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The Characteristics of Exciton in Single and Multiple Quantum Wells

Dr. Erada A. Aldabbagh
Science College, University of Mosul / Mosul
Email:erada_aldabagh@yahoo.com
Dr. Ragheed M. Ibrahim
Education College, University of Mosul of / Mosul

ABSTRACT

A study on the dynamic characteristics of the excitonsin finite GaAs single quantum wells surrounded by $Ga_{1-x}Al_xAs$ barriers. We consider the calculations of exciton binding energies as a function of well width was presented for five different values of mole fraction (0.15, 0.25, 0.35, 0.4, 0.45). In addition, we study the exciton Bohr radius λ as a function of the same previous mole fraction values. Also the effect of mole fraction on the binding energy was taken into account for a series of 5-period50 Å GaAs/50 Å $Ga_xAl_{1-x}As$ multiple quantum wells as a function of the equal well and barrier widths, also for different values of mole fraction (0.1, 0.12, 0.14, 0.16, 0.18, 0.2).

خصائص الاكسايتون في بئر الجهد الكمي المنفرد والمتعدد

الخلاصة

تمت دراسة الخواص الديناميكية للاكسايتون في بئر الجهد المنفرد المحدد من نوع GaAs محاط بحاجز الجهد من $Ga_{1-x}Al_xAs$, مع الأخذ بنظر الاعتبار حساب طاقة ترابط الاكسايتون كدالة لعرض البئر و لخمس قيم مختلفة للكسر المولي (0.15,0.25,0.35,0.4,0.45).

كما تناولت الدراسة تركيب متعدد بئر الجهد من حيث تأثير الكسر المولي على طاقة الترابط للاكسايتون لخمسة آبار متسلسلة من 50 Å GaAs/50 Å $Ga_xAl_{1-x}As$ كدالة لعرض حاجز الجهد وعرض البئر, وكذلك لقيم مختلفة للكسر المولي (0.1, 0.12, 0.14, 0.16, 0.18, 0.2). بالإضافة إلى ذلك ،أظهرت الدراسة تأثر اقطار بور للاكسايتون λ كدالة لنفس قيم الكسور المولية السابقة لبئر الجهد المنفرد والمتعدد.

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

INTRODUCTION

The confinement of electrons and holes in semiconductor quantum wells leads to the strong enhancement of excitonicoptical transitions. This provides strong optical non linearities that can be used for all-optical or electro-optical switching devices [1]. One fundamental nonlinearity is the absorption saturation of the exciton by photoexcited free and bound electron-hole pairs [2]. Understanding the basic physics of this saturation is essential for optimizing the performance of electro absorptive photonics devices [3, 4] If photons of energy comparable to the band gap are incident on a semiconductor, then they can be absorbed by the electrons forming atomic bonds between neighboring atoms, and so provide them with enough energy to break free and move around in the body of the crystal. Within the band theory of solids, this would be described as exciting an electron from the valence band across the band gap into the conduction band. If the energy of the photon is larger than the band gap, then a free electron is createdand an empty state is left within the valence band. The empty state within the valence band behaves very much like an air bubble in a liquid and rises to the top-the lowest energy state. This hole behaves as though it were positively charged and hence often forms a bond with a conductionbandelectron. The attractive potential leads to a reduction (by an amount E_x^o) in the total energy of the electron and hole. This bound electron-hole pair is known as an exciton. Photons of energy just below the band gap can by absorb, thus creating excitons directly [5].

PROCEDURE AND RESULTS

As the whole mass is generally much greater than the electron mass, then the two body system resembles a hydrogen atom, with the negatively charged electron orbiting the positive hole. The exciton is quite stable and can have a relatively long lifetime, ofthe order of hundreds of psto ns. Exciton recombination is an important feature of low temperature photoluminescence, although as the binding energies are relatively low, i.e. a few meV to a few tens of meV, they tend to dissociate a thigher temperatures [5].The refore, in asimilarmanner to the hydrogenicimpurities, the binding energy and orbital radius can be represented well by Bohr theory, with the correction for the finite mass of the central charge[6,7]. This is implementedby exchanging the (in the case of a hydrogen atom, or donor) orbiting electron mass, with the reduced mass of the two-body system, in this case, the electron-hole pair. The reduced mass is given by [6, 7]:

$$\frac{1}{\mu} = \frac{1}{m_e^*} + \frac{1}{m_h^*} \qquad \ldots (1)$$

Hence, the binding energy becomes [5]:

$$E_{X^0} = -\frac{\mu e^4}{32\pi^2\hbar^2\epsilon_r^2\epsilon_0^2} \qquad \ldots (2)$$

and the Bohr radius follows as[5]:

$$\lambda = \frac{4\pi\epsilon_r\epsilon_0\hbar^2}{\mu e^2} \qquad \ldots (3)$$

then the exciton binding energy andBohr radius follow respectively, as[5]

$$E_{X^0} = -4.7\,\text{meV} \quad \text{and} \quad \lambda = 115\,\text{Å} \qquad \text{... (4)}$$

In the same way as in bulk, excitons can be formed by the bonding of free electron free hole pairs or through resonant excitation. Whereas in bulk, the total energy of the exciton is simply the energy of the free electron-free whole pair (i.e. the band gap) plus the exciton binding energy E_x^o, in a hetero structure there are additional components due to the electron and hole confinement energies [5], i.e.

$$E = E_g + E_{X^0}\ \text{(bulk)} \quad E = E_g + E_e + E_h + E_{X^0}\ \text{(heterostructure)} \qquad \ldots (5)$$

The total exciton energy is clearly a function of structure because of the structural dependency of the confinement energies. In addition, it must be expected that the Coulombic potential energy, i.e. E_x^o, also depends upon the structure. This later effect arises because the electron-hole separation can vary quite considerably between heterostructures.The Hamiltonian representing the interacting two-body electron-hole complex canbe considered to be the sum of three terms [5]:

$$H = H_e + H_h + H_{e-h} \qquad \ldots (6)$$

Where $H_e$and $H_h$are the one-particle Hamiltonians appropriate to the conduction and valence bands, respectively, of the particular microstructure of interest. The third term, $H_{e\text{-}h}$represents the electron-hole interaction. The two dimensional exciton binding energy is related to the binding energy of bulk structure, and is given as, [5]

$$E^{2D} = -4\frac{me^4}{32\pi^2\hbar^2\epsilon_r^2\epsilon_0^2} = 4E^{3D} \qquad \ldots (7)$$

and the two dimensional Bohr radius is given as [5]:

$$\lambda_{2D} = \frac{4\pi\epsilon_r\epsilon_0\hbar^2}{2me^2} = \frac{\lambda_{3D}}{2} \qquad \ldots (8)$$

Increasing Al concentration in the barrier (both the conduction and valence band offsets are proportional to the mole fraction x) leads to an increase in the magnitude of the exciton binding energy for all well widths. We consider the barrier height (for x=0.15, 0.25, 0.35, 0.45) unlike the Harrison values in order to see the effects of the other values on the binding energy of exciton.

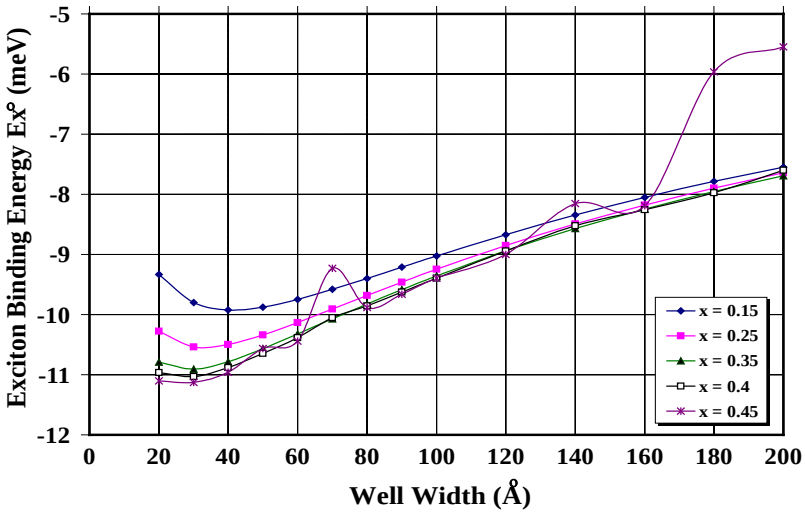

Figure (1) The exciton binding energy Ex^o in a GaAs quantum Well surrounded by $Ga_{1-x}Al_xAs$ barriers.

Figure (1) display the results of calculations of exciton binding energies in finite GaAs single quantum wells surrounded by $Ga_{1-x}Al_xAs$barriers.The negative values on the graph illustrate that it is in deeda bound state. Unlike the infinite-well Case, the exciton binding energy E_x^o is a non-monotonic function of well width especially for the law values barrier height (for x=0.15, 0.25, 0.35). This isdue to the effect of the well width on the electron and whole confinement. At very narrow well widths, the one-particle states are 'squeezed' up the well to reside at energies just below the top of the barrier. The wave function tends to 'spill' over the top, thus leading to a reduced probability of the particle being within the region of the quantum well [5]. This non-monotonic behavior has been observed in experiment [8].

However, there are two points to note regarding this. First, the effect of the barrier height is reduced at larger well widths [5]. Secondly, the effect of an increasing barrier height is largest at smaller well widths, and for any given well width, further increases in the barrier height lead to smaller increases in the binding energy. But at large values of barrier height (x=0.4, 0.45) the curves become approximately monotonic, i.e., it become the infinite-well case. Also, at high barrier (in limit x=0.45), the exciton binding energy firstly increases and at well width more than 40 Å, we expected that the exciton is recombined again, and secondly it overlap especially at well width 50, 70, 140, 180 Å and greater, i.e. the exciton binding energy is tending towards its bulk value of 4.7 meV[5].

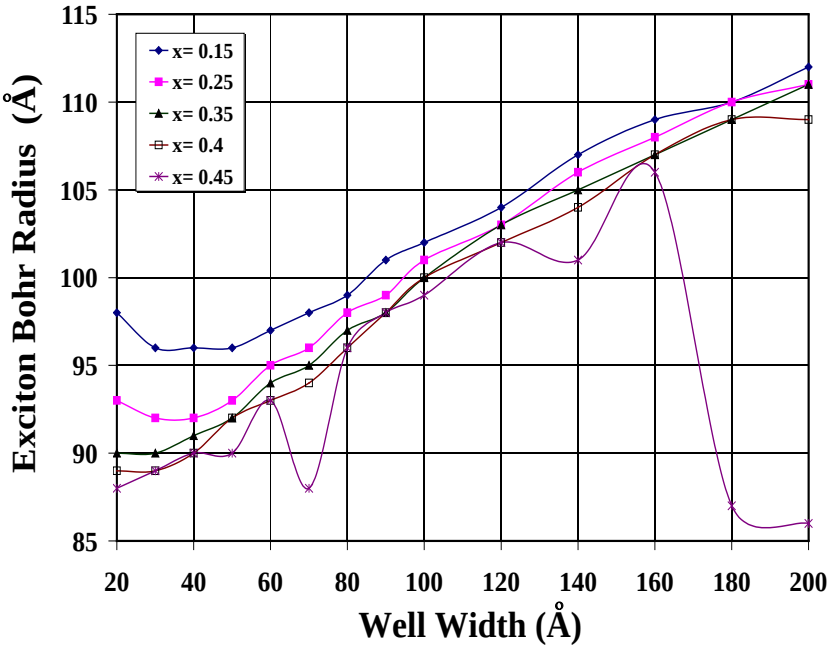

Figure (2) The exciton Bohr radius λ in a GaAs quantum Well surrounded by $Ga_{1-x}Al_xAs$barriers.

Figure (2) shows the functional dependencies of Bohr radius λ on well width and barrier height, which is mirror that of the binding energy $E_X{}^0$, except for x=0.45, it is an on-monotonic function of well width, decreases with increasing barrier height and tends towards its bulk value of 115 Å at large well widths. It is clear from the figure, that when x=0.45 there are minima values of Bohr radius in contrast to the maxima values of binding energy in Figure (1), i.e., the exciton start to annihilate.

The exciton binding energy for a series of 5-period multiple quantum wells is displayed in Figure (3) as a function of the equal well (l_w) and barrier (l_b) widths (50 Å) for many values of mole fraction (x=0.1, 0.12, 0.14, 0.16, 0.18, 0.2). In contrast to the finite well, the magnitude of $E_X°$ passes through a minimum, which in this material system is at around 50-60 Å, before increasing again. In each value of mole fraction there are many singularity points in a barrier region. That is, in the GaAs-$Ga_{1-x}Al_xAs$material system here, larger well and barrier widths reduced the interaction between the states in adjacent wells. Hence the truncation of the data at 60 and 80 Å will be occurred, as shown in Figure (4).

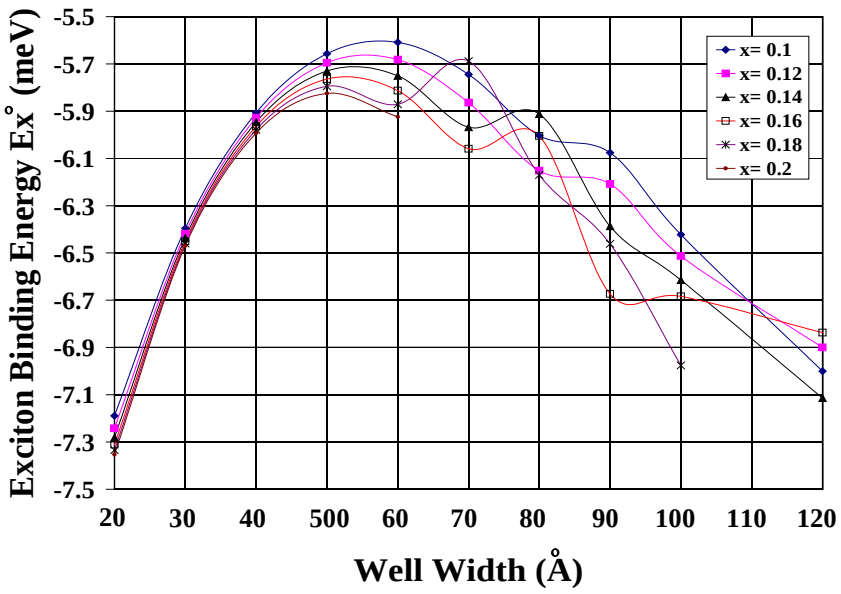

Figure (3) The exciton binding energy Ex^oas a function of well width in a 5-periodGaAs-$Ga_{1-x}Al_xAs$ multiple quantum well.

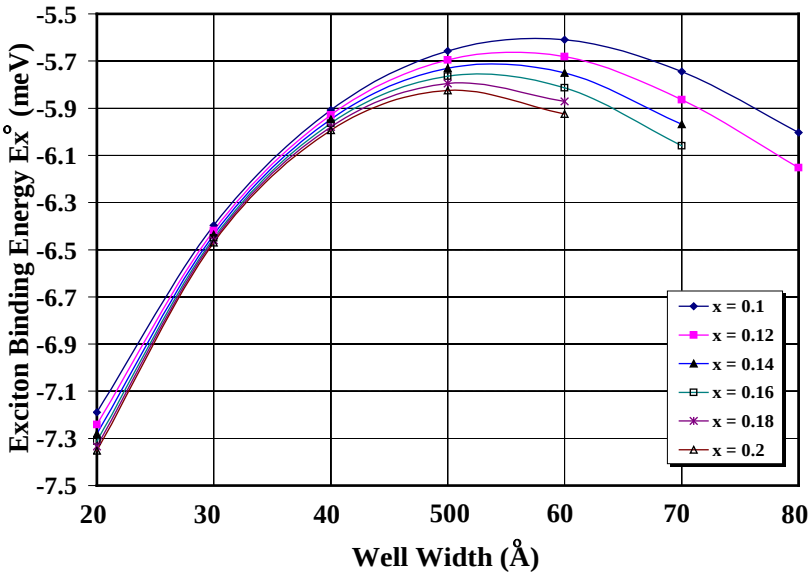

Figure (4)The exciton binding energy Ex^oas a function of well width in a 5-periodGaAs-$Ga_{1-x}Al_xAs$ multiple quantum well.

CONCLUSIONS

In conclusion, we investigate the effect of well width and the barrier height on the binding energy and Bohr radius for finite GaAs single quantum wells surrounded by $Ga_{1-x}Al_xAs$ barriers, anda series of 5-period multiplequantum wells. We note that, for a single well the exciton binding energy E_x^o is a non-monotonicfunction of well width especially for the law values barrier height (x=0.15, 0.25, 0.35), while at large values of barrier height (x=0.4, 0.45) the curves become approximately monotonic. In contrast, in multiple quanta well, the excitonic binding energy has the maxima values at well width between 50-60 Å.

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