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Diamagnetic susceptibility: An indicator of pressure induced donor localization in a double quantum well

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ABSTRACT

The influence of pressure along the growth axis on carrier localization in GaAs/$Al_{0.3}Ga_{0.7}As$ Double Quantum Well (DQW) is studied under strongly coupled regime and isolated regimes of the well. The effective mass approximation combined with variation technique is adopted with the inclusion of mismatches in effective mass and dielectric constants of the well and barrier material. Effect of the barrier and well on carrier localization is investigated by observing the diamagnetic susceptibility (χ_{dia}) for various impurity locations (z_i) and the critical limit of the barrier ($L_b \approx 50$ Å) for tunneling has also been estimated. The effect of Γ-X crossover due to the application of pressure on the donor localization is picturized through diamagnetic susceptibility.

1. Introduction

Existence of unique properties and survival of effective mass approximation for systems in ground state have made the semiconductor nanostructure an interesting material to explore until now. Semiconductor Quantum Heterostructures have been an interesting paradigm, whose physical properties are explored by solving an Eigen equation of a charged particle confined in such systems [1–5]. Towards this search, Double Quantum Wells (DQW) with various barrier frames and perturbations have been exploited to familiarize the physics of carriers inside it [6–8]. The quasi bound states in DQW can be tuned by altering the barriers or by any external perturbation which bring out resonant tunneling of electrons. These properties are exploited in generation and detection of ultrahigh frequency (terahertz) electromagnetic oscillations [9], fabricating low loss waveguides [1] etc. Asymmetric DQW are more preferable for such applications since they provide different resonant tunneling in each well. Comparing to a single QW with double barrier structure, DQW/Multiple QW (MQW) with triple barrier may regulate the resonant tunneling [7] effectively, whenever there is a resonance matching within the subband. There is voluminous literature on DQW associated with perturbations which are useful in fabricating optoelectronic devices and to study many body and nonlinear effects. Pressure has been recognized as a versatile tool for regenerative band structure tuning of nanostructures. As a primary effect applied pressure increases the carrier effective mass, reduces the dielectric constants, squeezes the well and changes the effective Rydberg of the respective layers. As a secondary effect, application of pressure induces hybridization of Γ and X–like Bloch states [10] in narrow wells. This effect is observed in photoluminescence spectra and is visible in resonant tunneling and magneto-optical measurements such as Far Infrared (FIR) Magneto spectroscopy. In GaAs/$Al_{0.3}Ga_{0.7}As$ QW, as pressure grows, lack of translational symmetry along

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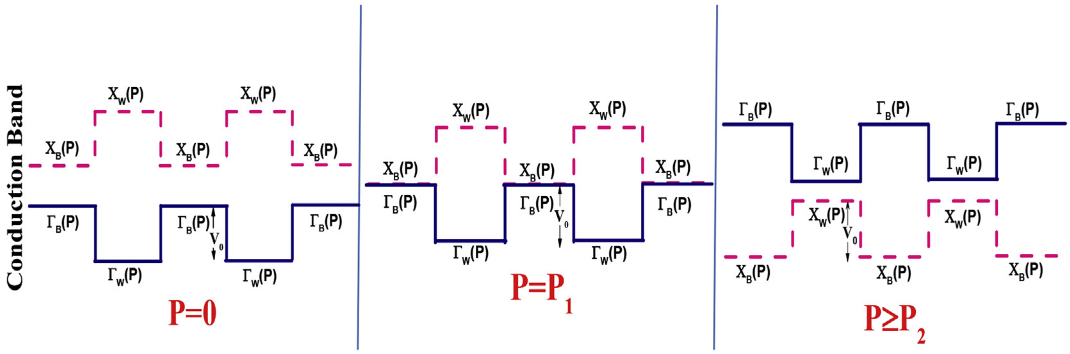

Fig. 1. Γ and X band crossover in the well (w) and barrier (b) regions due to pressure. V_0- potential barrier height and $P_1 = 13.5$ kbar and $P_2 = 33.2$ kbar are the first and second critical pressures for $GaAs/Al_{0.3}Ga_{0.7}As$ QW.

the growth axis may induce the Γ-X inter mixing. This mixing has direct dependency on the quality of interfaces, the position of Γ, X points and dimensions of well and barrier layer. Pressure upto 13.5 kbar does not alter the band structure, but pressure beyond that (13.5 kbar < P < 33.2 kbar) leads to reduction in barrier height, since X band of barrier drops below the Γ-point. Pressure above 33.2 kbar brings out Γ-X crossover in both the layers. At this stage, the system completely transforms from direct to indirect band gap material (Type I to Type II). Diamagnetic susceptibility is an inherent property of all materials. Irrespective of the dimensions of nanostructures, diamagnetic susceptibility (χ_{dia}) has direct impact on the manipulation of donor wave function [12] which can be estimated using variation approach. This property has been exploited by many authors during the last decade as it helps to understand magneto-electronic and Spintronic devices. Influence of Quantum confinement, structural dependence, impurity position and external perturbation [13,14] (such as Pressure, Temperature, Laser, Magnetic field etc.) on χ_{dia} in QW structure has been carried out by several authors. Rajashabala et al. [15], have shown that the influence of dielectric screening is ineffective for susceptibility calculations and anisotropic effective masses would squeeze the donor wavefunction distribution inside the growth axis. Nithiananthi et al. [16] have demonstrated semiconductor–metal transition through χ_{dia} of donor in $GaAs/Al_xGa_{1-x}As$ QW system which was confirmed experimentally [17]. The transition from semiconductor to metallic phase is clearly shown by the abrupt fall of χ_{dia} at the critical donor concentration. This work emphasises that observation of χ_{dia} is more suitable to investigate such transition. Diamagnetic susceptibility is a direct measure of $<r^2>$ (i.e.) the effective distance of the carrier from its parent donor. Investigation of χ_{dia} will give a clear picture of the carrier localization and its correspondence with its parent donor. Since the properties of nanomaterials are completely decided by the carrier localization, the study of χ_{dia} is very much essential and convenient to deal with nanostructures. This is also a favorable tool to measure the spatial extension of excitons in nanostructured systems. Since direct experimental measurement of $<r^2>$ is not feasible, measurement of χ_{dia} eases this difficulty. Hence, obviously susceptibility mapping is a good perception of the behavior of impurity states inside the nanomaterials. In the same line, in this work, a DQW formed by $GaAs/Al_{0.3}Ga_{0.7}As$ with a hydrogenic donor impurity has been considered. In view of predicting the dynamics and hence tunneling effect through barrier, χ_{dia} of hydrogenic donor and the influence of Γ - X crossover due to hydrostatic pressure on it have been investigated. Based on the results obtained, the critical barrier limit for tunneling has also been estimated.

1.1. A brief outline

Diamagnetic susceptibility (χ_{dia}) of a hydrogenic donor in a DQW has been estimated as a function of pressure for various impurity locations at temperature T = 4 K. This has been analyzed with the critical barrier widths, which decides the coupling or decoupling among the wells. It is found that $L_b \approx 50$ Å is the critical central barrier width irrespective of the well widths. Only within this limit there is coupling between the wells favoring tunneling of the electrons and beyond that the wells get isolated. Pressure effect on χ_{dia} is observed by considering the donor impurity in the alternate layers of $GaAs/Al_{0.3}Ga_{0.7}As$ DQW. The three pressure windows considered here are $0 < P < P_1$ ($P_1 = 13.5$ kbar), $P_1 < P < P_2$ ($P_2 = 33.2$ kbar) and $P > P_2$. P_1 and P_2 are the critical crossover pressures at which crossover between X-band & Γ-band takes place in the barrier (X_b and Γ_b) and in the well (X_w and Γ_w) respectively. The schematic representation of Γ- X band crossover in the well and barrier region at critical pressures is given in Fig. 1.

Location of the impurity is chosen as,

Case (i): Center of the Well (OCW) ($z_i = (L_b/2 + L_w/2)$).

Case (ii); Center of the Barrier (OCB) ($z_i = 0$).

Case (iii): Edge of the Barrier (OEB) ($z_i = L_b/2$).

Case (iv): Edge of the Well (OEW) ($z_i = (L_b/2 + L_w)$).