Improved Light Extraction Efficiency of Organic Light Emitting Diode using Photonic Crystals

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Abstract: In this work modelling of two dimensional of a fluorescence based Organic Light Emitting Diode (OLED) using plastic as flexible substrate is presented. The Finite Difference Time Domain (FDTD) mathematical modelling has been used to analyse the light extraction efficiency from fluorescence based Organic Light Emitting Diode (OLED). The OLED structure has been simulated by using 2D Hexagonal photonic crystal lattice. The Finite Difference Time Domain (FDTD) method is used to model and simulate the OLED structure. An enhancement of Internal Quantum Efficiency (IQE) and Light Extraction Efficiency (LEE) has been achieved by inserting Photonic Crystal above the emissive layer. The improvement in the extraction efficiency of OLED structure is achieved by increasing the radiative decay rate and by optimizing the angular distribution of light through the substrate.

1 INTRODUCTION

Organic Light Emitting Diode is an electroluminescence device which is formed using double layer structure of organic layers to produce light emission. This is achieved by driving voltage as dc source below 10 Volts (Tang and VanSlyke, 1987). If the radiative decay is high due to singlet exciton, then the process is said to be Fluorescence. In order to improve the extraction efficiency, the Photonic crystals is used upon the glass substrate to realize low power consumption using Nano imprint lithography technique which showed better performance than conventional OLEDs (Lee et al., 2003).

The state-of-art OLED stack is reviewed to determine radiative quantum efficiency and device efficiency during electrical operation which showed the significant results by varying electron transport layer. The efficiency is increased by incorporating various carrier transport layers in the OLED with different work functions (Do et al., 2003). The Silicon Nitride Photonic Crystals (PC) are used to control light which is acting as a dielectric medium to extract maximum amount of photons which is trapped in high index guided structures.

However different experiments on Organic LEDs are carried out using different structures of the Photonic crystals, substrates and the materials of the substrate may affect the thermal resistance (Kim et al., 2004). In this paper Poly (ethylene terephthalate) (PET) is used as a Plastic Substrate. PET has greater flexibility, robustness and is less expensive compared to glass substrate. The PET is a polymer electrode with high transmission in visible range of about 87% (Faraj et al., 2011).

Propitious research work is being carried out aiming at increasing the light extraction efficiency of OLED. In this paper an OLED with photonic crystals using plastic as flexible substrate with a point dipole source to increase the number of excitons in the emissive layer has been presented.

2 OLED STRUCTURE

2.1 Proposed Design

Figure 1, shows the structure of two dimensional OLED which is modelled using Numerical FDTD (Finite Difference Time Domain). The proposed structure uses plastic as a flexible substrate. The modelled device structure consists of thin active organic layers which are integrated with the transport layers. The radiative recombination of injected electrons and holes is taken place in the organic layers. These transport and organic Layers
which is about 200nm is placed between anode and cathode layer placed on a plastic substrate.

<table>
<thead>
<tr>
<th>Plastic Substrate=500nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photonic crystals: Lattice Constant(a)=350nm, Radius of crystal=150nm</td>
</tr>
<tr>
<td>Cover layer SiN=700nm</td>
</tr>
<tr>
<td>Anode ITO =120nm</td>
</tr>
<tr>
<td>HIL =CuPc=15 to 30nm</td>
</tr>
<tr>
<td>HTL= TPD =40nm</td>
</tr>
<tr>
<td>α-NDP =30nm</td>
</tr>
<tr>
<td>Alq3=60nm</td>
</tr>
<tr>
<td>HBL=BCP=30nm</td>
</tr>
<tr>
<td>Cathode =Al=100nm</td>
</tr>
</tbody>
</table>

Figure 1: Fluorescence based OLED.

This device has been simulated using materials described in Table 1, green light is simulated having a peak wavelength of 540nm.

2.2 Modelling of Photonic Crystals in OLED

Figure 2, shows the modelled Photonic Crystal (PC), used in OLED. The PC used in this work has lattice constant of 350nm and radius is of 150nm. The simulation is done using Photonic crystal made up of Silicon Nitride which has refractive index of 1.9.

3 OLED MATERIALS

The samples used in the structure are described in Table 1. The materials are chosen depending on the energy levels at metal organic interface abiding by Mott Schottky limit. The work function of electrodes, thickness variations and Organic Layers with the HOMO (Highest Occupied Molecular Orbital) and LUMO (Lowest Unoccupied Molecular Orbital) levels of organic molecules are given.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Work Function (eV)</th>
<th>Refractive index(n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indium Tin Oxide</td>
<td>4.7</td>
<td>1.806</td>
</tr>
<tr>
<td>Aluminium</td>
<td>4.1</td>
<td>1.031</td>
</tr>
<tr>
<td>Hole Blocking Layer (HBL)-BCP</td>
<td>3.2</td>
<td>1.686</td>
</tr>
<tr>
<td>Hole Injection layer(HIL)-CuPC</td>
<td>3.1</td>
<td>0.47</td>
</tr>
<tr>
<td>Hole Transport layer(HTL)-TPD</td>
<td>2.6</td>
<td>1.67</td>
</tr>
<tr>
<td>Alq3-Tris(8-hydroxyquinoline) aluminium</td>
<td>HOMO-5.62/eV LUMO- 2.85/eV</td>
<td>1.68</td>
</tr>
<tr>
<td>α-NDP-N,N’-diphenyl-benzidine</td>
<td>2.5</td>
<td>1.82</td>
</tr>
<tr>
<td>Cover layer –SiN</td>
<td>----</td>
<td>1.9</td>
</tr>
<tr>
<td>Substrate-Plastic</td>
<td>----</td>
<td>1.53</td>
</tr>
</tbody>
</table>

The most commonly used HIL is CuPC (Copper (II) phthalocyanine) is used to improve the carrier injection efficiency. The HTL used here is TPD (N, N’-Bis (3-methylphenyl)-N, N’-diphenylbenzidine). The hole transport layer and hole injection layer placed above organic layers. The hole injection layer is used to improve the carrier injection efficiency, and serves two purposes, first, it provides a path for smooth travel of injected holes up to emitting layer. Second, it functions like electron blocker to confine electrons within an emitting layer. The HBL used is BCP (2, 9 Dimethyl-4, 7-diphenyl-1, 10 phenanthroline with a work function 3.2eV. The organic layers used in the structure are α-NDP (N, N’-Di [1-naphthyl]-N, N’-diphenyl-(1, 1’-biphenyl)-4, 4’diamine) and Alq3- (Tris-(8-hydroxyquinoline) aluminium). The effective double injection is possible when the work function of metal electrodes
is close to Lowest Unoccupied Molecular Orbital (LUMO) and Highest Occupied Molecular Orbital (HOMO) for Organic materials (Narayan et al., 2013).

4 METHODOLOGY

The Finite difference Time Domain (FDTD) method is used for solving Maxwell’s equations in complex geometries. The Maxwell’s equations are time dependent hence, FDTD simulations has high performance optical solver which can capture using wavelength scale structure to improve the device. In order to achieve the maximum radiative decay, the derivation is published in (Novotny and Hecht, 2006), where the quantum radiative decay is proportional to classical dipole power radiated, the relationship as in equation (1)

\[ \Gamma_{\text{decay}} = P_{\text{rad}} \]  

(1)

This relation is shown to relate the radiative decay rate to Fermi’s golden rule about the density of photonic modes which is represented in equation 2, as represented in (Joannopoulos et al., 2008),

\[ \Gamma_{ij} \propto |M_{ij}|^2 \rho(v_{ij}) \]  

(2)

where \( \Gamma_{ij} \) = transition rate from higher energy state i to lower energy state j, \( M_{ij} \) related to wave function overlap of excited states, \( \rho(v_{ij}) \) is photonic mode density of transition.

In this work two results have been interpreted, Internal Quantum Efficiency (IQE) and Light Extraction Efficiency (LEE) (Chutinan et al., 2005).

The Internal Quantum efficiency is the radiative decay process achieved by relating decay rate to the power radiated by the single dipole source. With the dipole source implementation, we can formulate IQE. From, Fermi’s Golden rule, we can relate decay rate to density of states and is related to Classical EM power emitted by a dipole to imaginary part of green’s function (Novotny and Hecht, 2006).

The decay rate enhancement is given by,

\[ \frac{\gamma_{\text{decay}}}{\gamma_{\text{source}}^0} = \frac{\text{dipole power}}{\text{source power}} \]  

(3)

The Light Extraction Efficiency (LEE) is defined as the fraction of optical power generated in the active layer of the OLED that escapes into the air above the OLED within a desired range of angles.

\[ LEE = \frac{\gamma_{\text{rad}}}{\gamma_{\text{rad}} + \gamma_{\text{loss}}} = \frac{\text{LEE}_{\text{pattern}}}{\text{LEE}_{\text{no-pattern}}} \]  

(4)

where, \( \gamma_{\text{rad}} \) = Electro Magnetic decay to Far-field radiation, \( \gamma_{\text{loss}} \) = EM decay trapped by Total Internal Reflection

The light escaping to the glass substrate within a particular solid angle (e.g. bounded by the TIR critical angle) is considered. Therefore, the total extraction efficiency (TEE) is given by, combination of internal quantum efficiency (IQE) and Light extraction efficiency (LEE).

\[ TEE = IQE \times LEE \]  

(5)

5 RESULTS

5.1 Extraction Efficiency Analysis

For the proposed OLED structure, the far field into air with Photonic crystals (PC) patterning and without PC patterning is simulated. The Improvement in the light extraction within bounded critical angle for a wavelength of 540nm is observed in Figure 3.

![Figure 3: Light extraction efficiency (far-field in air, with and without PC.](image)

5.2 Angular Distribution of Light at 540nm

![Figure 4: Angular Distribution of light.](image)
Figure 4 shows the Far field intensity observed for the bounded critical angle of about 3.2 \(\mu\)m Volts/m with the presence of photonic crystal in the OLED structure and 2.1\(\mu\)m Volts/m for structure without Photonic crystal at a wavelength of 540nm. The proposed model having photonic crystals inserted above the emissive layer, if implemented in the organic light emitting diode will improve the light extraction efficiency.

5.3 Internal Quantum Efficiency

540 nm using the photonic crystals at 550THz. Fabrication of such OLED structures can find future application as a monolithically integrated light source for integrated optical Lab-on-a-Chip based bio-sensors.

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