enhance electrical conductivity of organic semiconductors due to increased free charge carrier density[7-9]. *P*-type doping can be easily created by incorporating strong electron acceptors (e.g. 2,3,5,6-tetrafluoro-7,7,8,8- tetracyanoquinodimethane, F_4-TCNQ[8,9]) or oxidants (MoO_x[10], ReO_3[11] etc.) in hole transport layers (HTLs). However, *n*-type dopants need to be strong electron donors and are consequently rare because of stability issues induced by oxidation. Typical *n*-type dopants include low-work-function alkaline metals (e.g. Li[8,9,12]and Cs[13-15]) and their compounds (LiF[16,17] and Cs_2CO_3[18-20] etc.). Alkaline metals are very sensitive to oxygen and humidity. In contrast, their derivatives are better candidates for replacing reactive metals since these materials are not sensitive to oxygen and thus have been widely investigated to improve OLED performance.

LiF, the earliest used alkaline metal compound, can enhance electron injection as a buffer layer between organic layers and metal cathodes and thus reduces driving voltages of devices[21]. Meanwhile, LiF as an *n*-type dopant in electron transport layers (ETLs) can greatly reduce resistivity and enhance carrier mobility compared with undoped samples, resulting in a low-driving voltage diode[17]. Afterwards, many other alkaline metal compounds are explored in the development of OLED technology [20,22-23]. Nevertheless, LiF still remains the most commonly used by far because of its excellent electrochemical stability.

In this work, LiF was served as an *n*-type dopant in bathophenanthroline (Bphen) to reduce driving voltage of devices. Firstly, charge carrier behaviours of LiF-doped Bphen (LiF:Bphen) were investigated by fabricating single carrier devices: electron-only devices of ITO/bathocuproine(BCP, 15nm)/tris(8-

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hydroxyquinoline)aluminum(Alq$_3$, 40nm)/LiF:Bphen(x, 20nm)/LiF(0.5nm)/Al and hole-only devices of ITO/N,N'-diphenyl-N,N'-bis(1-naphthyl-phenyl)-1,1'-biphenyl-4,4'-diamine(NPB, 40nm)/Alq$_3$(40nm)/LiF:Bphen(x, 20nm)/NPB(40nm)/Al, x=0:100, 5:100, 10:100, 15:100 by weight ratio. Then, LiF:Bphen was employed as an ETL to fabricate electroluminescent (EL) devices: ITO/NPB(40nm)/Alq$_3$(40nm)/LiF:Bphen(x, 20nm)/LiF(0.5nm)/Al. The energy levels and device configurations are depicted in Fig. 1. All devices were fabricated on ITO-coated glass substrates, cleaned by sonication in de-ionized water, alcohol and isopropanol and followed by O$_2$ plasma for 7 minute at a power of 75W under a pressure of 50–100Pa. All materials (BCP, NPB, Alq$_3$, Bphen, LiF and Al), used as received, were evaporated on the substrates in turn under a pressure of 10^{-6}Torr. The thickness and deposition rate are monitored *in situ* by a series of 6MHz quartz-crystal oscillators during evaporation. LiF:Bphen were performed by thermal co-evaporation from independent sources and the composition is determined with the deposition rate. Current density–voltage–luminance (J–V–L) characteristics were simultaneously recorded by a software-controlled Keithley 2400 source meter combined with CS2000 spectrometer after preparation at room temperature under ambient condition.

Generally, in OLEDs, both electrons and holes are present and can be trapped inside semiconductors[24]. That is, both electron and hole traps are present. Nevertheless, in unipolar diodes, only single carriers are present. For instance, in electron-only devices, there is hardly any hole injected from ITO anode due to deep HOMO (the highest occupied molecular orbital) level of BCP (Fig. 1(a)). Likewise, in hole-only devices, electrons are absent due to shallow LUMO (the lowest unoccupied molecular orbital) level of NPB (Fig. 1(b)). This can be verified by the absence of detectable EL signals.

J–V characteristics of electron-only devices are illustrated in Fig. 2. The data clearly show that doping results in much higher currents compared to the undoped device. These results are in good agreements with other reports[17]. The phenomena are attributed to better electron transport property of doped layers, probably induced by filling of intrinsic electron traps in Bphen by LiF doping [17]. Similarly, J–V curves of hole-only devices are displayed in Fig. 3. Double-logarithmic plots of J–V in Fig. 4 yield a power law behaviour of $J \propto V^{m+1}$, where m+1 is 7.3, 6.5, 13.5 and 14.9 for the devices with 0:100, 5:100, 10:100 and 15:100 LiF:Bphen, respectively. This indicates that trapped-charge-limited current (TCLC) [25] dominates the hole transport in hole-only devices. And the increase of m+1 would imply that hole trap depth and density

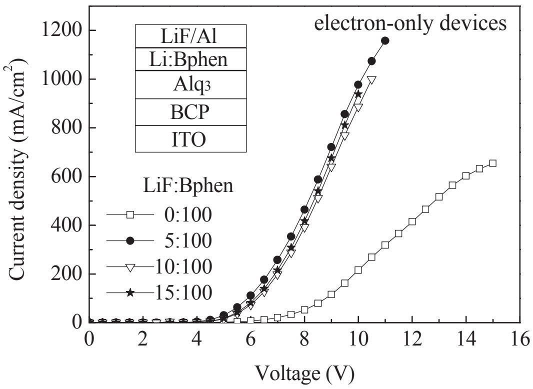


Fig. 2. Cross section and J–V characteristics of electron-only devices with various ratios of LiF:Bphen

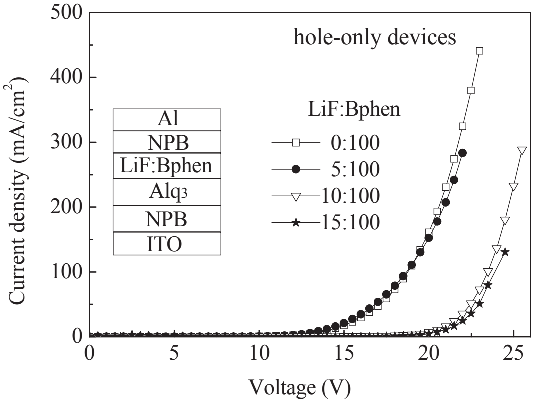
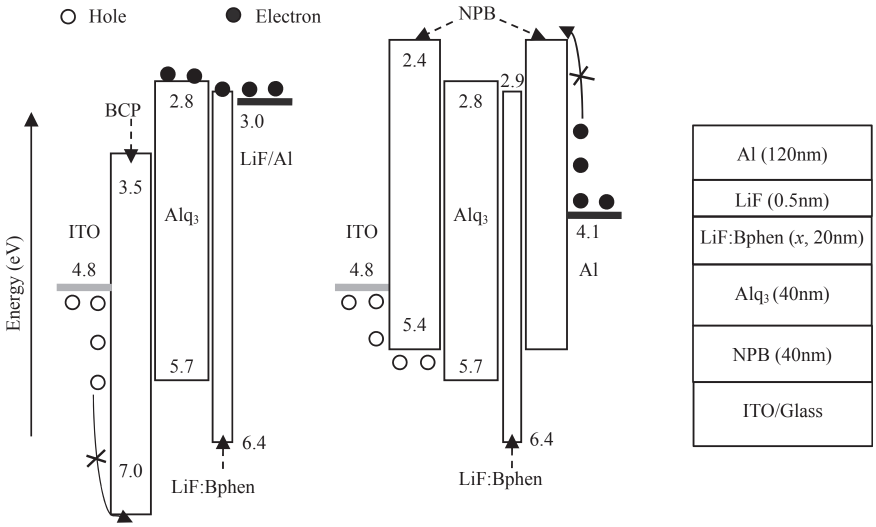


Fig. 3. Cross section and J–V plots for hole-only devices with different concentrations of LiF:Bphen



(a) electron-only devices (b) hole-only devices (c) EL devices

Fig. 1. Energy levels and structures of devices in the experiments