# Effect of Poole-Frenkel emission on electroluminescence in quantum dot light emitting devices with Nickel Oxide layer

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***Abstract*—Theoretical analysis of hybrid quantum dot-light emitting devices incorporating CdSe/ZnS core/shell quantum dots and Nickel Oxide (NiO) as hole injection layer (HIL) has been carried out in this work. The replacement of organic HIL such as poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) with solution-processed NiO layer has led to enhancement of current density and luminance in the device by bringing a control in the hole current. The Poole-Frenkel emission affects the current-voltage relationship in low-bias along with space-charge limited current in high-bias voltage range. The temperature and bias-dependent current density has been investigated in this work.**

***Index Terms*—quantum dots, current density, light-emitting devices, nickel oxide, Poole-Frenkel emission**

## I. Introduction

The incessant advancement of quantum dot light-emitting devices (QLEDs) due to unique properties of inorganic materials and easy processing and chemical synthesis of colloidal quantum dots has been substantial in its development. The continuous efforts in this field is leading to improvement in the performance of these devices by proper choice of materials for charge transport layers in near-infrared and visible spectral regions. Recently, NiO has been the appreciable choice as p-type material in QLEDs as well as OLEDs due to its ease of deposition and chemical compatibility with the CdSe QDs [1].

Most efficient QLED reported till date has been hybrid QLEDs composed of organic charge transport layers. However, the degradation of the organic materials in these devices has always been a matter of concern and thus the possibility of replacing the organic hole injection (HIL) with inorganic NiO layer owing to its chemical and electrical stability, ease of deposition and chemical compatibility with the QDs has been explored. Many methods for improvement of the efficiency of the device has been explored in recent times [2].

## II. Device Structure and Theoretical Modelling

The state-of-the-art QLEDs were composed of organic layers where hole injection layer were preferably taken as PEDOT:PSS. The combination of PEDOT:PSS HIL along with poly-TPD hole transport layer (HTL) resulted in dominant behaviour of holes due to lower heterojunction barrier and higher mobility. The charge balance between hole and electrons for HTL and electron transport layer (ETL), respectively is very much required, thus the substitution of PEDOT:PSS by inorganic NiO thin films resulted in substantial suppression of excessive currents and thus bringing charge balance within the device.

The Fig. 1. shows the NiO-based QLED with Poly-TPD HTL and $Alq_3$ ETL, CdSe/ZnS colloidal QD layer and ITO anode and Al cathode. The NiO-based device suppresses excessive hole currents and the analysis of temperature dependence shows that current variations are highly dependent on thermal changes. The Poole-Frenkel (PF) emission within the device which is due to electric field enhanced thermal emission of charge carrier might be responsible for this behaviour of hole current in subthreshold voltage region. The current density then becomes dependent on electric field and temperature and can be given as

$$J = C \cdot E \cdot exp(\frac{-q(\phi_t - \sqrt{qE/\pi\epsilon_0\epsilon})}{kT}) \qquad (1)$$

where E is the electric field in HIL layer, q is the charge, $\epsilon_0$

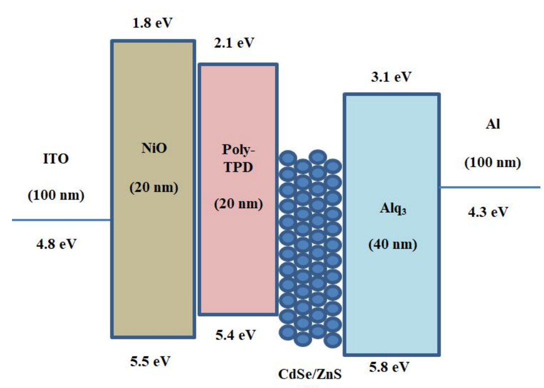


Fig. 1. Band alignment diagram of hybrid QLED with NiO HIL

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TABLE I
VALUES OF THE PARAMETERS USED AND CALCULATED [3]

| $\epsilon_{NiO}$ | $\epsilon_{PEDOT:PSS}$ | $\epsilon_{eff(NiO)}$ | $\epsilon_{eff(PEDOT:PSS)}$ | $\phi_t^{NiO}$ | $\phi_t^{PEDOT:PSS}$ | $V_{bi}$ | d | T |
|---|---|---|---|---|---|---|---|---|
| 3 | 2.27 | 4.3 | 4.1558 | 0.27 eV | 0.25 eV | 0.5 V | 100 nm | 150 K,200 K,230 K |

is the permittivity of free space, $\epsilon$ is the relative dielectric permittivity of the HIL layer, $\phi_t$ is the barrier height for charge-carrier emission from the trap states, k is the Boltzmann's constant and T is the absolute temperature [3]. Electric field inside a NiO based device is proportional to corrected bias which can be found by difference between work functions of anode and cathode. The electric field can be given as $E_{NiO} = (V - V_{bi})/(\epsilon_{eff} d_{ie})$ where $\epsilon_{eff}$ is the effective dielectric permittivity and $d_{ie}$ is the interelectrode distance. The effective dielectric permittivity can be calculated as

$$\epsilon_{eff} = \frac{\epsilon_1 \cdot d_1 + \epsilon_2 \cdot d_2 + \cdots + \epsilon_n \cdot d_n}{d_{tot}} \tag{2}$$

The effect of PF emission mechanism on the hole currents can be corroborated by linear relation of current density divided by corrected bias as given by

$$ln[J/(V - V_{bi})] = m\sqrt{V - V_{bi}} + b \tag{3}$$

where 'm' and 'b' are temperature-dependent slope and intercept respectively and can be given as

$$m = \frac{q}{kT}\sqrt{\frac{q}{\pi\epsilon_0\epsilon_{NiO}\epsilon_{eff}d}} \tag{4}$$

$$b = -\frac{q\phi_t}{kT} + ln\frac{C}{\epsilon_{eff}d} \tag{5}$$

The relative dielectric permittivity has been considered 3.5 for organic layers. The emission barrier height in NiO varies according to the way of deposition and the values considered in this work is provided in Table I.

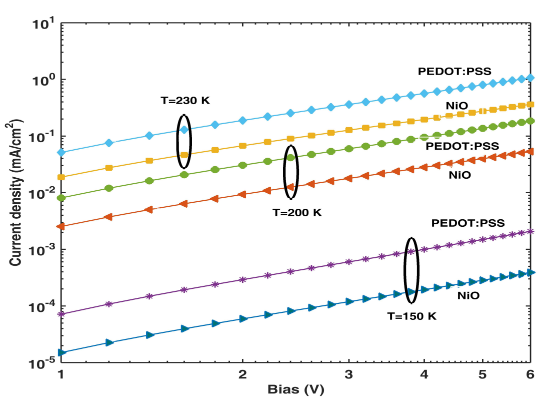


Fig. 2. Current density with reference to variation in bias at different temperature values for hole-only device with PEDOT:PSS and NiO HIL

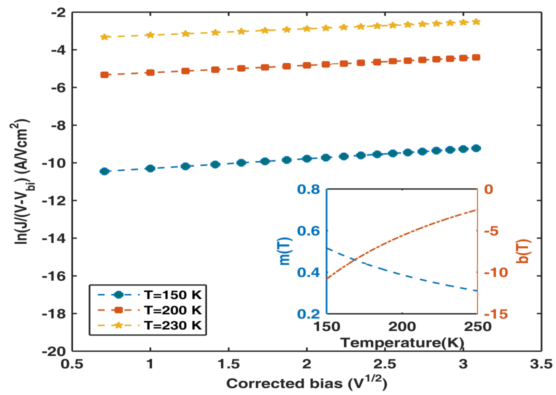


Fig. 3. Poole-Frenkel emission plots for $ln(J/(V - V_{bi}))$ for varying corrected bias, inset shows the variations of the temperature-dependent coefficients

## III. Results and Discussion

Fig. 2. shows the variations of current density at different temperature values for NiO and PEDOT:PSS based devices. The hole current is dominant in case of PEDOT:PSS device as compared to NiO device which brings about charge imbalance in the device. NiO induces substantial control on the hole current. Fig. 3 shows the Poole-Frenkel emission plots which can be given in terms of corrected bias and the inset shows the temperature-dependent slopes which are inversely proportional to temperature. The linear variation of the result with respect to corrected bias shows that PF emission mechanism is the reason for hole current in NiO-based devices.

## IV. Conclusion

The NiO-based QLEDs are affected by Poole-Frenkel emission which are related to electric-field-enhanced thermal emission of charge carriers. The suppression of excess hole current in NiO-based devices leads to increase in efficiency of the device and the ease of fabrication of NiO films in the devices make them more favourable to use in the modern day light-emitting devices.

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