Dependence of conduction mechanism on bias and temperature in quantum-dot based electroluminescent devices

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Abstract- **Quantum dots (QDs) provide some unique properties which make them preferable over other luminescent materials, one such property being adjustable and sharp emission which makes it an interesting candidate for electroluminescent devices. A QD based electroluminescent device has been taken into consideration in this theoretical study. The effect of the bias, temperature, the presence of traps and thickness of QD layers on the conduction mechanism and overall performance of the device has been studied.**

I. Introduction

Quantum dots (QDs) have been used as light-emitting material in electroluminescent devices that are generally layered. The QDs draws the attention due to the fact that it shows size-quantization effects which means that on changing the nanoparticles size, the band gap of the material can vary by several electron volts. Various II-VI semiconductor nanocrystals have been used in the construction of electroluminescent devices [1]. Colloidal CdSe/ZnS core-shell QDs exhibits strong band-edge fluorescence and is a strong candidate for designing a layered light-emitting device. The spectrum of the emission band can be tuned from red to blue just by decreasing the size of the QD. The shell surrounding the core provides stability and increases the efficacy of the dots.

In this work, an electroluminescent device with QD active layers such as QD light-emitting diode has been taken into consideration. The device consists of an electron transport layer (ETL) interfaced with a cathode, generally made up of metal, a hole transport layer (HTL) attached with an anode and QD active layers sandwiched between HTL and ETL [2]. The light generation or fluorescence from these devices is due to recombination of charge carriers within the QDs and is strongly dependent on the bias and temperature provided to the device. A strong dependence also lies on the construction of the device, specifically on the thickness of the QD active layers and presence of traps in the QD environment. The QDs are prone to charge trapping due to staggered interface or uncontrolled environment and thus it affects the efficiency of the device [3]. Charge trapping impedes carrier recombination process and charge transport mechanism and thus limits the efficient use of these devices. The effect of electric field on the conduction process and the voltage dependence of the current density have also been analyzed.

II. Theoretical Formulation

Numerous studies have been carried out in the area of charge transport and charge injection in the QD-based devices. The behavior of QDs is studied to understand the conduction mechanism process in an electroluminescent device. The electric field at low intensity follows Ohm's law for the current density in the device.

$$J = \frac{e\mu_n n_T V}{d} \qquad (1)$$

However, at high electric field the current density can be best described by Mott-Gurney law [4].

$$J = \frac{9\mu_n \varepsilon\, \varepsilon_0 V^2}{8d^3} \qquad (2)$$

where e is charge, μ_n is the mobility of charge carriers, V is the bias applied, d is the thickness of the QD layer, ε is the dielectric constant of the material used and n_T is the thermally generated charge density which is calculated as $n_\infty exp(-\Delta E/kT)$ where n_∞ is the thermally generated charge carrier density and ΔE is the activation energy.

Considering that trap states are present in the QD environment and a part of injected charge carriers are trapped and therefore are not mobile leads to a different analysis and presents the adverse effects of presence of trap states in the QD system. The current density in that case can be given as

$$J = N_{CB}\mu_n e^{(1-t)} \left(\frac{\varepsilon\varepsilon_0 t}{N_{td}(t+1)}\right)^t \left(\frac{2t+1}{t+1}\right)^{(t+1)} \left(\frac{V^{(t+1)}}{d^{(2t+1)}}\right) \qquad (3)$$

where N_{CB} is the density of states in the conduction band, t is the ratio of characteristic temperature, T_t and the considered temperature, T, N_{td} is the density of traps and the value is close to the value of density of QDs as each QD is capable of holding one charge carrier.

TABLE I
Values Of Parameters Used [5]

Parameter	Value
Mobility (μ_n)	$1.5 \times 10^{-10} m^2/Vs$
Density of states (N_{CB})	$3 \times 10^{25} m^{-3}$
Density of traps (N_{td})	$8 \times 10^{23} m^{-3}$
Dielectric constant (ε)	4
Characteristic temperature (T_t)	1750 K
Thermally generated charge density (n_∞)	$6 \times 10^{21} m^{-3}$
Activation energy (ΔE)	0.13 eV

III. Results And Discussion

Low electric field strength renders limited current density and the characteristics show ohmic behavior which can be seen in Fig. 1. However, at high electric fields, the space charge limited current appears when concentration of injected carriers overtakes the concentration of thermally generated carriers. The current density then becomes dependent on the mobility and not on the charge carrier density. The traps even if present in the sample becomes filled at high electric fields and the conspectus of the effect of bias can be seen for low and high electric fields. The result shown in Fig. 1 elucidate the effect of electric field, however, practically the effect does not abruptly change but in a slower manner and the result just provides the behavior of the device under different conditions which follows different laws. The inset plot shows the thermally generated free charge carrier density as a function of inverse of temperature. The density of free charge carriers is largely dependent on the temperature as can be seen through the plot.

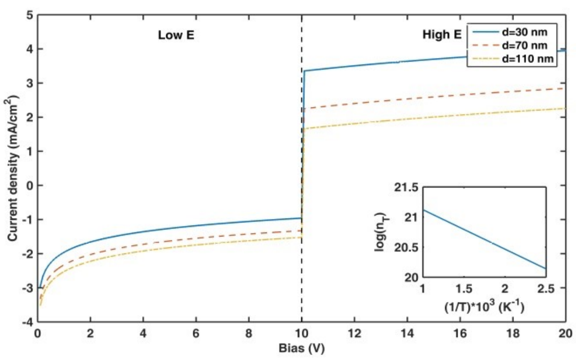

Fig. 1. Current density for varying bias at different QD layer thickness and no. of free charge carriers as function of inverse temperature (inset)

The presence of trap states in the device deteriorates the performance of the device. Fig. 2 shows the characteristics of the device in presence of traps and for varying thickness of the QD layer. The QD layer with thickness as low as 30 nm provide better characteristics as compared to a sample of 110 nm. The result has been compared with experimental results and our result complies with the experimental data [6].

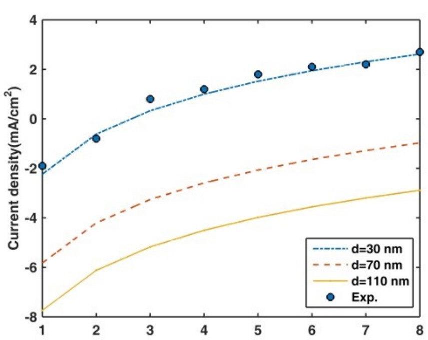

Fig. 2. Current density for varying bias at different QD layer thickness in presence of traps

The effect of temperature on the behavior of the device is also evident from the results shown in Fig. 3. The number of free charge carriers increases with the increase in temperature which contributes in charge transport. With the increase in the temperature, the current density tends to improve and so does the conduction mechanism of the device. The experimental result shows a similar behavior at 400 K of temperature.

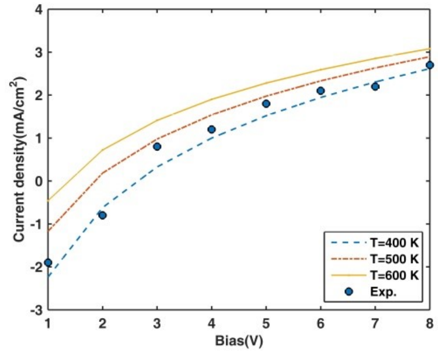

Fig. 3. Current density for varying bias at different temperatures in presence of traps

IV. Conclusion

Electroluminescence in QD-based electroluminescent devices shows dependence on the strength of electric field and bias. A lower electric field leads to lower efficiency of the device, however at higher electric fields a higher concentration of injected carriers and filling of traps leads to a better performing device. A trap-free device is not practically feasible and our analysis also deals with the performance of the device under the effect of deep trap states present in the system. Each QD acts as trap and if the trap density becomes almost equal to density of states in conduction band, the current characteristics is adversely affected. The current characteristics show a profound adverse effect due to the presence of traps and show deterioration by four to six fold. However, even in the presence of traps, an optimum device can be designed by considering a proper thickness of the QD active layer used to construct the device and an optimum value of temperature of operation also provides desired results from an electroluminescent device.

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