

## Bright and Efficient Electrophosphorescence from Polymer Based LED

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### Abstract

The electrophosphorescent emission properties were investigated in polymer light-emitting diodes (PLEDs) based on a poly(9-vinylcarbazole) (PVK) doped with a green phosphorescent dye of fac-tris(2-phenylpyridine) iridium (III) [Ir(ppy)<sub>3</sub>]. A green light peaked at 516 nm was emitted from devices with a configuration of ITO/PEDOT:PSS/PVK:Ir(ppy)<sub>3</sub>/BCP/Alq<sub>3</sub>/LiF/Al. The optimal doping concentration of Ir(ppy)<sub>3</sub> in PVK was found at 2% by weight, under which maximum current efficiency of 24.3 cd/A and peak external quantum efficiency of 6.8% were achieved at the high luminance of 4240 cd/m<sup>2</sup>. The external quantum efficiency of 5% and current efficiency of 18 cd/A can be sustained even at the very high luminance of 35000 cd/m<sup>2</sup>.

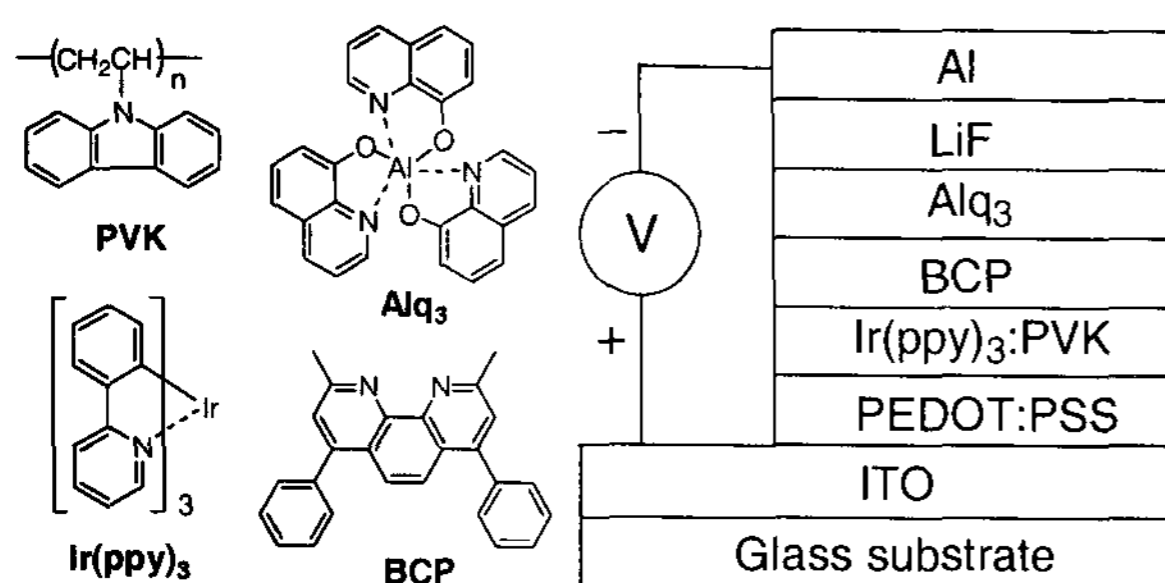
### 1. Introduction

Recently, effective external quantum efficiency ( $\eta_{EQE}$ ) of 19% photons/electron and luminance power efficiency ( $\eta_p$ ) of 70 L/W have been demonstrated in small molecule organic light-emitting diodes (OLEDs) [1,2]. The reason is that nearly 100% internal emission quantum efficiency can be obtained by harvesting both singlet and triplet excitons in OLEDs doped with phosphorescent emitters containing heavy metals since the strong spin-orbit coupling of a heavy metal enhances inter-system crossing and mixes the single and triplet states [1-3].

Phosphorescent dopants have also been applied to OLEDs based on polymers [4-14]. An important advantage of polymer-based OLEDs over their small-molecule counterparts is their compatibility with solution processing. This potentially allows a lower cost of production using room temperature spin-coating, screen printing or ink-jet printing techniques.

Using a single 100-200nm thick blend of hole-transporting poly(9-vinylcarbazole) (PVK) and an electron-transporting 2-(4-biphenyl)-5-(4-tert-butylphenyl)-1,3,4-oxadiazole doped with tris[9,9-dihexyl-2-(pyridinyl-2') fluorene] iridium (III), Gong et al [12] demonstrated a high  $\eta_{EQE}$  of 10% photons/electron at an optimal doping concentration of 0.3wt%. However, the highest luminance of 8320 cd/m<sup>2</sup> was observed at a doping concentration of 1 wt% with corresponding current efficiency ( $\eta_c$ ) of 11 cd/A. Using a double-layer structure of fac tris(2-phenylpyridine) iridium(III) - Ir(ppy)<sub>3</sub> - doped PVK as the hole-transport layer and 1,3-bis[(4-tert-butylphenyl)-1,3,4-oxadiazolyl] phenylene as the electron-transport layer, Yang et al [13] reported a high  $\eta_p$  of 5.8 L/W and high  $\eta_{EQE}$  of 7.5% photons/electron at the luminance of 106 cd/m<sup>2</sup>. However, the highest luminance of about 5000 cd/m<sup>2</sup> was observed at 25 V and 50 mA/cm<sup>2</sup> with corresponding  $\eta_c$  about 10 cd/A. Adding a hole-blocking layer, Vaeth et al [14] recently reported a high  $\eta_{EQE}$  of 8.5% in a relatively more complex triple-layer device. The highest luminance of about 12500 cd/m<sup>2</sup> was observed at 60 mA/cm<sup>2</sup> with corresponding  $\eta_c$  of 21 cd/A.

In this paper, we constructed EL devices as shown in Figure 1. The optimal doping concentration of Ir(ppy)<sub>3</sub> in PVK was found at 2% by weight, under which maximum  $\eta_c$  of 24.3 cd/A,  $\eta_p$  of 4.5 L/W, and peak external quantum efficiency of 6.8% were achieved at the high luminance of 4240 cd/m<sup>2</sup>. The highest luminance of 35000 cd/m<sup>2</sup> can be achieved at 1950 A/m<sup>2</sup> with corresponding  $\eta_{EQE}$  of 5% and  $\eta_c$  of 18 cd/A, respectively. This 74% sustentation of peak  $\eta_{EQE}$  is also unusual in both OLED and PLED.



**Fig. 1.** The structures of chemicals and an EL device.

## 2. Experimental

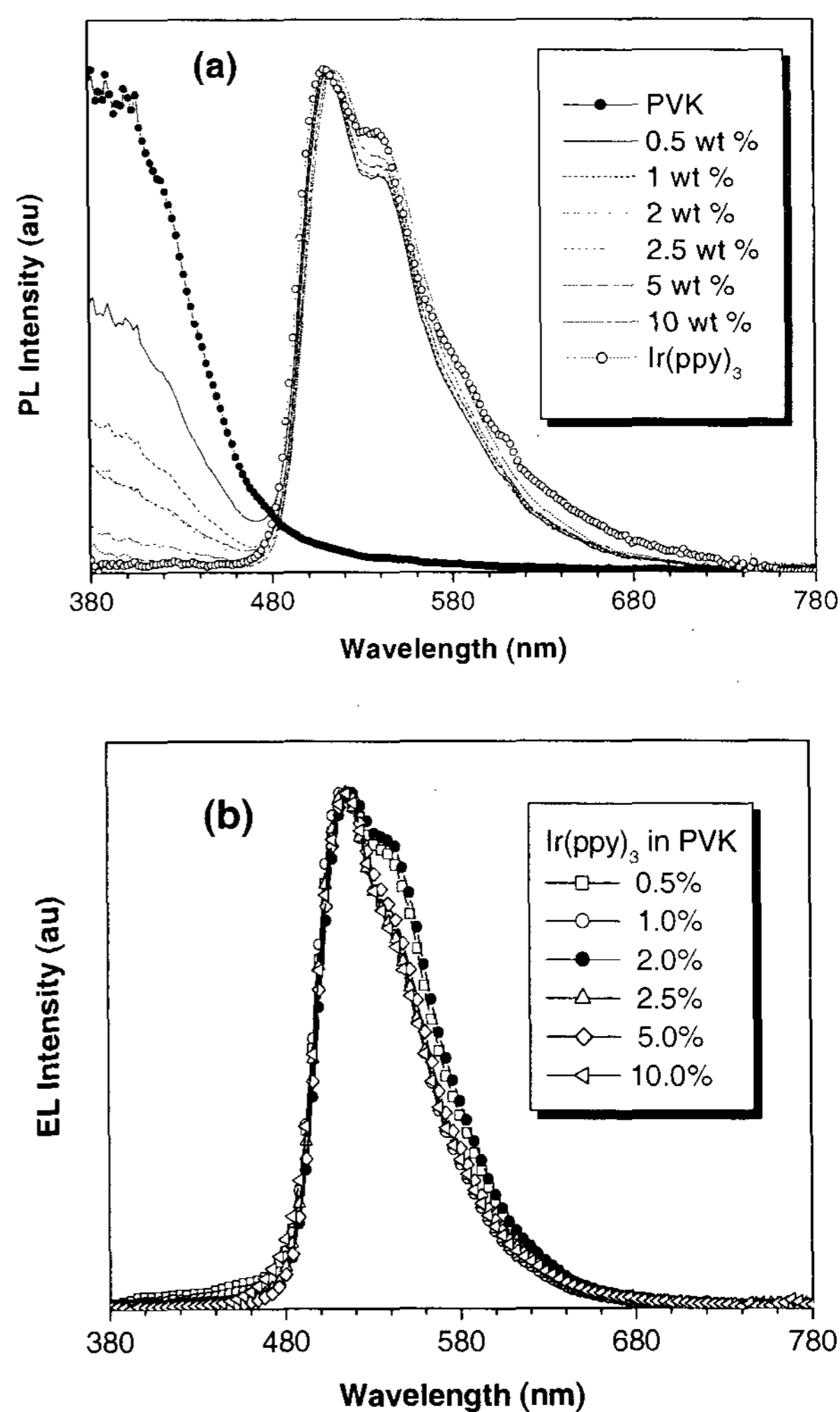
Glass coated with 70nm, 30  $\Omega/\square$  indium-tin oxide (ITO) was used as the starting substrate. The sequence of pre-cleaning prior to the deposition of the organic layers consisted of a 50°C ultrasonic detergent soak for 30min, de-ionized water spray for 10min, ultrasonic de-ionized water soak for 30min, 110°C oven bake dry for 1-2hr and ultra-violet/ozone illumination for 10min. Sequential spin-coatings of 60nm poly(ethylene dioxythiophene): poly(styrene sulfonic acid) (PEDOT:PSS) and 50nm Ir(ppy)<sub>3</sub> doped PVK at room temperature under ambient conditions were followed by 54°C vacuum oven solvent evaporation and bake dry for 2hr. Subsequently, 50nm BCP or Alq<sub>3</sub> were deposited by thermal vacuum evaporation in a chamber with a base pressure of 1  $\mu$ Torr. The cathode, consisting of 1nm lithium fluoride (LiF) and 150nm aluminum (Al) [15], was subsequently evaporated through a shadow mask. The layer thickness during evaporation was measured in situ using a quartz crystal monitor. A Tencor P-10 Surface Profiler was used to determine the thickness of the spin-coated films.

Electro-luminescence (EL) photometric characteristics were measured using a Kollmorgen Instrument PR650 photo-spectrometer. Current-voltage characteristics were measured using a Hewlett-Packard HP4145B Semiconductor Parameter Analyzer.

## 3. Results and discussion

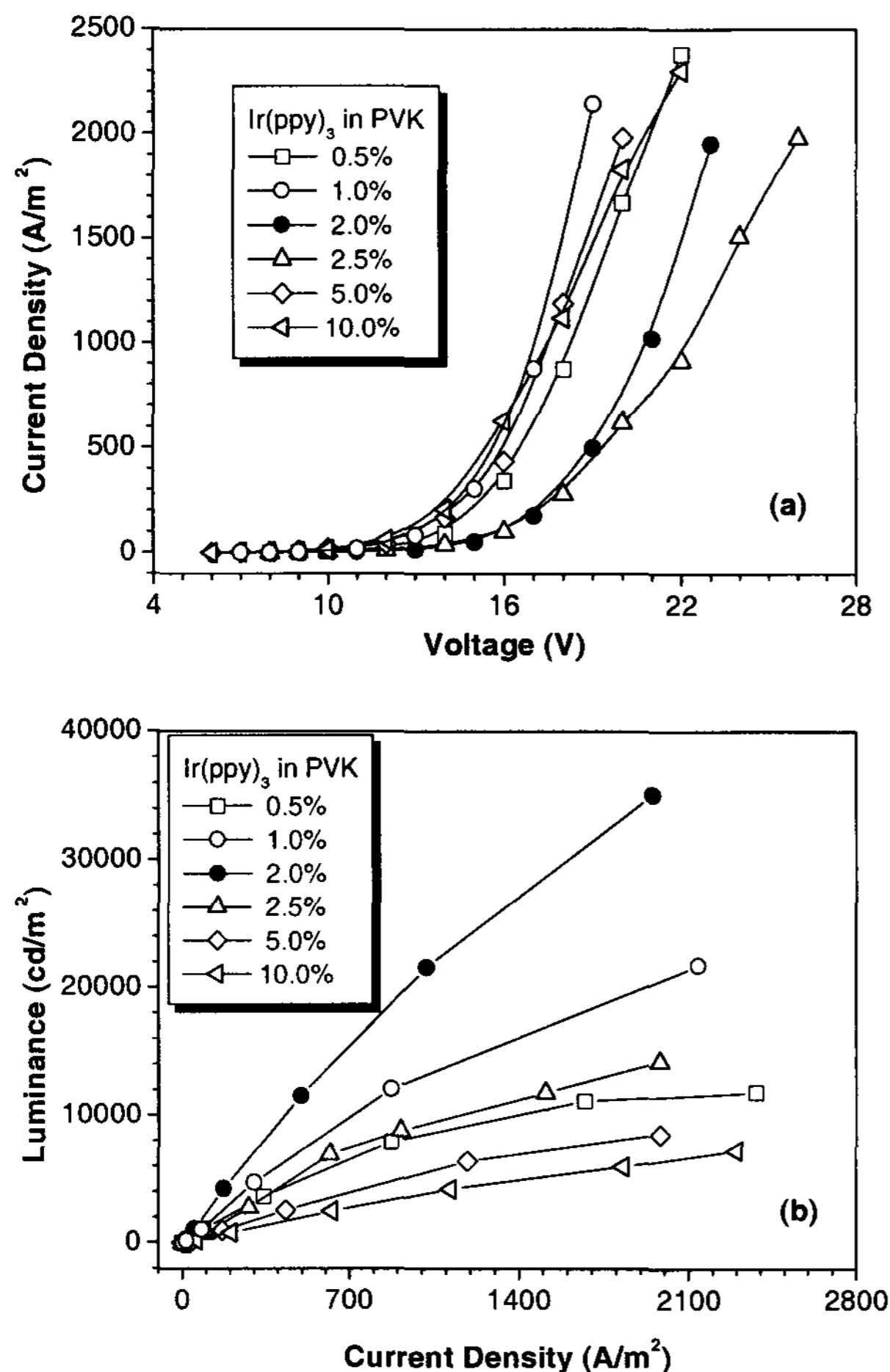
Excited using the 337nm line of a He-Cd laser, the normalized photo-luminescence (PL) spectra of pure Ir(ppy)<sub>3</sub>, PVK doped with various concentrations of Ir(ppy)<sub>3</sub> and pure PVK are shown in Fig. 2(a). PL peaks are observed at ~400nm for PVK singlet

emission and at ~516nm for Ir(ppy)<sub>3</sub> triplet emission. Below a critical Ir(ppy)<sub>3</sub> concentrations of 10wt%, the Förster transfer of excitons is incomplete because of the larger average separation between an excited site on the PVK host and an Ir(ppy)<sub>3</sub> dopant. Therefore an emission near ~400nm attributed to the PVK host is observed. The separation reduces and the exciton transfer efficiency and improves with increasing concentration of Ir(ppy)<sub>3</sub>, leading to almost complete disappearance of the emission near 400nm at Ir(ppy)<sub>3</sub> concentrations above 10wt%.



**Fig. 2.** (a) PL spectra of pure Ir(ppy)<sub>3</sub>, PVK doped with various concentrations of Ir(ppy)<sub>3</sub> and pure PVK. (b) EL spectra of PVK doped with various concentrations of Ir(ppy)<sub>3</sub>.

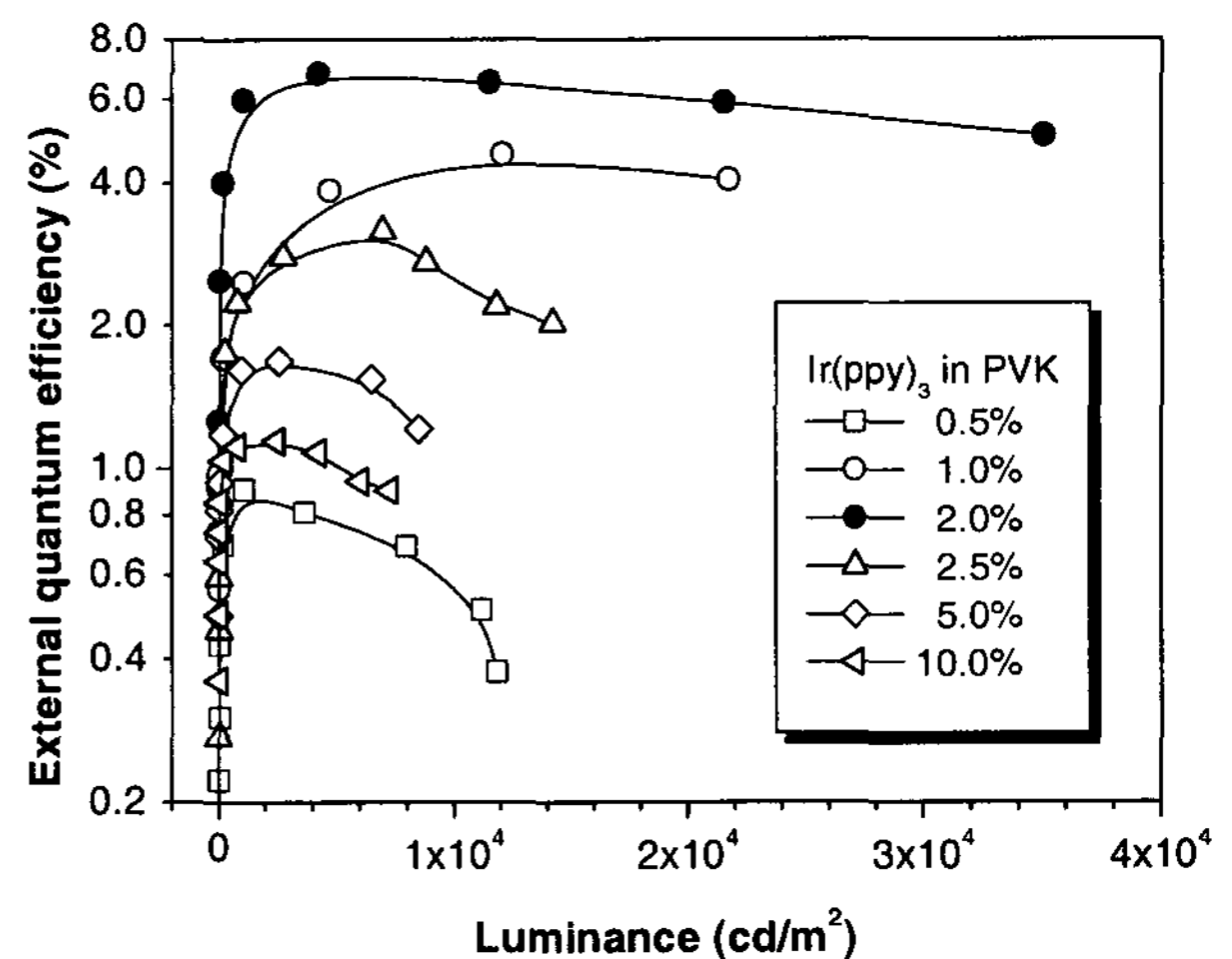
The EL spectra of the devices are shown in Figs. 2(b). Unlike the PL spectra, the most distinguishing feature of the EL spectra are the absence of any PVK-induced emission near  $\sim 400\text{nm}$  and all EL spectra are quite similar, irrespective of the  $\text{Ir(ppy)}_3$  concentration. The absence of major PVK related emission features implies a charge trapping rather than an exciton transfer mechanism [16].



**Fig. 3. (a) Current density (J) –Voltage (V) characteristic of the devices with various doping concentrations. (b) Luminance (L)-Current density (J) characteristic of the devices with various doping concentrations.**

The Current density–Voltage ( $J$ - $V$ ) and Luminance–Current density ( $L$ - $J$ ) characteristics of the diodes are shown in Figs. 3(a) and 3(b), respectively. It can be seen that both ( $L$ - $J$ ) and ( $J$ - $V$ ) curves show large

change with the variation of the doping concentration. On the ( $V$ - $J$ ) characteristics at the same voltage [Fig. 4(a)], the lower current density are observed at the  $\text{Ir(ppy)}_3$  concentration in the range of 2 ~ 2.5 wt%. Beyond this range, the current density becomes higher. For the ( $L$ - $J$ ) characteristics at the given current density [Fig. 4(b)], the luminance increases with increasing  $\text{Ir(ppy)}_3$  concentration from 0.5 to 2wt%. Further increasing the concentration results in a decrease in luminance.



**Fig. 4. Dependence of the External quantum efficiency on Luminance of the devices with various doping concentrations.**

The dependences  $\eta_{EQE}$  on Luminance of the devices with various doping concentrations are shown in Fig. 4. At the given current density, the  $\eta_{EQE}$  increases with increasing  $\text{Ir(ppy)}_3$  concentration from 0.5 to 2wt%. Further increasing the concentration results in a decrease in  $\eta_{EQE}$ . A peak  $\eta_{EQE}$  of 6.8% can be obtained at 2wt%. The corresponding current efficiency and  $\eta_p$  are  $24.3 \text{ cd/A}$  and  $4.5 \text{ L/W}$ , respectively. Beyond this optimal concentration, the emission efficiency decreases due to aggregate quenching [12]. Surprisingly, the highest luminance can be achieved up to  $35000 \text{ cd/m}^2$ , to my knowledge, which is best luminance for polymer LED so far. Under the highest luminance, the  $\eta_{EQE}$  can be sustained even at 5%, which is 74% of its peak  $\eta_{EQE}$ .

**Table 1. Characteristics of the devices with 2wt% doping concentration and comparison with Vaeth's.**

	luminance	Current density	$\eta_c$	$\eta_p$	$\eta_{EQE}$
	$cd/m^2$	$A/m^2$	$cd/A$	$L/W$	%
Ours	11500	496	23.3	3.84	6.52
	21600	1020	21.1	3.15	5.90
	35000	1950	18.0	2.45	5.03
Vaeth	12500	600	21.0	~3.5	~5.9

Table 1 summarizes the characteristics of our device with 2wt% doping concentration under very high luminance. The best luminance and its corresponding device efficiencies are also list for comparison. Clearly, at the luminance of 11500  $cd/m^2$ , which is almost same to Yaeth's, all efficiencies of our device are better than those of Vaeth. If the luminance is twice to Yaeth's, all efficiencies are nearly same to the results of Yaeth. When the luminance is up to 35000  $cd/m^2$ , which is nearly three times enhancement, all efficiencies of our device are also comparable with the Yaeth's.

#### 4. Conclusion

In conclusion, the performance of OLEDs fabricated with Ir(ppy)<sub>3</sub> doped PVK as phosphorescent emitting layer has been studied. It is found that at the optimal concentration of 2wt%, a peak  $\eta_{EQE}$  of 6.8% and  $\eta_p$  of 24.3  $cd/A$  can be obtained at high luminance of 4240  $cd/m^2$ . Even at the highest luminance of 35000  $cd/m^2$ , the 74% of peak  $\eta_{EQE}$  can be sustained.

#### 5. References

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