Vol. 18, No. 3 (2019) 825-830
Revista Mexicana de Ingeniería Química

QUANTUM WELLS BASED STRUCTURES TESTED BY PHOTOREFLECTANCE ANISOTROPY SPECTROSCOPY AT ROOM TEMPERATURE

ESTRUCTURAS BASADAS EN POZOS CUÁNTICOS ANALIZADAS POR FOTORREFLECTANCIA ANISOTRÓPICA A TEMPERATURA AMBIENTE

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Received: July 3, 2018; Accepted: September 27, 2018

Abstract

We report the visualization of interface optical anisotropies in III-V semiconductor based coupled double quantum wells by using photoreflectance anisotropy spectroscopy. Interfacial optical anisotropies were detected from buried layers with quantum dimensions at room temperature through a piezoelectric shear strain. The discrete transitions associated to coupled double quantum wells were observed in near-infrared range, specifically in the second telecommunication band. We propose to use this extended photoreflectance spectroscopy through a polarization contrast as a simple and complementary optical method for analyzing anisotropic quantum structures with polarizable defects or anti-symmetries.

Keywords: semiconductors, photoreflectance, quantum wells, optical anisotropies.

Resumen

Se reporta la detección de anisotropías ópticas interfaciales de pozos cuánticos dobles acoplados basados en semiconductores III-V por medio de la espectroscopía de fotorreflectancia anisotrópica. Las anisotropías corresponden a películas no superficiales y de dimensiones cuánticas detectadas a través de un esfuerzo piezoeléctrico de cizalla en condiciones ambientales. Las transiciones discretas asociadas a los pozos acoplados se encuentran en el rango del cercano infrarrojo, específicamente en la segunda banda de menor absorción de telecomunicaciones. Se propone usar la técnica de fotorreflectancia extendida por contaste de polarización como un método óptico simple y complementario para analizar estructuras cuánticas con defectos polarizables o antisimetrías.

Palabras clave: semiconductores, fotorreflectancia, pozos cuánticos, anisotropías ópticas.

1 Introduction

Over the years, complex semiconductor devices such as lasers, solar cells, photodetectors or optical switches, for instance, have been improved using low dimensional structures as for instance quantum well, dots or wires due to their quantum properties (Huwer *et al.*, 2017; Li, 2017; Mukhtarova *et al.*, 2016; Wierer, Koleske, & Lee, 2012; Zheng, Gan, Zhang, Zhuge, & Zhai, 2017). For optical fiber communications devices, the semiconductor active zone must be optimized for low absorption window (1.3?1.55 ?m). Multiple alloys and quantum size structures are combined and used for achieving this goal. Coupled double quantum wells (CDQWs) have attracted much attention due to interesting electronic properties and the formation of suitable energy levels, for example in near and mid infrared. In CDQWs, the electronic properties are then further modified by their coupling barrier width. When the barrier thickness changes a little bit, for example 1 monolayer, the lower energy level change too. The thickness of the coupling barrier could work as a tuning parameter for interband energy transitions. The research about CDQWs is going to reduce stress, strain or defects in semiconductor devices. CDQW structures based on III-V semiconductor alloys have been characterized by a number of techniques, for example electroreflectance, absorbance, transmittance,

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https://doi.org/10.24275/uam/izt/dcbi/revmexingquim/2019v18n3/Gonzalez
issn-e: 2395-8472

photoluminescence, magnetophotoluminescence, photoreflectance, etc. (González-Fernández *et al.*, 2016; Gozu & Mozume, 2015; Huang, Qiang, Pollak, Lee, & Elman, 1991; Lopes *et al.*, 2012; Neogi, Yoshida, Mozume, Georgiev, & Wada, 2001). Photoreflectance (PR) spectroscopy has become an important characterization tool to study semiconductor nanostructures and offers important advantages over other techniques, such as contactless, room temperature sensibility and detection not only the lowest but also higher energy transitions even at room temperature (Pollak & Shen, 1993).

In this work, a detection of interface optical anisotropies in InGaAs/AlAs/AlAsSb based CDQWs at room temperature by extending the standard PR modulation technique is reported. We use photoreflectance spectroscopy with polarization contrast, also termed photoreflectance difference or photoreflectance anisotropy (PRA), as a complementary tool for optical characterization. We show that PRA spectroscopy is suitable for testing the electronic structure details of high complex quantum systems, such as InGaAs/AlAs/AlAsSb based CDQWs at room temperature. Furthermore, the two samples have their quantum levels associated to 11H and 22H transitions and they are located in the near infrared. The notation mnH indicates transitions from the mth conduction to the nth valence subbands.

2 Experimental

The samples used in this work were fabricated by solid source molecular beam epitaxy (equipped with III-V group species) at 460° C. The elemental Ga, In, and Al were supplied by the standard Knudsen cell, A_{s2} and Sb were supplied using the valved cracker cells. Growth procedures for samples used in this work (two samples named M57 and M59) were identical. Each samples comprises on sixty periods of $In_{0.8}Ga_{0.2}As/AlAs/Al_{0.56}As_{0.44}Sb$ symmetric CDQWs grown on Fe-doped (001) InP substrates (Mozume & Gozu, 2010). For sample M57, each symmetric $In_{0.8}Ga_{0.2}As$ QWs have a thickness of 2.50 nm and an AlAs coupling barrier of 0.85 nm (3 monolayers). For the M59 case, the thickness of QWs is 2.65 nm and the coupling barrier is 0.57 nm (2 monolayers). For both samples, each one of the 60 CDQWs has a 3 nm of $Al_{0.56}As_{0.44}Sb$ separation barrier in order to avoid overlapping of the wave functions. Finally, as capping layer, 10 nm of $In_{0.35}Al_{0.65}As$ was deposited to avoid oxidation.

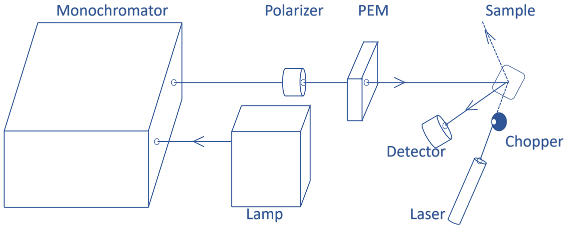

Fig. 1. Experimental setup of photoreflectance anisotropy spectroscopy using a photoelastic modulator.

The PR spectra were measured at room temperature using a standard setup such as (Fuertes-Marrón *et al.*, 2013), for instance. The probe beam was obtained from a 150 W tungsten-halogen lamp, which was used in conjunction with a 0.5 m monochromator. The signal was collected with a thermocooled InGaAs photodetector in the wavelength range from 1000 to 1500 nm. The signal was preamplified and detected by conventional lock-in technique. As a pump modulation beam, a chopped HeNe laser was used at a frequency of 150 Hz.

To achieve the photoreflectance anisotropy setup, the PR technique was extended by placing a Rochon prism and a photoelastic modulator (PEM) at the output of the monochromator as is showed in Figure 1. Two light polarized states were obtained at each wavelength to retrieve PRA measurements.

3 Background theory

The standard PR spectroscopy modulation technique relies on the measurement of reflectance changes as produced by a chopped pump beam. PRA spectroscopy is an extension of the PR technique and is obtained by making a contrast in polarization along [110] and [010] crystallographic directions for (001)-oriented semiconductor surfaces (Lastras-Martínez, Balderas-Navarro, Lastras-Martínez, & Vidal, 1999). To avoid mechanical backlash, at each wavelength, the PR spectrum with polarized light was recorded by turning the PEM off whereas for the unpolarized PR spectrum the PEM was turned on. The existing electrical field induces a piezoelectric strain which induces a linear electro-optic effect (LEO). Such strain field can be modulated by an external pump beam, usually a laser.

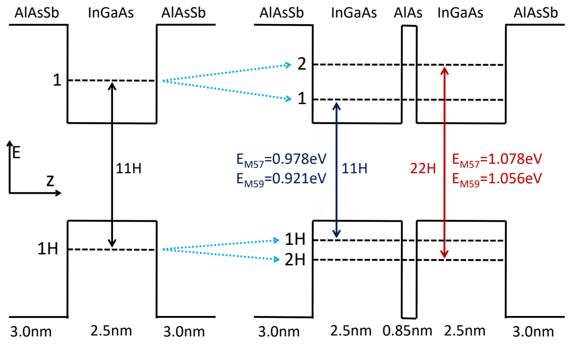

Fig. 2. Simplified schemes of quantum levels with heavy hole character at flat bands regime. Left: simple QW transitions. Right: CDQW interband transitions (11H and 22H) for M57 and M59 samples.

The polarized light PR spectrum along [110] of (001) zinc-blende semiconductors comprises linear and quadratic electro-optic components associated to anisotropies and isotropies respectively. While the linear line shape is polarization dependent, the quadratic spectrum is isotropic (Aspnes & Studna, 1973; Kyser & Rehn, 1970). Thus, the unpolarized light PR spectra should comprise only the quadratic component, since the linear component averages out to zero (Lastras-Martínez *et al.*, 1999). In this way, by subtracting the unpolarized PR from the polarized PR we obtain the LEO spectrum associated to PRA spectroscopy.

The CDQWs system tested have an extremely thin AlAs coupling barrier between InGaAs quantum wells. This is particularly useful for red-shifting the interband transition energy in order to achieve the communication wavelength of 1.55 μm. Varying such coupling barrier, typically around 1 nm, is enough to open the possibility to change the grown state inside of the new system and thereby the device performance. In addition, coupling barrier layer plays a very important role when the critical layer thickness of InGaAs QWs approach at maximum; if this occurs, the stress accumulation could induce device loss efficiency. The CDQWs used in this work both have a symmetric system with two interband transition energies with heavy hole character. Figure 2 indicates the allowed transitions from the valence subbands to the conduction subbands.

4 Results and discussion

The PR spectroscopy spectra of InGaAs based CDQWs obtained from 1000 to 1500 nm are shown in Figure 3 for two samples. Typical excitonic lineshape are observed in samples M57 and M59. The 22H transition does not exhibit a significant shift of the peak position, whereas a clear redshift appears in 11H transition of M59 with respect to M57. Additionally, anisotropies can be noted due to the light polarization states in [110] and [010] crystallographic direction. The first one obtained turning the PEM-off (blue) and the second one turning the PEM-on (red). A clear difference between two PR spectra can be observed close to both subband transitions, 11H and 22H, for each sample. By using the generalized excitonic lineshape of the PR spectrum model developed by Aspnes (1973),

$$\left[\frac{\Delta R}{R}\right]_{PR} = Re[Ae^{i\theta}(E - E_g + i\Gamma)^{-m}] \qquad (1)$$

where A is the relative amplitude, θ is the phase angle, E is the photon energy, E_g is the band-gap associated to each subband transition and Γ is the energy broadening, we obtain the energies of the subband transitions 11H and 22H associated to CDQWs levels: 1267.3 nm and 1149.7 nm for sample M57, and 1345.7 nm and 1173.7 nm for sample M59. The 11H and 22H transition energy parameters used for M57 are: A (1.23×10^{-9} and 1.18×10^{-9}), θ (0 and 5 rad), Γ (23 and 31 meV) and E_g (0.978 and 1.078 eV). The parameters used for M59 are: A (0.41×10^{-9} and 0.64×10^{-9}), θ (0 and 5 rad), Γ (20 and 31 meV) and E_g (0.921 and 1.056 eV). Fitting procedures were carried out in energy domain.

As discussed above, by performing the numerical subtraction PR[110] - PR[010], photoreflectance anisotropy spectroscopy lineshape was obtained for both samples. Even at room temperature, PRA spectra show a clear shaped curve that indicates an anisotropic basis. The origin of these anisotropies could be a residual strain caused by the 60 CDQWs repetitions or a very low non-intentional impurities caused by Sb interdiffusion in each CDQW in the growth process. Whatever the origin of the anisotropies, PRA spectra could test strain presence or quality growth sensed via the subbands transitions. PRA experimental data and theoretical (González-Fernández *et al.*, 2016) lineshape are depicted in Figure 4 for samples M57 and M59.

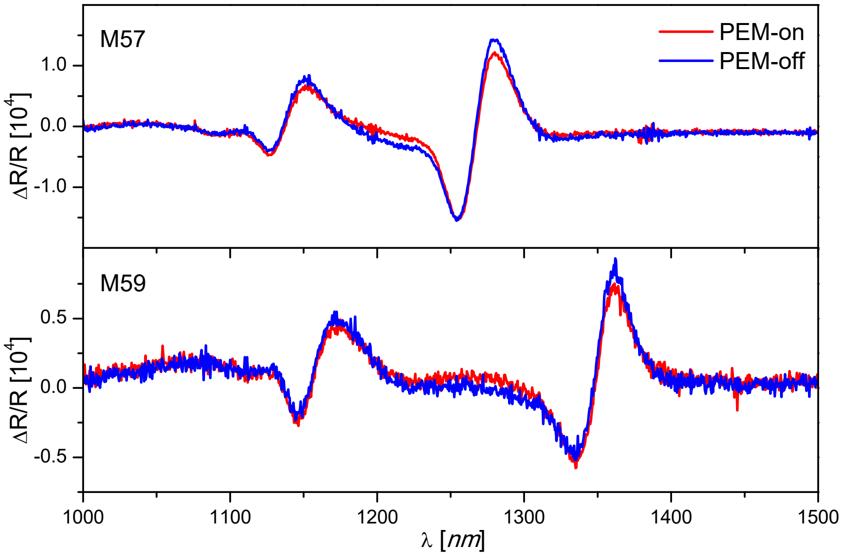

Fig. 3. Photoreflectance of M57 and M59 samples at room temperature. In red line: unpolarized-PR measurements by turning-on the PEM. In blue line: polarized-PR measurements by turning-off the PEM.

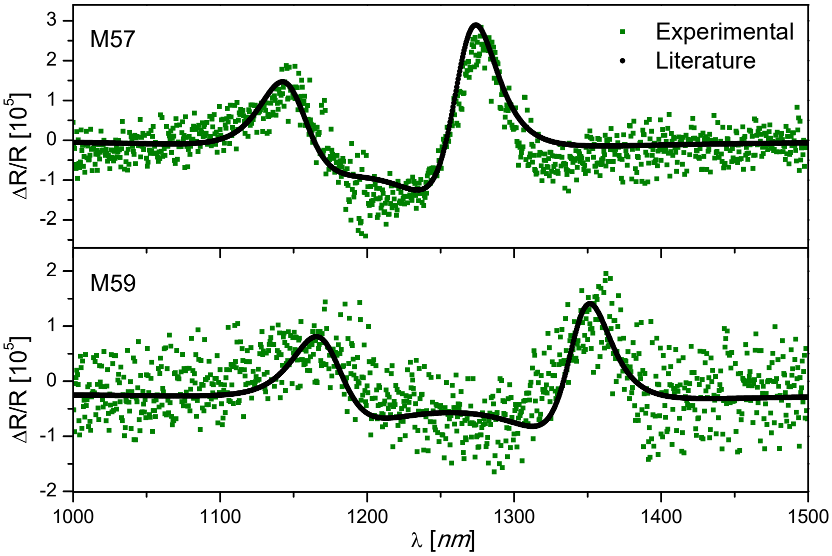

Fig. 4. Photoreflectance anisotropy of M57 and M59 samples at room temperature. In green dots: the experimental measurement of the samples is observed. In black dots: a theoretical adjustment is observed.

PRA signal amplitude must be interpreted as the correlation proposed above that describes these anisotropic phenomena which could derive in a residual electric field for superlattice structures.

Despite optical and electrooptical characterization usually are carried on at low temperatures to sense phenomena, PRA technique is capable to detect allowed subband transitions, in this case 11H and 22H, through anisotropies in whole structure. For samples M57 and M58, the anisotropies origin could be cumulative strain increasing in the growth direction or partially interdiffusion inside each CDQW, namely, non-cumulative phenomena origin (Mauger *et al.*, 2016). Both hypotheses could be probed by growing CDQWs system with different composition or elements preventing the interdiffusion that modifies the electric potential profile or by adding an extra film to avoid Sb interdiffusion, in this case the CDQW analysis most be adjusted.

Conclusions

We have used PRA to measure electro-optical anisotropies, through the measurement of the piezoelectric shear strain induced by the interface electric fields of buried InGaAs/AlAs/AlAsSb based CDQWs with extremely thin coupling barriers. Optical probes, such as the one employed in the manuscript, offer the possibility to be applied in-situ to investigate the electric fields existing into CDQWs based structures. PRA spectroscopy is very competitive in order to shed light onto internal breaking symmetry phenomena in complex semiconductor heterostructures. PRA also offers to detect energy transitions of quantum systems who have films with a thickness difference lower than 1 nm, such as CDQWs structures without decreasing temperature. This advantage place PRA as a simple and complementary tool for analyzing anisotropic quantum structures with polarizable defects such as quantum dots, wells or wires; or even more complicated systems such as quantum cascade lasers or high electron mobility transistors at room temperature.

Acknowledgements

The authors are grateful to T. Mozume and S. Gozu from the AIST (Tsukuba, Japan) for providing the samples used in this work. Also, the authors are grateful to R. Balderas, A. Lastras and L. F. Lastras for many helpful discussions. This work was partially supported by CONACYT, SECITI-DF and Tecnológico Nacional de México.

Nomenclature

QWs	Quantum wells
CDQWs	Coupled double quantum wells
PR	Photoreflectance
PRA	Photoreflectance anisotropy
mnH	Indicates transitions from the mth conduction to the nth valence subbands
PEM	Photoelastic modulator
LEO	Linear electro-optic effect

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