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Coupled quantum wells as a novel source of optical anisotropies in nanostructured systems

Doctoral Thesis in Applied Sciences
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Statement of authorship

I, Oscar Ruiz Cigarrillo, student of the Graduate Program in Applied Sciences of the School of Sciencies of the Universidad Autonoma de San Luis Potosi, as author of the thesis "Coupled quantum wells as a novel source of optical anisotropies in nanostructured systems", declare that the thesis is an original, unpublished, authentic, personal work, that the corresponding sources have been cited and that in its execution the legal provisions in force that protect the copyright and intellectual and industrial property rights were respected. The ideas, doctrines, results and conclusions I have reached are my absolute responsibility.

Abstract

In the present work, is it proposed a new source of IOAs occurring in asymmetric coupled quantum wells ACQWs, namely a reduction of the symmetry from D_{2d} to C_{2v} as imposed by asymmetry along the growth direction. We report on reflectance anisotropy spectroscopy (RAS) of double GaAs quantum wells structures coupled by a thin (< 2 nm) tunneling barrier (CQWs). Two groups of DQWs systems were studied: one where both QWs have the same thickness (SCQWs) and another one where they have different thicknesses (ACQWs). RAS measures the in-plane optical anisotropies (IOAs) arising from the intermixing of the heavy- and light- holes in the valence band when the symmetry of the DQW system is lowered from D_{2d} to C_{2v}. If the CQWS are symmetric, residual IOAs stem from the asymmetry of the QW interfaces; for instance, associated to Ga segregation into the AlGaAs layer during the epitaxial growth process. In the case of an ACWQs with QWs with different thicknesses, the AlGaAs layers (that are sources of anisotropies) are not distributed symmetrically at both sides of the tunneling barrier. Thus, the system losses its inversion symmetry yielding an increase of the RAS strength. The RAS line shapes were compared with reflectance spectra in order to assess the heavy- and light- hole mixing induced by the symmetry breakdown. The energies of the optical transitions were calculated by numerically solving the one-dimensional Schrödinger equation using a finite-differences method. Our results are useful for interpretation of the transitions occurring in both, symmetric and asymmetric CQWs.

Acknoweldgement

Contents

Abbreviations

BS	Band structure
BZ	*Brillouin zone*
QS	Quantum Structures
QW	Quantum Well
SQW	Single Quantum Well
CQWs	Coupled Quantum Wells
VB	Valence Band
CB	Conduction Band
SCQWs	Symmetric coupled quantum wells
ACQWs	Asymmetric coupled quantum wells
RAS	Reflectance Anisotropy Spectroscopy
PL	Photoluminiscense spectroscopy
PR	Photoreflectance spectroscopy
R	Reflectance spectroscopy
PRD	Photo-Reflectance Differential Spectroscopy
FDM	Finite differnce method
CCD	Charge coupled device
0D	Zero-dimensional
1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
fcc	Face-centered cubic
2DEG	Two-dimensional electron gas
BL	Beer-Lambert-Law
TB	Tight-Binding method
PD	Photo-Detector
PEM	Photo-Elastic Modulator
QM	Quantum Mechanics
$\boldsymbol{k} \cdot \boldsymbol{p}$	Semiempirical theoretical tool to calculate band-structure
TB	Semiempirical Thight-Binding Method
DFT	Density Functional Theory
SOC	Spin-Orbit Coupling, also called Spin-Orbit interaction
LFLM	Dr. Luis Felipe Lastras Martinez group.
EFA	Envelope function Approximation
EMA	Effective Mass Approximation
FKOs	Franz Keldysh oscillations
IOA	In-plane Optical Anisotropy

List of codes and packages

This list denote the *Open-Source* packages, codes, tools, and repositories for the development of this work. All inside of this work as images or numerical calculations are subject to the *Open-Source* ideology. Our codes are housed in our own GitHub repository, both personal and laboratory repository. It's important to say that without the development of the *Open-Source* codes like contents in this list, our codes, they couldn't be enhanced.

cqws-codes Repository of our codes implemented in this work. [1]

kp-lflm-group $\boldsymbol{k}\cdot\boldsymbol{p}$ julia [2] package developed by Our group research [3]

ASE The Atomic Simulation Environment (ASE) is a set of tools and Python modules for setting up, manipulating, running, visualizing and analyzing atomistic simulations. [4]

Spglib Software library for crystal symmetry search [5]

SOLCORE A multi-scale, Python-based library for modelling solar cells and semiconductor materials [6]

Aestimo One-dimensional (1D) self-consistent Schrödinger-Poisson solver for semiconductor heterostructures [7]

VESTA 3D visualization program for structural models, volumetric data such as electron/nuclear densities, and crystal morphologies. [8]

PGF/TikZ PGF is a macro package for creating graphics. It is platform- and format-independent and works together with the most important TEXbackend drivers, including pdfTEXand dvips. It comes with a user-friendly syntax layer called TikZ. [9]

pst-optexp PStricks package to drawing optical experimental setups. [10]

Symbols

$\mathbf{X^-}$ Negative Trion

$\mathbf{X^+}$ Positive Trion

X Direct Exciton

IX Indirect Exciton

$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ AlGaAs semiconductor as a function of Al concentration x

$\hbar$ Planck's constant (eV)

m_0 electron effective mass

(hkl) Family of lattice planes with Miller indices h, k and l

E_g Energy bandgap

e eletron

hh heavy-hole

lh light-hole

$\mathrm{e_n - hh_n}$ **or** $\mathrm{e_n - lh_n}$ Electronic transitions

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Conclusions and Future Work

In this chapter raise the principal conclusion of this work and present the future experiments on these structures in the wake of obtained results.

THE aim of this work finally results in important publications, the CQWs continue to be an excellent platform to study optical and quantum-mechanical properties, this work presents an important result and enhance the importance of study these structures. The principal idea to exposes our results was planned to simplify but specify the physical basis, starting from explain a single QW and structural properties then raise the relevance of symmetry context to understand the physical behavior of electrons. In section exposes the symmetry importance in this work and their fundamental role in emergence of the IOA. Then focus on symmetry reduction (symmetry breaking) which is the causes of appearance of interesting physical properties, in our case optical properties.

The perturbative model purposed to understand of the IOA is simple and useful, as this depend on grade of asymmetry in the CQWs system, the more asymmetry increases the RAS signal. Also, this model is support by the numerical calculations with a good approximation. When it had obtained the firsts results, we purposed to developed codes to generate numerical results and although this represented a new area to explore, we decided to dedicated enough time to get a new tool to support our experimental work. Already inside in numerical solutions' area, we realized of complexity of generate reliable results, overall to existence of numerous proposals to get it, then we decided implemented the simplicity context. Our numerical results are simple but reliable in accordance with the numerical results, by this reason we create a GitHub repository [11] with aim to developed new codes and numerical models which in future work can will be implemented. In the experimental part, the results are the proof of the arduously work that it was inverted, along of the project it was realized experiments to study and understand the physics which involves the CQWs systems, although this has been study for several years ago, our contribution it's novel.
The quantum confinement is the key of these structures, if add the symmetry breaking by coupled wells width asymmetry exhibits wonderful physics, from spin dynamics to excitonic effects. With respect to spin dynamics into CQWs structures, it was realized experiments of circularly polarized PL over the samples shown in this work, reveals that the spin relaxation time τ_s. It has been demonstrates that the degree of circular polarization is directly related to the asymmetry of the CQWs [12].
The excitonic properties shown in the **??** are really interesting, the PR experiments performed as a laser power function reveal a non-common transition in these experiments, this transition associated with a trion, commonly occurs in structures under external disturbance as an electric field applied, in our case, we not only detect the trion transition, but also it modulated with a light source. This means this can be applied as a laser transistor. These PR results are very relevant, in fact as a future work we planned to publish them.

Finally, in the RAS experiments it's clearly the wonderful physics which exhibits ACQWs structures, the results obtained are the principle of an experiments' series which we're thinking to carried out. Without intention to being repetitive since the results proofs our

hard work, we purpose to take further the RAS technique to explore with more detail the ACQWs structures. The first upgrade of RAS experiments, it's do it spin sensitive, this means, spin resolve RAS experiments.
The principal idea is enhancing the RAS setup to measure spin response. Our proposal is to carry out the experiments just changing the modulated PEM polarization. In the RAS setup (as can see in **??**) the monochromatic beam is first polarized to then modulated linear polarization by the PEM between mutual perpendicular polarization states, to finally spot on sample along [110] and [1$\bar{1}$0] directions. Then, in the spin resolve RAS experiments, it purpose to modify PEM polarization modulation, to this it's possible to choice that the modulation being right circular and left circular polarization, in the PEM device this is $\lambda/4$ and $3\lambda/2$ which in contrast with the $\lambda/2$ of the traditional RAS experiments.

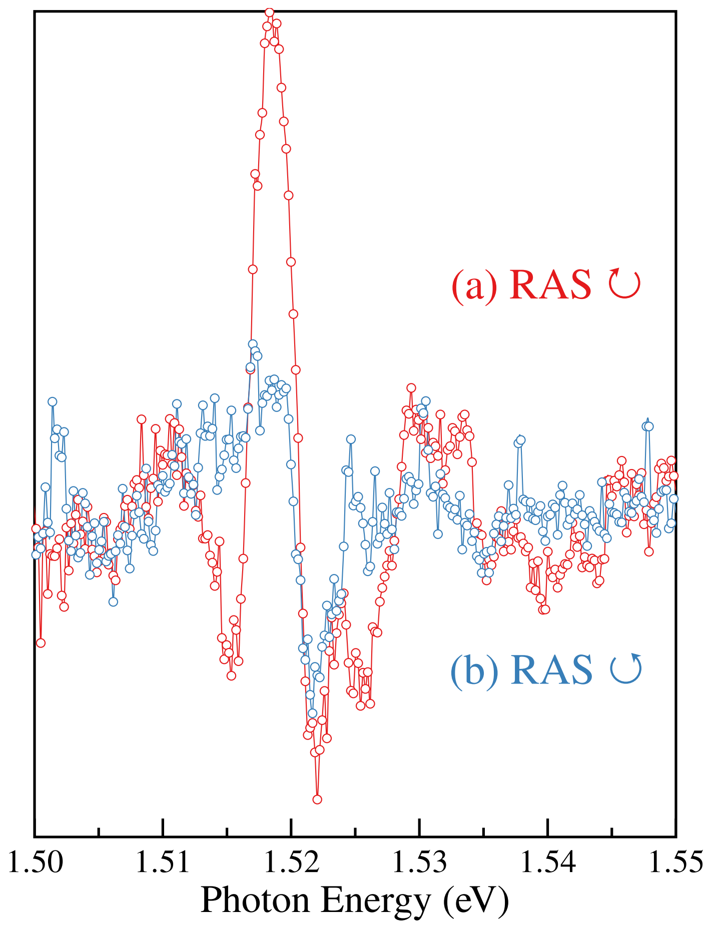

Figure 1.1: Spin resolve RAS experiments worked on ACQWs-2 sample, this experiments carried out in sequential way, firstly measured with one polarization state and then the second state. The sample it was placed along preferential direction ([1$\bar{1}$0]), maybe this be a reason can observer a structural signal of RAS, this means, the line shape of anisotropy due to the asymmetry structure. Although, it's notable the difference between mutual polarization states.

The first results obtained from worked on ACQWs-2 sample shows in Figure 1.1, these experiments were it performed with the sample position in a preferential direction [1$\bar{1}$0] and as a sequential way, this means, firstly with a polarization state then the other state. The results shown in Figure 1.1 are the average of sequential experiments, each of one with their respective polarization. The signals results exhibit an interest difference, although, maybe the line-shape has a remainder of structural anisotropy due to the asymmetry in the structure (C_{2v}). If taken into account the contribution of structural anisotropy, it appears to be polarization is longer. Even if, these results are really first approximation, the technique has powerful to explore spin properties. The second RAS upgrade to spin resolve, it's a proposal, instead of polarization states with the PEM will be used a laser beam circular (left and right) focused onto the sample, while the RAS signal it's measured traditionally. We expected that these upgrades the RAS experiments, turning a tool for spin study.

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