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The effect of secondary electrons on emission

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ABSTRACT

The effect of secondary electrons on emission is studied by modelling the electrons behaviours in multi-layers, including electron injection, transportation, multiplication, and emission. The dielectric constant model and carrier mobility model are presented to describe the voltage distribution in multi-layers for the non-current injection and current injection respectively. After injection, the electrons are accelerated in SiO_2, where they collide with the electrons, generating secondary electrons, consequently contributing to emission. A multiplying factor M is introduced to describe the secondary electrons multiplication in certain electrical field strength. The prediction was further proved by comparing two groups of devices with and without the accelerating layer: ITO/MEH-PPV/SiO_2/Al and ITO/MEH-PPV/BCP/Al. The current avalanche observed in current–illumination experiment is a proof of the existence and contribution of secondary electrons.

1. Introduction

Solid state cathodoluminescence (SSCL) is widely reported as a solution to compensate for the drawbacks of inorganic electroluminescence and organic electroluminescence [1–7]. This is also used to reconcile the contradiction between the band model in inorganic electroluminescence and the molecular theory in organic electroluminescence, [8] i.e., the recombination obeys band model and the exciton emission obeys the molecular theory. Since the ionisation changes with the electric field continuously, there is a region where these two processes coexist [8]. This illumination is observed in many materials, including electron transport layers such as Tris(8-hydroxyquinolinato)aluminium (Alq_3), and hole transport material such as Poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) [2,5,9–15]. The main characteristic of SSCL is that the generation of secondary electrons is beneficial to the improvement of the emission. In this process, the electrons are accelerated in accelerating layer (SiO_2, ZnS) to become hot electrons with higher energy, and then give birth to the secondary electron (SE) in collisions. Furthermore, these secondary electrons contribute to the emission in the illumination layer. This work proposed a model to describe the process of electron injection, transportation, multiplication and emission in organic–inorganic multi-layers, followed by the proof of our prediction by comparing the simulation with the experiment.

As shown in Fig. 1, there are two classical architectures of device fabrication, namely DC structure with one accelerating layer and AC structure with two accelerating layers. The AC structure is a sandwich-like structure joined by two DC structures, with a high frequency voltage applied to neutralise the carrier accumulation at interface. Each side of the AC structure works in a half period of alternating current, and switch between each other. In this work, the DC structure is chosen as a basic unit to study the secondary electrons behaviours, including current avalanche and high threshold voltage.

2. Electron injection and transport

The threshold voltage determines the electron injection and divides the voltage distribution into two cases: non-electron injection case and electron injection case. They are described by the dielectric constant model and the carrier mobility model, correspondingly.

In the non-electron injection case, i.e., when the voltage is lower than threshold voltage V_0, the distribution follows the dielectric constant principle, and the voltage rises with dielectric constant increasing, [16] as follows:

$$V_i = \frac{V_{total}}{\varepsilon_i / d_i \sum_j d_j / \varepsilon_j} \quad (1)$$

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where V_{total} is the total voltage on the device; d_i, ε_i and V_i are thickness, dielectric constants and voltage of each layer, respectively. As shown in Eq. (3), the total threshold voltage V_0 is defined as the applied voltage that makes all distributed voltages V_i on each layer higher than its injecting threshold voltage V_{0i}, namely $V_i \geq V_{0i}$, but mostly $V_0 \geq \Sigma V_{0i}$ due to Eq. (1):

$$V_0 = max\left(V_i\, \varepsilon_j/d_j \sum_j d_j/\varepsilon_j\right) \tag{2}$$

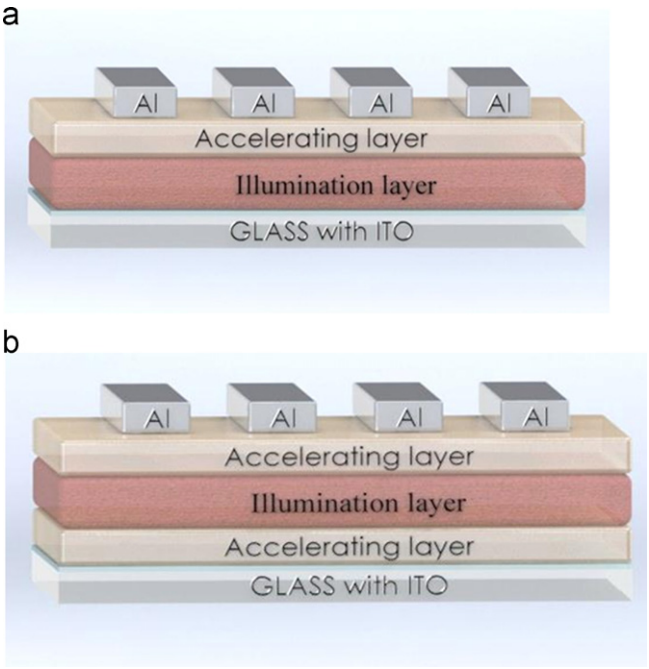

Fig. 1. Achitecture of device: (a) DC structure with one accelerating layer and (b) AC structure with two accelerating layers.

In current injection scenario, since the voltage distribution could not be described using the static model of dielectric constant [17], we designed a parameter U_i based on carrier mobility, which comes from the Painleve Equation [18,19]:

$$U_i = \sqrt{\frac{|\mu_{ie} - \mu_{ih}|}{\mu_{ie}\mu_{ih}}} \tag{3}$$

where μ_{ie} and μ_{ih} are electron mobility and hole mobility, respectively. Therefore, the voltage distribution in electron injection case is described as

$$V_i = \frac{V_{total} - V_0}{\frac{U_i}{d_i}\sum_j d_j/U_j} + V_{0i} \tag{4}$$

When current is injected in multi-layers, in terms of Lampart's study for SCL current,[20] the dependence of current density on voltage can be written as $J=(9/8)\varepsilon\mu\theta V^2/d^3$. When the thickness d and injection area S are constant, the injected current density becomes $I=a(V-V_0)^2$, where a is a combined efficiency and V_0 is the threshold voltage. Here, a tunnelling factor $B=\exp(b\sqrt{x})$ should be further taken into account for the hybrid inorganic–organic architecture, where b is related to materials. In terms of the voltage distribution models, after current injected into the device, the sharply increasing voltage on organic layer will lead to a current avalanche [21]. Therefore, a revised injected current to voltage model is written as $I=aB\,(V-V_0)^2$.

Due to the huge difference of carrier mobility between organic and inorganic materials, the injected electrons are accumulated at the interface, and go through the organic layer slowly. As shown in Fig. 2, the carrier mobility resembles pipes; the thinnest pipe limits the current, and the thinnest one determines the whole mobility of device. In other words, the lowest carrier mobility of organic layer decides the current going through the device. Based on the equation of Poole–Frenkel [22], the carrier mobility is affected by the electrical field $E=V/d$, as

$$\mu = \mu_0 \exp\left(-\frac{\theta}{k_B T}\right)\exp\left(\gamma\sqrt{E}\right) \tag{5}$$

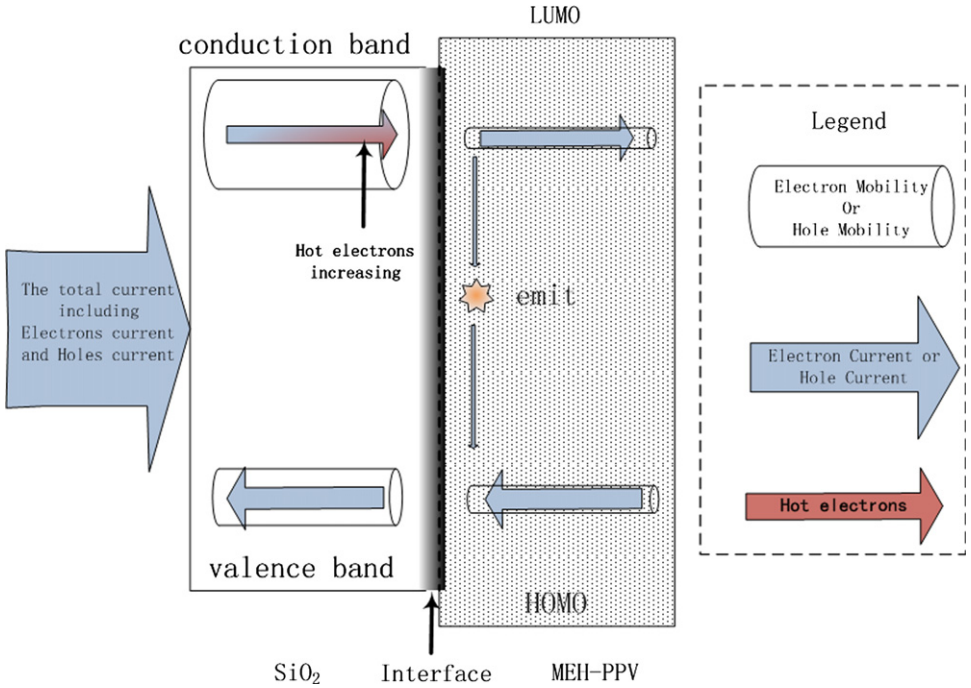

Fig. 2. Carrier injection and transport in multi-layers, from the left to the right. Electrons in SiO_2 are accelerated as hot electrons to impact the electrons in MEH-PPV to improve emissions.