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STUDY OF OPTICAL GAIN IN AlGaAs QUANTUM DOT PHOTODETECTOR

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ABSTRACT: - The Quantum Dot Infrared Photo Detectors (QDIPs) become the leading technology in semiconductor detectors. This attraction comes from the properties of these devices that overpowers over the currently available detectors like Quantum Well Infrared Photo Detectors (QWIPs). In this paper, different Z-length dimensions are used to investigate the behavior of energy levels inside the quantum dots. The Z-length is also applied to investigate the shift of the operating wavelength and adjust the quantum dot performance by multiband Schroedinger-Poisson simulation. The generated electrons in the detection process are one of the most important properties of these dots. A software program is used to simulate the wave function, energy state, and absorption for different Z-dimensions. Results showed that the bandgap decreases and the absorption response shifts with increasing Z-dimension.

Keyword: Quantum-Dot, Infrared, Photodetector.

INTRODUCTION:

The quantum dot photo detectors (QDIPs) are industrialized after the success of fabrication of quantum wells. The Quantum Dot Infrared Photo Detectors (QDIPs) are like Quantum Well Infrared Photo Detectors (QWIPs) but the quantum dots replace the structure of quantum wells, in which there is confinement in all directions. Self-organization process is used to identify the quantum dot islands produced from the strained epitaxial growth of heterostructure material. Growing InGaAs on GaAs leads to such production. The produced island have pyramid shaped structure. These pyramids act as a one dimensional confinement boxes that traps the electrons inside the heterostructure material. Such confinements have been studied experimentally and theoretically. [1-2]

The improvements in fabrication process results efficient and profession creation of quantum dot semiconductor layers. These types of detectors depends on the transitions that occur in between bound states of the conduction band in side quantum dot. In addition, it takes the advantage of using the technology of semiconductors with large bandgaps. The first intersubband transition was observed in early 1990s. The transitions occurred in far infrared wavelength region in Indium Antimony quantum dots [3]. Such transitions also occurred in 2-dimentional electron gas structures [4]. The first successful demonstration of quantum dot was done in 1998 [5]. Since then, the characteristics and performance have greatly improved [6-7] and it is used in focal plane arrays in thermal imaging [8].

In this paper, the Z-dimension of AlGaAs Quantum Dot is altered and the change in energy bandgap with the absorption response is studied. Changing the Zdimension of the Quantum dot redistributes the energy states inside the Quantum dot and changes the position of the discreet energy levels. The Quantum dots have different shapes depending on the material and the fabrication process [17-18].

THEORY

QDIP devices can be fabricated in such a way that each layer can sense and detect different wavelength resulting in different wavelength detection in the same detector. A schematic structure of a QDOT device is shown in fig. 1 [9]. Every layer of QDIP absorption band consists of ten to twenty periods of GaAs/AlGaAs Quantum Dot layers fabricated between the top and bottom electrodes. Different biasing levels for the simplified band diagram is shown in fig. 2 [10].

An effective mass single band model is simply deployed and is simulated to generate an interactive 3D visualization that predicts the wave function [11].

The quantum dot lab yields the wave function, the electron energy levels, absorption strength of an electron, the QD lab is a tool that solves the Schrodinger equation for an electron in (QD). Equation (1) explains the energy levels and absorption in 3 Dimensional shape expressing the physical dimension of the Quantum Dot, where L is the physical dimension of the quantum dot in nm. n is the excited state level, [12]

$$E_{nxnynz} = \frac{h^2\pi^2}{2m}\left[\left(\frac{nx}{Lx}\right)^2 + \left(\frac{ny}{Ly}\right)^2 + \left(\frac{nz}{Lz}\right)^2\right] \quad (1)$$

Where h is Planck's constant, m is the mass of the electron, and E is the total energy.

For fabricated QDs, the optical and electronic spectra follows a Gaussian distribution. Depending on a Gaussian line shape, the absorption spectra for an ensemble of QDs has been modeled by Phillips [13].

$$\alpha(E) = \alpha_o \frac{n_1}{\delta}\frac{\sigma_{QD}}{\sigma_{ens}} exp\left[-\frac{(E-E_g)^2}{\sigma_{ens}^2}\right] \quad (2)$$

Where n_1 is the electrons' areal density in the ground state of quantum-dot, α_o is the maximum absorption coefficient, δ is the density of quantum-dot, and $E_g = E_2 - E_1$ is the energy difference of optical transition between excited and ground states in the quantum dots. The parameters σ_{QD} and σ_{ens} expresses the standard deviations of intraband in the Gaussian line shape absorption in a quantum dot and for the distribution in energies for the QD ensemble. Equation (2) evaluates the absorption coefficient for the necessary existence of electrons in the quantum dot ground state [13].

The parameters n_1/δ and σ_{QD}/σ_{ens} describe a reduction in absorption because of the lack of available electrons in the ground state of quantum dots and inhomogeneous broadening, respectively. Quantum dots are fabricated by epitaxial growth of semiconductor layers in Droplet Epitaxy or Molecular Beam Epitaxy fabrication process [14]. The type of the semiconductor material used in the Quantum Dot depends on the lattice mismatch between them. GaAs/AlGaAs is used because of the structure tunability properties and the doping control of the structure [15]. Photoluminescence studies are also done on AlGaAs based quantum dots for characterizing and identifying the optical properties [16],

RESULTS

The simulation is done using Quantum Dot Lab software. Different Z-dimensions are used to analyze its effect. When Z-dimension equals to 5nm, the all, are shown in figures (3), (4), and (5). Figure (3) shows the 3D eave function of the desired pyramid shaped quantum dot with high of 5 nm. The cloudy region represents the electrons that can be stand in the quantum dot. Figure (4) shows the energy state of the Quantum Dot with the bandgap equals to 0.5779 ev. This bandgap defines the wavelength that the quantum dot responds. Figure (5) shows absorption is also depends on the size of QD. Two peaks can be observed 1.2 and 1.7 arbitrary units. Increasing the Z-value results in new dimensions which also leads to examining the shift in the energy states as well as the absorption properties of the Quantum Dot. Figure (6) shows the new Z dimensions after increasing it to 10 nm. Increasing new size of the Quantum Dot results in smaller bandgap than 5nm Quantum Dot. As shown in figure (8), the new bandgap for the 10nm Quantum Dot is 0.3607 ev. The absorption response is also shifted for 10nm Quantum Dot to 0.4 and 0.7 arb units with a new peak at 0.85 as in figure (9). The new peak is resulted from the alteration of the density of states inside the Quantum Dot. When the Z is changed to 15 nm, the bandgap is decreased to 0.2591 ev as in figure (10). The absorption peaks are also shifted to 0.25 and 0.63 arb units which shown in figure (11). Table (1) shows the results of the three Quantum Dots.

CONCLUSIONS

In conclusion, quantum dot devices seems a promising solution as a new generation of devices that suppress noise by confining the electrons in 3D quantum dots and controlling the free movement of the electrons. This suppression confinement of the electrons comes from the confinement of the electrons in 3D structures. However, the operation wavelength of the quantum dot needs to be determined according to the desired wavelength. This operation is done by altering the Z- dimension of the quantum dot. Results showed that increasing the Z-dimension of the quantum dot leads to decrease in bandgap as well as decrease in absorption response. In other words, a Quantum Dot detector can be fabricated according to the required wavelength by choosing the exact and true value of Z. Changing Z-Value results in stress from the small lattice content mismatches leads to the formation of new energy states that electrons can transfer to. These energy levels determine the bandgap and hence the wavelength that the device operates. Several quantum dot layers can be built into the same devices to compromise different wavelength layers. Though, the absorption needs to be calculated for each layer to determine the minimum detection threshold.

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Table (1): Bandgap difference and Absorption response for 5, 10, 15nm Quantum Dots

Z-Diemnsion (nm)	Bandgap (ev)	Absorption response (Arb Units)
5	0.5779	1.2 , 1.7
10	0.3607	0.4, 0.7, 0.85
15	0.2591	0.25 , 0.63

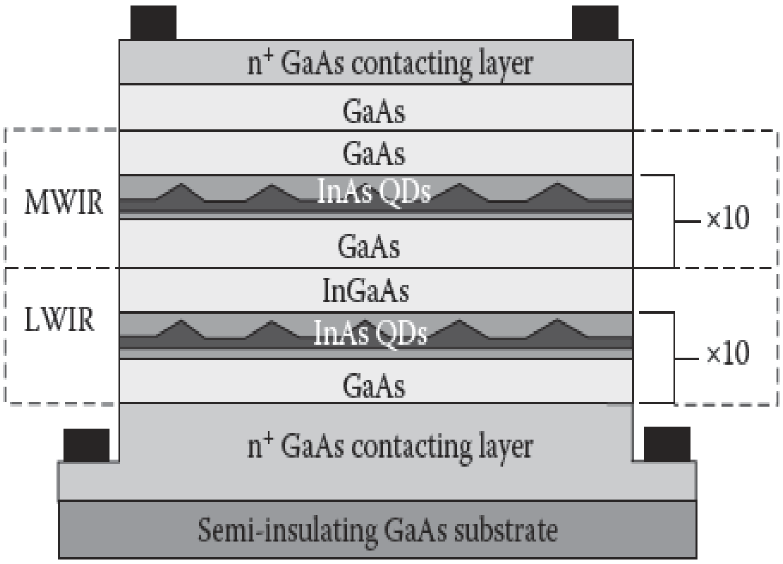

Fig. 1: schematic structure of the multispectral QDIP device

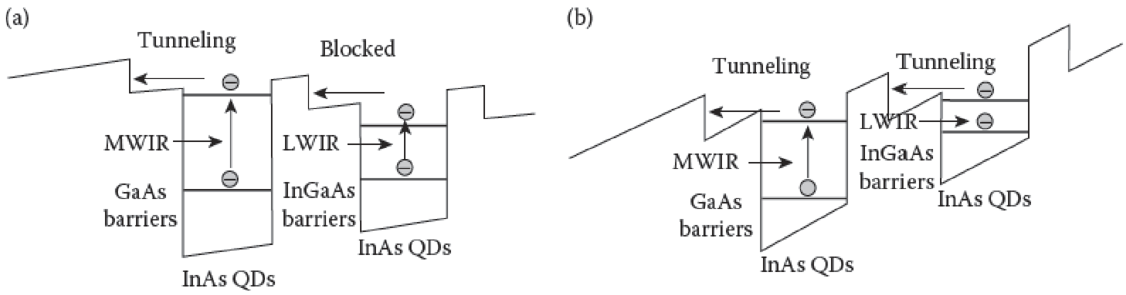

Fig. 2: simplified band diagram of the structure
Low bias voltages (a) and higher bias voltages (b)

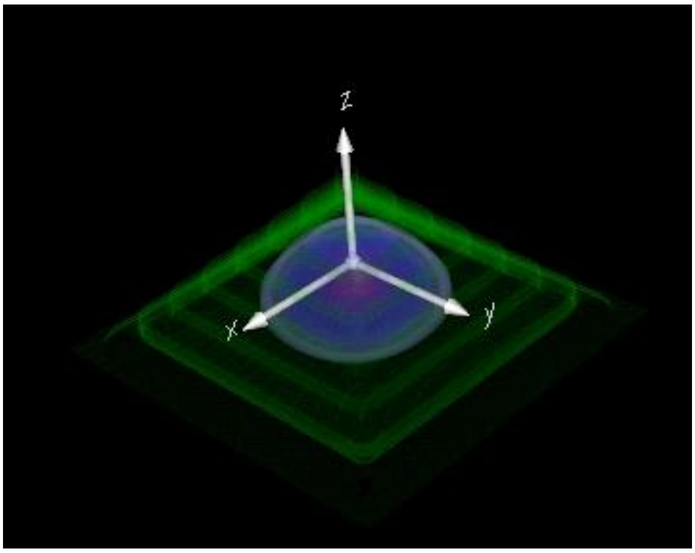

Fig. 3: 3-D wave function plot of 5nm pyramid AlGaAs Quantum Dot

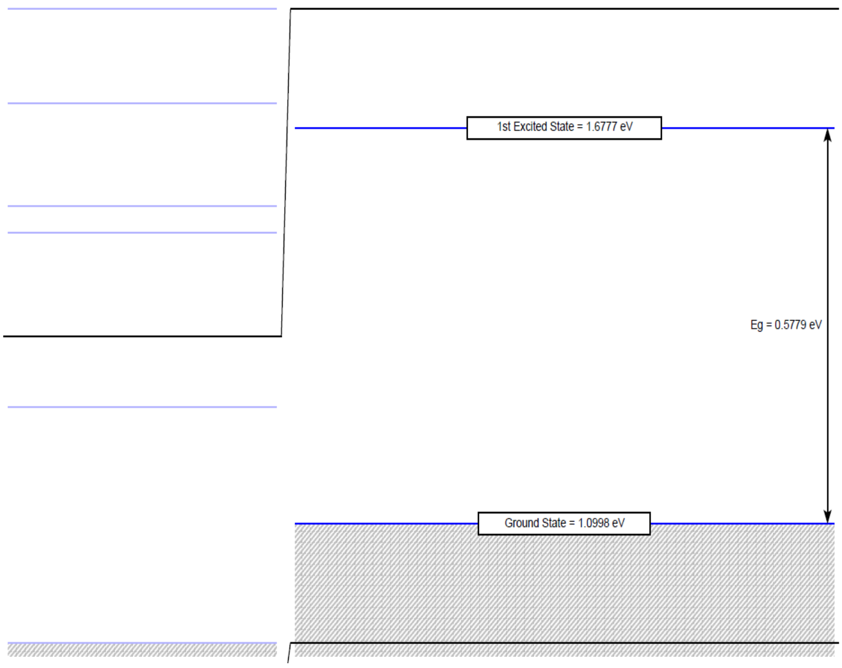

Fig. 4: Energy bandgap in 5nm pyramid AlGaAs Quantum Dot

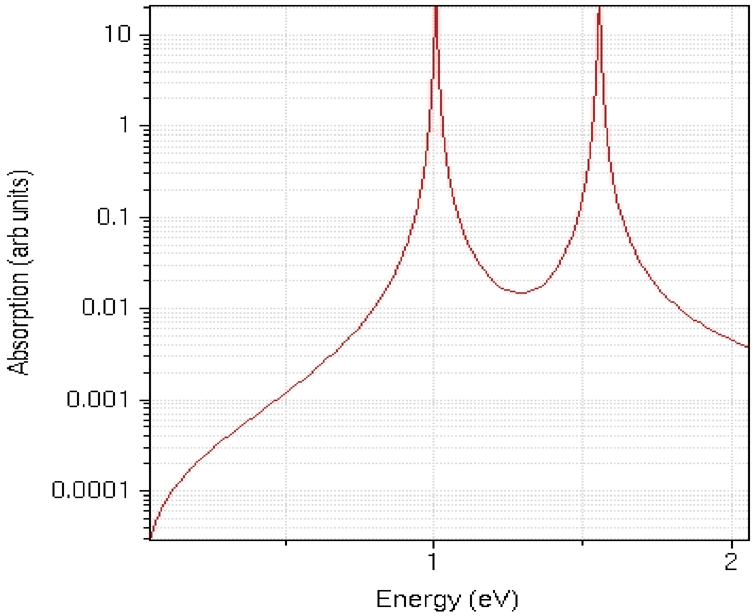

Fig. 5: Absorption response vs. Energy for 5nm AlGaAs Quantum Dot

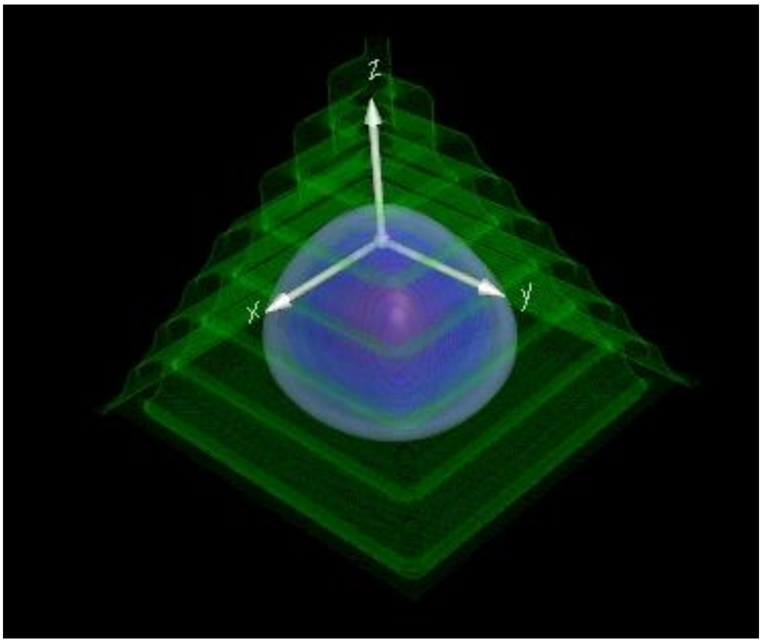

Fig. 6. 3-D wave function plot of 10nm pyramid AlGaAs Quantum Dot

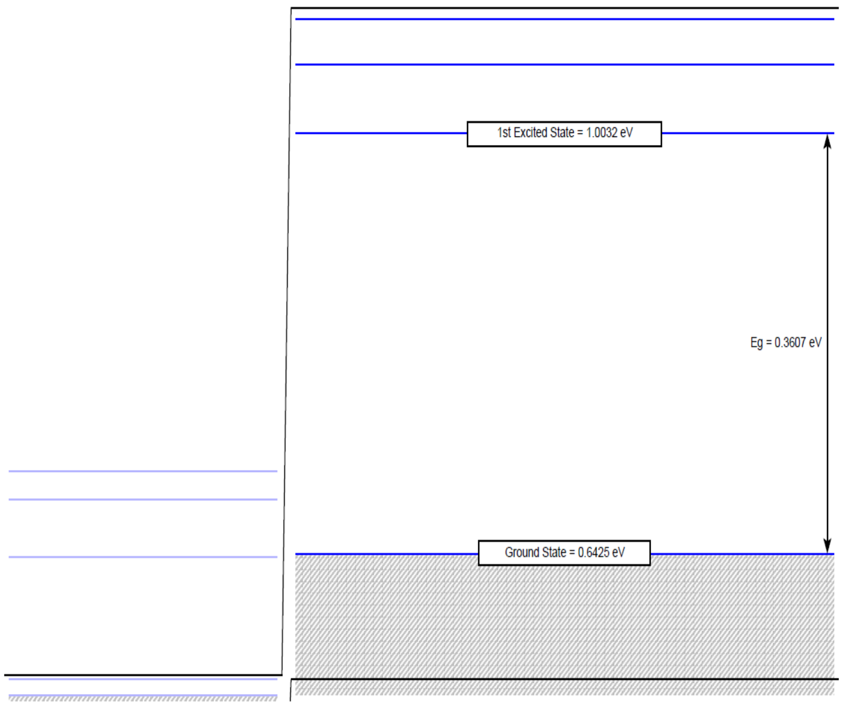

Fig. 7: Energy bandgap in 10nm pyramid AlGaAs Quantum Dot

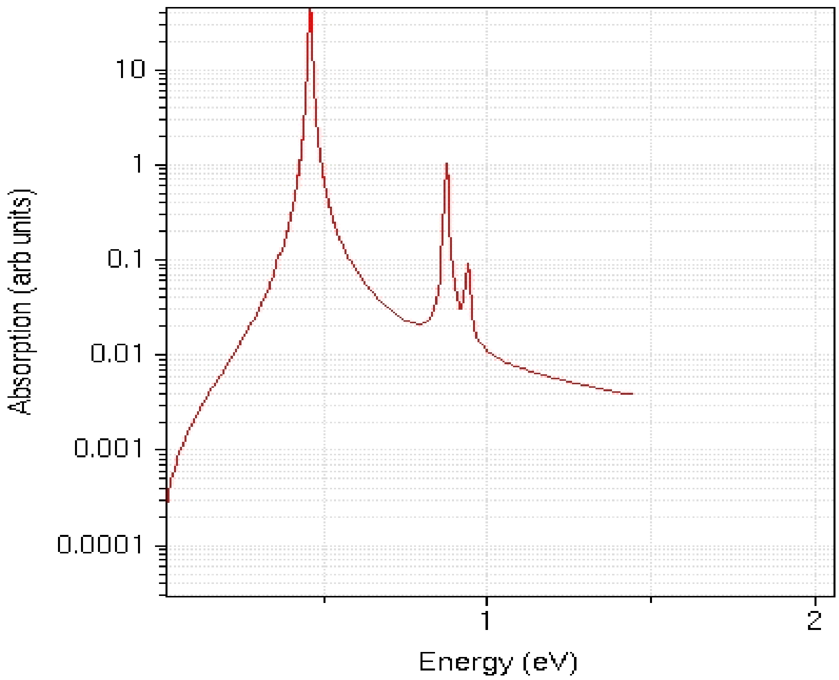

Fig. 8: Absorption response vs. Energy for 10nm AlGaAs Quantum Dot

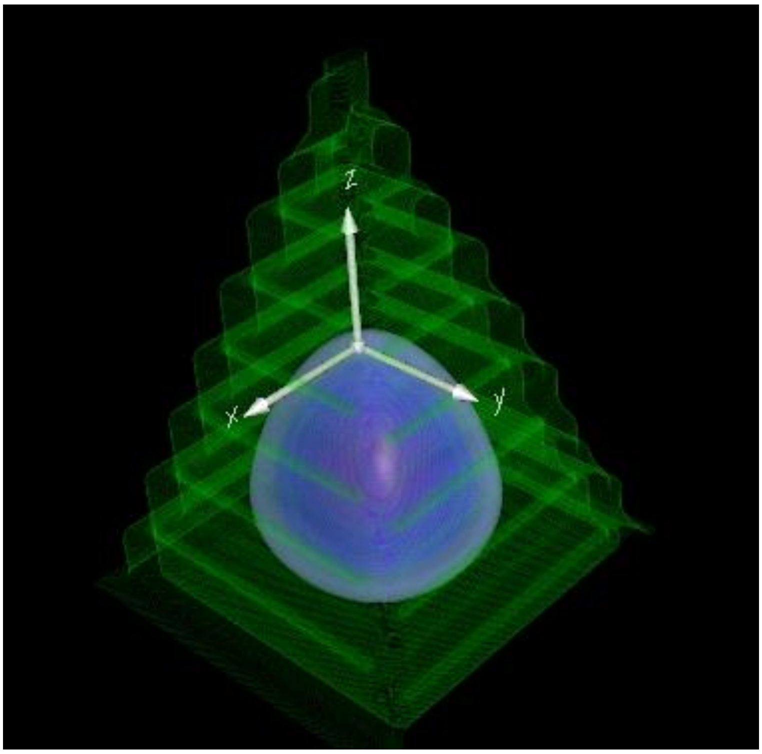

Fig. 9: 3-D wave function plot of 15nm pyramid AlGaAs Quantum Dot

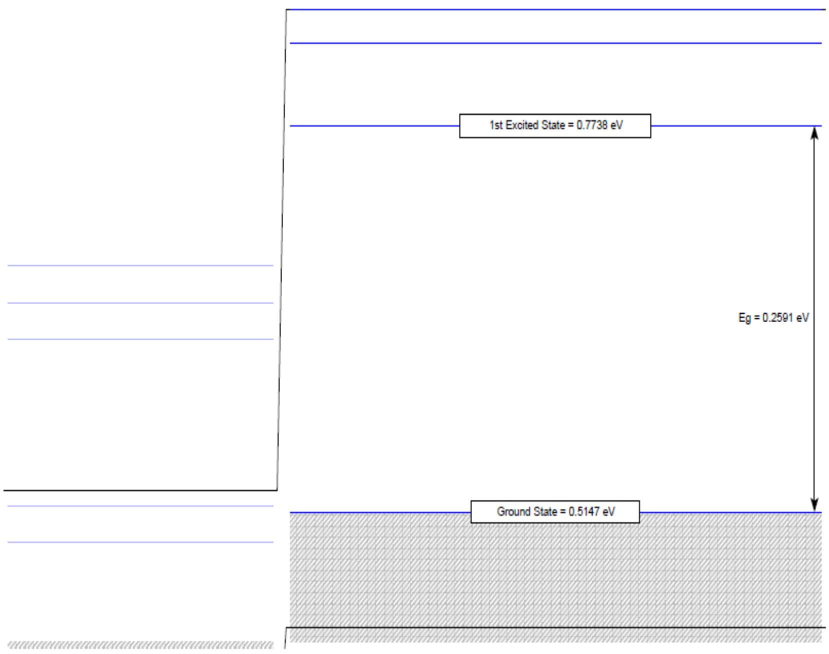

Fig. 10: Energy bandgap in 15nm pyramid AlGaAs Quantum Dot

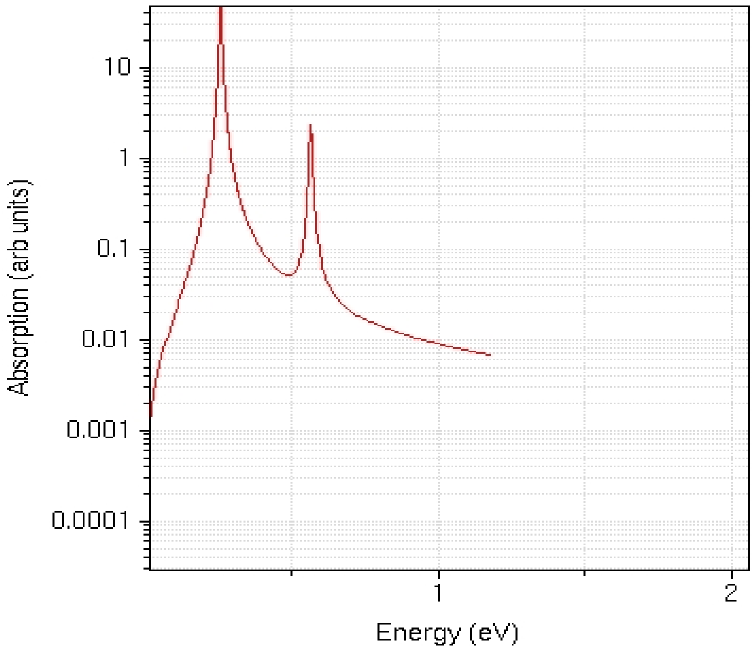

Fig. 11: Absorption response vs. Energy for 15nm AlGaAs Quantum Dot

دراسة الربح الضوئي في الكاشف الضوئي المكون من النقاط الكمية الالمنيوم / غاليوم/ زرنيخ

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الخلاصة:

الكواشف التحت الحمراء المكونة من النقاط الكمية اصبحت في مقدمة كواشف الاشباه الموصلات والسبب يعود الى خصائص هذا النوع من الكواشف التي تعطيها مميزات اكثر من قريناتها مثل الكواشف التحت الحمراء ذات البئر الكمي. في هذا البحث, تم دراسة تأثير تغيير البعد Z للنقاط الكمية على مستويات الطاقة والتي بدورها تأثر على الاستجابة الضوئية للكاشف. وتم دراسة تأثير تغيير البعد Z على تغير استجابة الكاشف للطول الموجي بطريقة المحاكاة باستخدام طريقة شرودنكر– بويسون. ألالكترونات الناتجة مهمة جدا لاعطاء خواص النقاط الكمية. تم استخدام برنامج المحاكاة لتوليد دالة الموجة, مستويات الطاقة, وخواص الامتصاص. واظهرت النتائج ان فجوة الطاقة تقل والامتصاصية تزداد مع زيادة البعد Z.