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Temperature and Recombination Lifetime Effects on Amorphous Silicon Quantum Dot's Light Emitting Diodes

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Abstract
The internal quantum efficiency of amorphous silicon quantum dots (a-Si DQs, has been studied theoretically as a function of temperature and recombination lifetime of excited carriers. The increase in the internal quantum efficiency with decreasing QD size was attributed to the quantum confinement effects in a-Si QDs. This type of confinement has changed the optical energy gap of the material from indirect to nearly direct transition structure. It is found that the visible-light emission from a-Si QDs is most efficient at room temperature, and the efficiency increases with temperature and decreases with increasing recombination lifetime.
Keywords: Nano-LED, Quantum dots, a-Si, Quantum confinement.

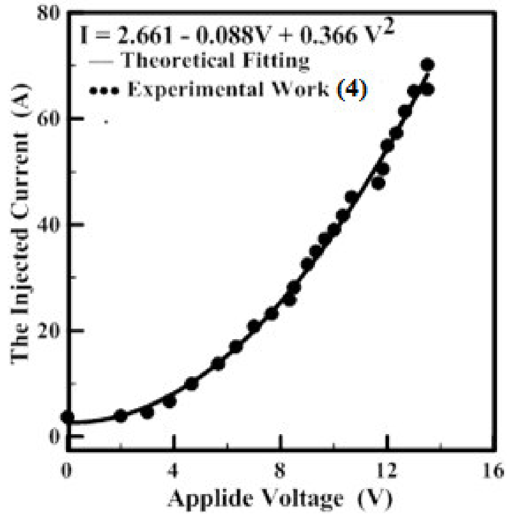
1. Introduction

Silicon-based light-emitting diodes (LEDs) represent promising candidates for the next generation of full-color and flat panel displays. The advantages of silicon-based LEDs include full-color emission, complementary metal-oxide-semiconductor compatibility, system feasibility, and low cost of fabrication. Although a variety of emission colors from silicon, such as porous silicon and nanocrystalline silicon, Park et al. (2001) show a sufficiently high efficiency that can be used in LED applications, the tuning of emission color, particularly in the short wavelength region, continues to be a challenge. Quantum confinement effects (QCE) make silicon a likely candidate for full-color displays because the tuning of emission color and efficient emission can be achieved by QCE. Another important issue in realizing silicon-based LEDs is the operation voltage. Silicon oxide is typically used as a material for enclosing nano-sized silicon. However, silicon oxide is a very large wide band gap insulator and, thus, results in a high operation voltage. Silicon nitride is a promising alternative material because it has lower barriers for electrons and holes than silicon oxide.

Furthermore, amorphous silicon (*a*-Si) has two important advantages compared with bulk crystalline silicon: the luminescence efficiency in bulk *a*-Si is higher than that in crystalline silicon due to its structural disorder; Park et al. (2001) and the band gap energy of bulk *a*-Si (1.6 eV) is larger than that of bulk crystalline silicon. As a result, *a*-Si represents a good candidate for short-wavelength luminescence. It would, therefore, be expected that these intrinsic advantages of *a*-Si and the quantum and special confinement effects in *a*-Si quantum dot (*a*-SiQD) could be used in silicon-based optoelectronic devices.

2. Structure and Theory

In this work we adopted the structure of Ni/Au contact on silicon nitride containing a-Si QDs to improve the light internal efficiency Park et al.(2001a) and Park et al. (2002). 38 nm silicon films containing a-Si QDs were grown by plasma enhanced vapor deposition (PECVD), in which nitrogen-diluted 5% SiH_4 and were used as the source of reactance. A lowly doped p-type Si wafer (100) with a hole concentration of about 10^{15} cm^{-3} was employed as a substrate. The Ni (9 nm)/Au (21 nm) contact deposited on the silicon nitride films was annealed in an air ambient for 80 sec. Fig. (1), shows the current –voltage (I-V) characteristic of a-Si QD LEDs with Ni/Au contact annealed at 400 ^{o}C in air. The forward voltage 8.5 V for the annealed Ni/Au contact, at input current annealed Ni/Au contact was drastically decreased by 5 V. The series resistance of the LED with annealed Ni/Au contact was also decreased. This is attributed to the decreased in resistance 2.46/sq for the annealed Ni/Au contact, Park and Sung (2006).



Fig(1): shows the current-voltage (I-V) characteristics of a-Si QD LEDs with Ni/Au contact annealed at 400 °C in air Park and Sung (2006).

The energy gap (E) for three-dimensionally confined a-Si QD can be expressed as E (eV) = $E_{Bulk} + c/d^2$ based on an effective mass theory, where E_{Bulk} represent the bulk a-Si band gap, d the dot size, and c the confinement parameter. The data in Fig. (2) are the best fitted by the equation E (eV) = $1.56 + 13.9/d^2$, Kim et al. (2006). The fitted Fig. (2), the emission color could be changed by controlling the dot size. Fig. (3) shows the structure of a-Si QD LED which has been adopted in this work.

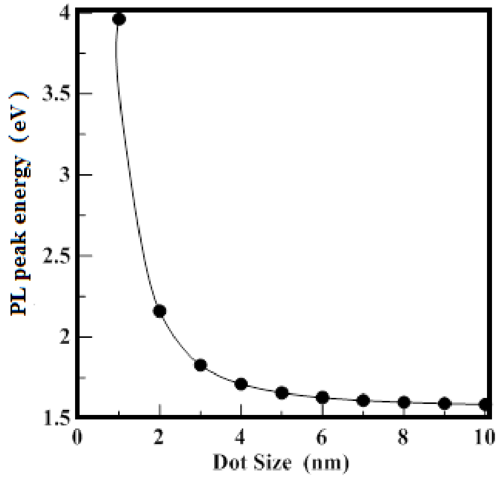


Fig. (2):PL peak energy of a-Si DQs as a function of dot size a-Si QDs, Kim et al. (2006).

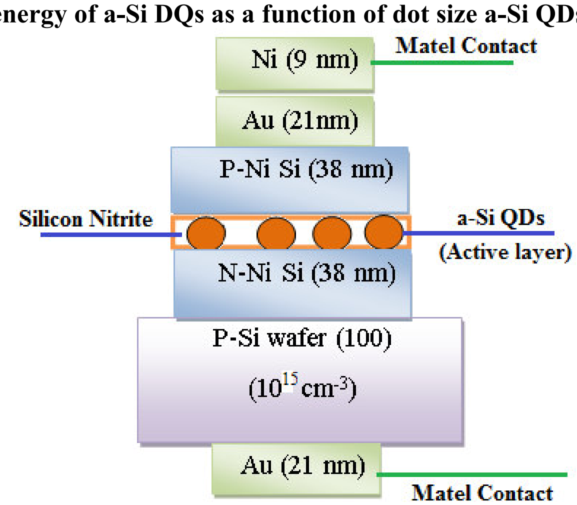


Fig (3): The structure of a-Si QD LEDs which has been adopted, Murphy (2014).

The internal quantum efficiency gauges what fractions of e-h recombination in the forward biased pn-junction are radiative and therefore lead to photon emission. Nonradiative transitions are those in which e-h recombine through a recombination center such as a crystal defect or an impurity and emit photons, Helm and Dekorsy (2009). By definition,

$$\eta_{\text{int}} = \frac{rate\ of\ radiative\ recombination}{total\ rate\ of\ recombination} \tag{1}$$

The total rate of recombination whereas the number of photons emitted per second Φ_{ph} is determined by the rate of radiative recombination.

$$\eta_{\text{int}} = \frac{\Phi_{ph}}{I/e} \tag{2}$$

For parabolic electron-hole bands, the LED spontaneous emission rate can be written as: Manasreh (2005).

$$r_{sp} = P_{em} N_j(E) e^{E/KT} \tag{3}$$

and after compensation the joint density of state in a zero dimensions system, the spontaneous emission rate written as:

$$r_{sp} = \frac{2}{\tau_r}\, \delta\left(E - E_{N1,N2,N3}\right) e^{E/KT} \tag{4}$$

the total photon flux emitted from the QDs LED can be obtained by integrating over r_{sp}, and from the properties of delta function the total photon flux is:

$$\Phi_{ph} = \frac{\text{v}}{\tau_r}\, e^{E/KT} \tag{5}$$

Where E the energy gap for three-dimensionally confined a-Si QDs, v is the volume of the active region and I_{inj} is injected current. Then compensate equation (5) in equation (2) we obtain:

$$\eta_{\text{int}} = 2\frac{\text{v}}{\tau_r I_{inj}}\, e^{E/KT} \tag{6}$$

where, τ_r is the recombination lifetime.

3. Results and Discussion

Figure (4) shows the internal quantum efficiency as a function of the wavelength for different values of recombination lifetime at constant temperature. Fig. 4 (a), the internal quantum efficiency is higher for lifetime 40 nsec compared with lifetime $11x10^{-6}$ sec at room temperature. Fig. 4 (b) shows the internal quantum efficiency decreased at 200 K comparing with that at 300 K.

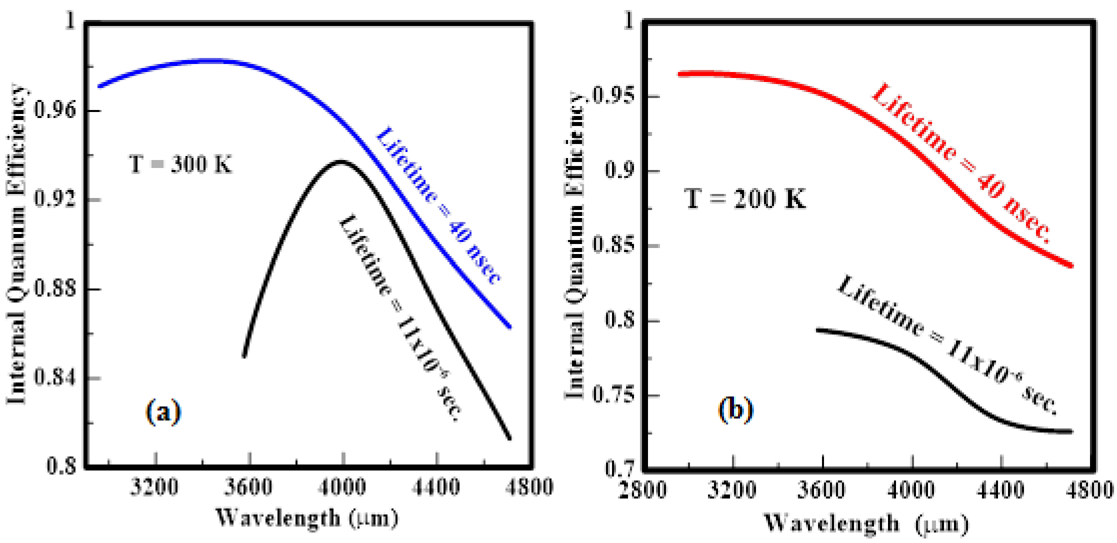


Fig 4 (a, b): The internal quantum efficiency as a function of wavelength at constant temperature.

So, the internal quantum efficiency is higher when the recombination lifetime 40 nsec, in both recombination lifetimes are decreasing at low temperature 200 K. The emission color is from 2800-4800 m. For example, the dot size corresponding to green and blue colors emitted are 2.3 and 1.8 nm respectively. The tuning of colors emitted and efficient emission can be achieved due to quantum confinement effects, Perez et al. (1992). Fig (5) shows the internal quantum efficiency as a function of wavelength, at different temperature and the same lifetime. In Fig. 5 (a) show the internal quantum efficiency is higher when T = 300 K than that T= 200 K. In Fig. 5 (b), it is clear, that the internal quantum efficiency is higher when T = 200 K.

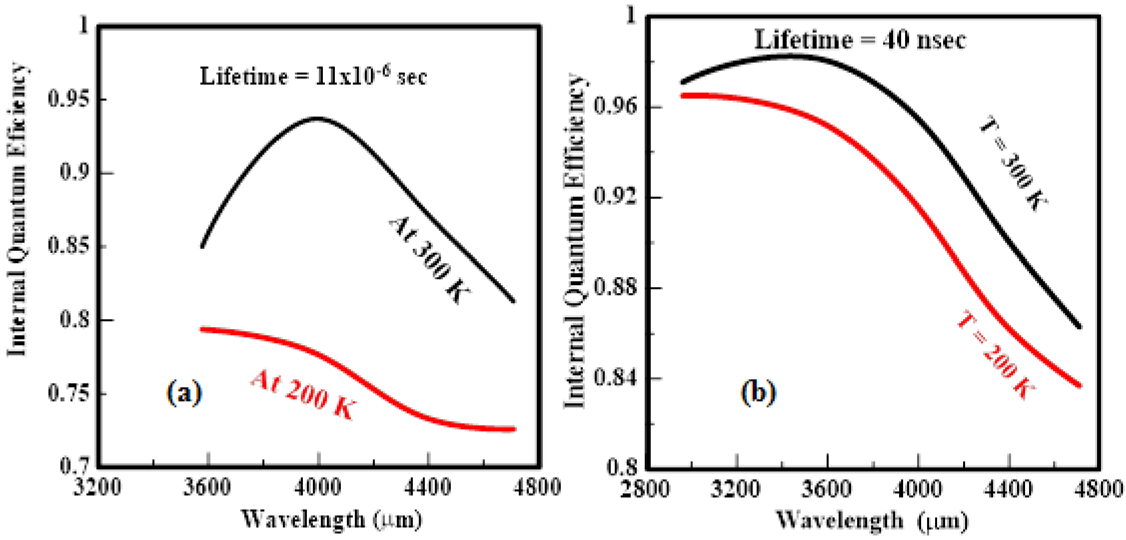


Fig 5 (a, b): The internal quantum efficiency as a function of wavelength at constant recombination lifetime.

So, the internal quantum efficiency at 300 K and lifetime 40 nsec is higher than at T= 300 K and lifetime $11\text{x}10^{-6}$ sec.

The internal quantum efficiency η_{int} of a-Si QDs LED is increasing with temperature, and shows the maximum value of η_{int} at room temperature (300 K). The reason of this result to increase internal quantum efficiency η_{int} with temperature can be in increase in the number of photogenerated carriers with temperature. To explain more about this change in internal quantum efficiency η_{int} with temperature, similar anomalous temperature dependence have been reported for other silicon-based structure, Kwack et al. (2003). Observed similar phenomenon in bulk a-Si:H, which was explained by Auger effect due to nonradiative recombination from the different excitation power dependent PL experiments, Kwack et al. (2003). Although we carried out temperature dependent PL experiments with different excitation power for our a-Si QDs sample, no different of the temperature dependence was observed, in contrast to the case of the bulk a-Si:H. However, the internal quantum efficiency η_{int} of a-Si QDs sample increase with temperature and recombination lifetime decrease. The decrease in internal quantum efficiency η_{int} with increase temperature and internal quantum efficiency η_{int} caused by the emission probability it is previously, the emission probability of photoluminescence in LED is inverse of recombination lifetime. Therefore, whenever decrease in τ_r the probability of carrier radiative recombination process increases and hence increasing in the number of emitted photons it is increase in internal quantum efficiency η_{int}. Moreover, the shifting of energy levels becomes more when the dot size decreases. As the dot size decreases the effective mass of electron decreases (hole increases), therefore; the energy levels are shifted to higher (lower) magnitude of the conduction (valence) band. For this reason, the energy gap has different values depending on the dot size. The photon energy has value for each size, where it increases as the dot size decreases (blue shifting), Abdul-Ameer (2008) and Avadhanucu and Hemne (2011).

4. Conclusions

The quantum confinement effect occurs and changes the a-Si QDs structure from indirect to direct optical energy gap. At room temperature, the internal quantum efficiency shows most efficient more than temperature 200 K. The quantum confinement makes to shift the photoluminescence into visible region (blue shift) by controlling the dot size of a-Si QDs. From this behavior and the quantum efficiency, it is led to the performance that the a-Si QDs material has been changed to be direct band gap material. The temperature and recombination lifetime are effects on quantum efficiency (increase or decrease).

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