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Photoluminescence from GaAs nanostructures

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The confinement properties of semiconductor nanostructures have promising potential in technological application. The main objective of this study is to describe the dependence of Photoluminescence (PL) intensity on different parameters like temperature, excitation wavelength, time and photon energy of GaAs quantum dots (QDs). The model equations are numerically analyzed and simulated with matlab and FORTRAN codes. The experimental fitted values and physical properties of materials are used as data source for our simulation. The result shows that at low temperature the peak is quite sharp, as temperature increases the PL intensity decreases and get quenched at particular thermal energy.

Key words: Photoluminescence (PL) intensity, GaAs quantum dots, nanostructures, quantum confinement, thermal quenching energy.

INTRODUCTION

Nanomaterials are the cornerstones of nanoscience and nanotechnology and are anticipated to play an important role in future economy, technology, and human life in general. The strong interests in nanomaterials stem from their unique physical and chemical properties and functionalities that often differ significantly from their corresponding bulk counterparts. Exceptionally large surface area to volume ratios relative to the bulk produces variations in surface state populations that have numerous consequences on material properties (Jin and Christian, 2007).

The small size of nanostructures permits the infamous electronic device scaling for faster operation, lower cost and reduced power consumption. These unique properties enable the variety of electronic, photonic and optoelectronic information storage, communication, energy conversion, catalysis, environmental protection, and space exploration applications based on semiconductor nanostructures (Alivisatos, 1996). Semiconductor nanoparticles, generally considered to be particles of material with diameters in the range of 1 to 10 nm (Pan and Feng, 2008).

GaAs has advantages in electronic properties which are superior to those of silicon. It has a higher saturated electron velocity and higher electron mobility, allowing transistors made from it to function at frequencies in excess of 250 GHz. Unlike silicon junctions, GaAs devices are relatively insensitive to heat owing to their wider band gap. It tends to have less noise than silicon devices especially at high frequencies. Because of its wide direct band gap transition, GaAs is an excellent material for space electronics and optical windows in high power applications. Combined with the high dielectric constant, this property makes GaAs a very good electrical substrate and unlike Si provides natural isolation between devices and circuits (Blakemore, 1982).

Photoluminescence (PL) is the spontaneous emission of light from a material under optical excitation. The

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excitation energy and intensity are chosen to probe different regions and excitation concentrations in the sample. PL investigations can be used to characterize a variety of material parameters. PL spectroscopy provides electrical characterization; it is selective and extremely sensitive probe of discrete electronic states.

Intensity of the PL signal has received the most attention in the analysis of interfaces. This interest is due to the fact that, although several important mechanisms affect the PL response, it is generally found that large PL signals correlate with good interface properties (Timothy, 2000).

Dependence of PL intensity on different parameters

Temperature dependence of PL emission

The overall shift of the QD emission to lower energies is caused by band gap narrowing. At low temperature (T < 100K) the carriers are captured by the QDs randomly. Once captured, the carriers in the QDs cannot be thermally excited (Teo et al., 1998). So the emission reflects the normal distribution of the QD. Irrespective of the specific quenching mechanism, the temperature dependence PL intensity for GaAs nanostructures with intensity near absolute zero I_0, rate parameter C and activation energy E_τ is given by Kittel (2005):

$$I(T) = \frac{I_o}{1 + C\exp\left(\frac{-E_T}{k_B T}\right)} \quad (1)$$

This equation is used to simulate data on the dependence of PL intensity on temperature.

Optical absorption

The absorption coefficient α describes how the light intensity is attenuated on passing through the material. The intensity transmitted through the sample of thickness z with incident light intensity I_0 is given by:

$$I(z) = I_0 \exp(-\alpha z) \quad (2)$$

The quantum confinement model

The low-temperature PL spectrum of the GaAs QD ensembles shows a Gaussian profile with a line width broadening of 30nm (Jung et al., 2004).

The photon energy emitted would be slightly larger than the band gap energy (Sze and Kwok, 2007):

$$h\upsilon = \hbar\omega = E = E_c + \frac{\hbar^2 k^2}{2m_e^*} - \left(E_v - \frac{\hbar^2 k^2}{2m_h^*}\right) = E_g + \frac{\hbar^2 k^2}{2m_r^*} \quad (3)$$

According to the Quantum Confinement (QC) model, the emission wavelength and intensity depend on nanocrystal diameter, size distribution and concentration. This model can explain the general tendency of most experimental results such as the blue shift of the luminescence spectrum with decrease of the GaAs-nanocluster size.

Weak confinement

The electrons and holes can now be thought of as independent particles; excitons are not formed. Separate quantization of motion of the electron and hole is now important factor. The optical spectra should consist of a series of lines due to transitions between sub bands. The shift in energy is now:

$$\Delta E = \frac{\hbar^2 \pi^2}{2\mu R^2}. \quad (4)$$

Strong confinement

When the excitonic mass is replaced by the reduced mass µ in the weak confinement regime the dominant energy term is the Coulomb term, and quantization of the motion of the exciton occurs. The shift in energy of the lowest energy state is:

$$\Delta E = \frac{\hbar^2 \pi^2}{2m_e^* R^2} \quad (5)$$

Where, $\frac{1}{M} = \frac{1}{m_e^*} + \frac{1}{m_h^*}$

Assuming that a Gaussian size distribution about the mean diameter d_0 for the nanocrystallites (Mic´ic´ et al., 1997):

$$I(d) = N\frac{1}{\sqrt{2\pi\sigma}}\exp - \frac{(d - d_0)^2}{2\sigma^2} \quad (6)$$

The number of electrons N in a column diameter d participating in the PL process is proportional to d^2 .

Dependence of PL intensity on time

Photoluminescence experimental samples are excited with ultra-short light pulses and the change of the emitted light as a function of time is observed (Lingmin et al., 2009).

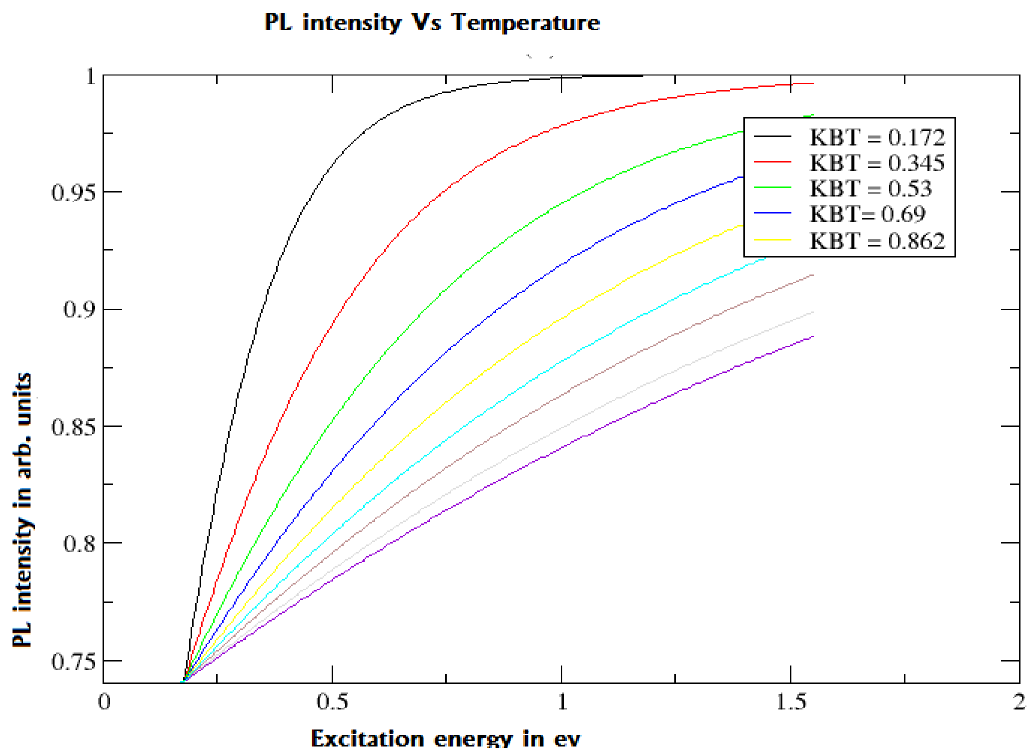

Figure 1. PL intensity versus thermal energy for GaAs nanostructures.

To gain information about the carrier dynamics is necessary to find the relationship between the photoluminescence decay and the carrier lifetimes. The photoluminescence intensity, that is, the light signal emitted by the material due to radiative recombination, is proportional to the product of electron and hole concentrations (GhodsiNahri et al., 2010):

$$I(t) = I_0 exp\left(\frac{-t}{\tau}\right)^{\beta} \quad (7)$$

Where I(t) and I_0 are the PL intensity as a function of time and at t = 0, respectively, τ is the PL decay time constant, and β is a dispersion factor $\leq$1. Thus, the capture rates can be extracted from PL transients if either the radiative recombination rate is known or at least much smaller than the capture rate. However it is not possible to distinguish between the influences of electron and hole capture (GhodsiNahri et al., 2010).

METHODOLOGY

In this work problems are solved analytically and numerical techniques had been used to determine the most important optical parameter for PL intensity. In order to obtain the desired result for this work we have simulated data using matalab codes for temperature and time dependent intensity. We assumed Gaussian model equation that describes the dependence of PL intensity on the size of the nanocluster and matlab Fortran 90 program have been developed for the model equation that simulates the data to compare with experimental results. The results obtained with this simulated data with the model equation agree with experimental results done by other researchers.

RESULT AND DISCUSSION

PL intensity versus temperature

Figure 1 depicts the PL intensity as a function of thermal energy for temperatures ($T = 20k, 40k, 60k, 80k, 100k, 120k, 140k, 160k, 180k$ and $E_a = 0.08\ eV$) fitting parameters are involved. This simulation result is in good agreement with experimental results; the emission spectra for GaAs show that PL intensity very high at low thermal energy. The activation energy is about 0.25 eV. Due to the increasing temperature the thermal energy increase at which 1.5 eV PL gets quenched, thus 1.5 eV is quenching thermal energy.

PL intensity versus wavelength

Figure 2 shows the PL intensity as a function of wavelength for GaAs nanostructures. For both values of

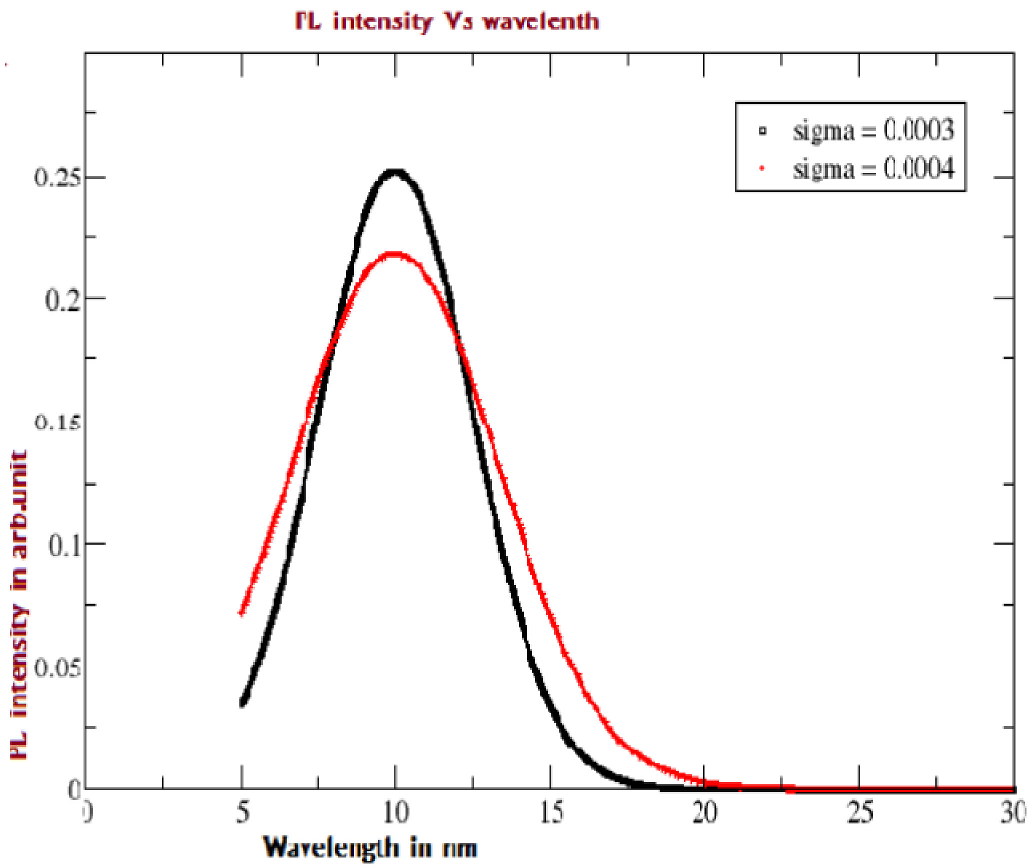

Figure 2. PL intensity versus wavelength.

the standard deviation sigma, the PL intensity has sharper peak when near the center of the Gaussian curve. Semiconductors are transparent to photons whose energies lie below their band gap and are strongly absorbing for photons whose energies exceed the band gap energy (Ardyanian and Ketabi, 2011). The simulation result shows that the PL intensity decreases as the wavelength increases to a certain peak and then decreases continuously.

PL intensity versus photon energy

Figure 3 depicts the simulation result of PL intensity versus Photon energy for GaAS nanostructures. The photo flux absorbed by semiconductor nanostructures enforces the material's property got to be changed from one phase to other. The excitation of electron- hole changed to tunneling of electron from valance band to conduction band.

PL intensity versus time

Figure 4 shows the simulated result of PL intensity versus time (a) and the experimental result carried out by other researchers (b) from literature (Jong, 2009) for comparison. It is observed that as decay life time increases the PL intensity decreases.

The PL decay time of GaAs nanostructures decreases monotonically with increasing time. A shorter decay time constant allows a higher modulation frequency, but reduces the efficiency. This is due to the decrease in oscillation period and resulting non radiative recombination of the particles in the nanocrystal.

Conclusion

The emission spectra of GaAs QD show that there is high PL intensity at low temperature. As the temperature increases, the thermal energy increases and the PL gets quenched. The result also shows that PL intensity decrease as wavelength increases. Sharp peak PL intensity is observed near the mean diameter of GaAs QD. PL intensity observed between limited visible photon energy. As photon energy increased exceeding energy gap the peak PL intensity become lowered. The PL intensity decays with time; this is because of the contributions of radiative and non-radiative transitions.

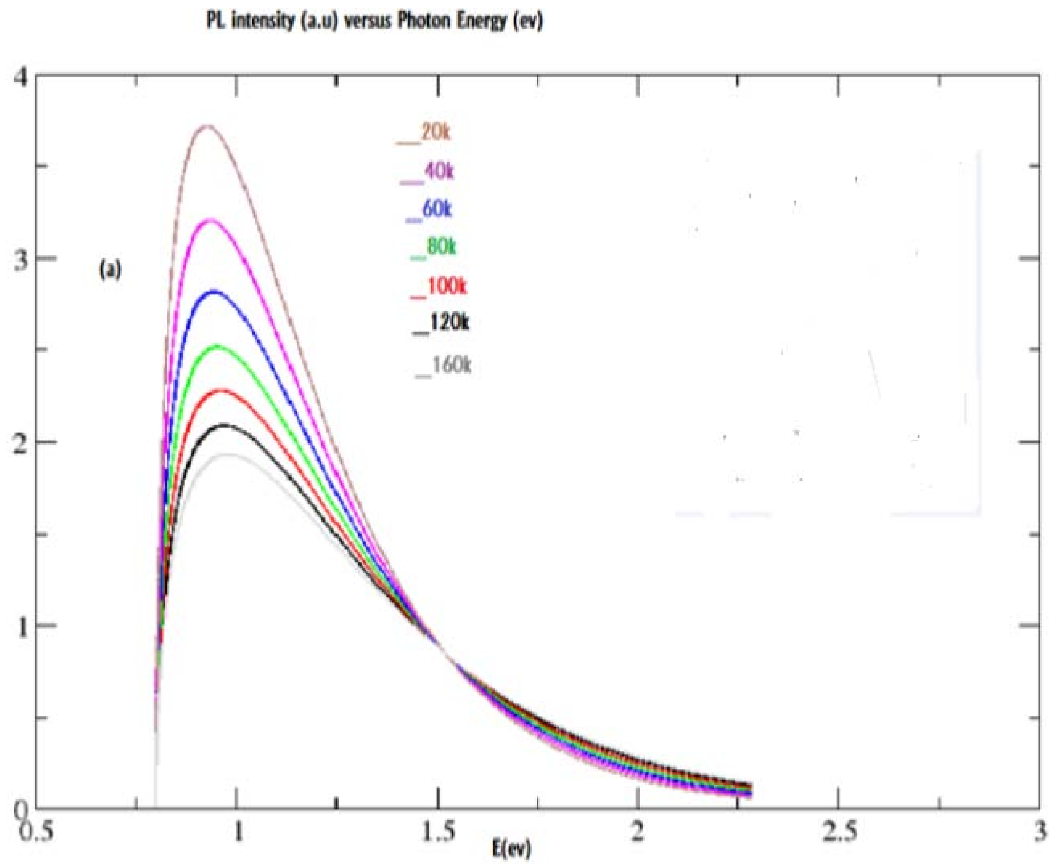

Figure 3. PL intensity Vs. photon energy.

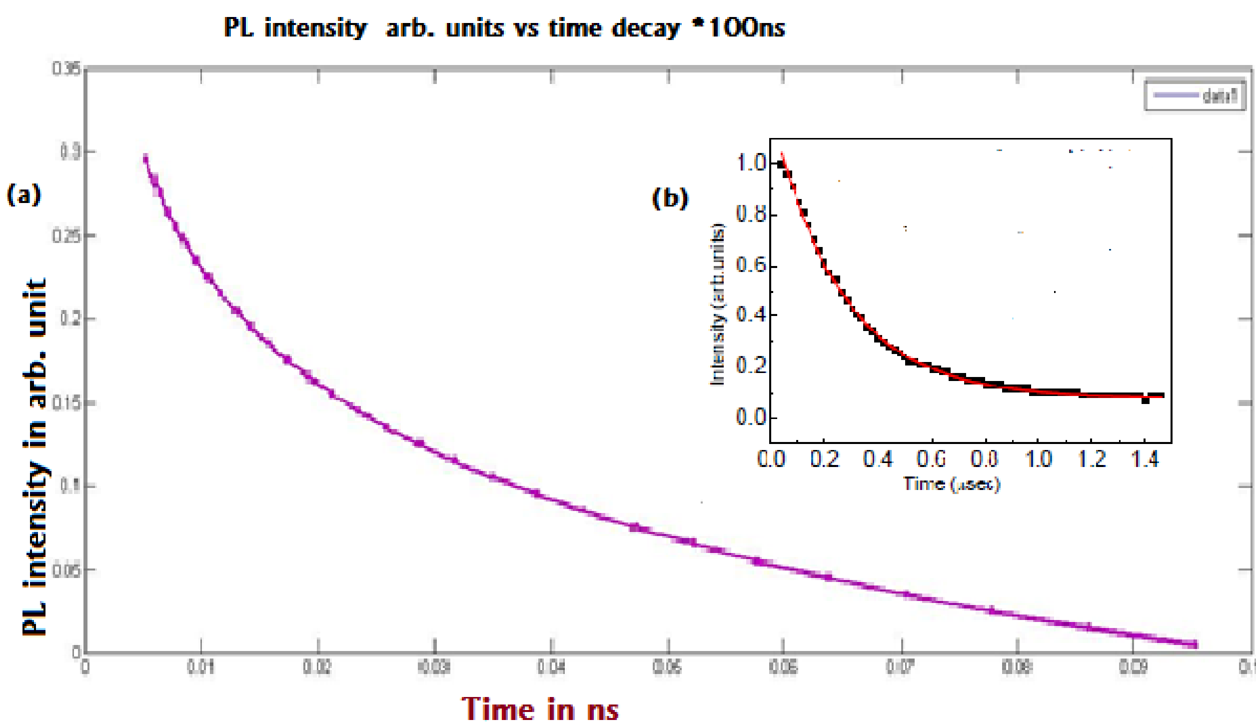

Figure 4. PL intensity vs. decay time.

Conflict of Interest

The authors have not declared any conflict of interest.

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