Revista Brasileira de Aplicações de Vácuo, v. 25, n. 1, 20-23, 2006.

TEMPERATURE-DEPENDENCE OF PHOTOLUMINESCENCE PROPERTIES OF GaAs/AlAs SUPERLATTICES GROWN ON DIFFERENT GaAs ORIENTATIONS

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Received: July 27, 2005; Revised: March 31, 2006

Keywords: short period superlattice; $(GaAs)_5/(AlAs)_5$; photoluminescence; *pseudodirect* transition; non-(001) GaAs substrates.

ABSTRACT

Optical characterization of $(GaAs)_5/(AlAs)_5$ superlattices grown on (111)A, (311)A and (001) oriented semi-insulating substrate of GaAs is reported in this work. The samples were grown by the MBE technique. An investigation of the photoluminescence spectra as a function of the temperature reveals an increase of thermal activation energy in sample grown on (311)A plane when compared with the others, evidencing an additional lateral confinement. The results suggest that the superlattice grown on (111)A has a better interface. The energy peak dependence on temperature shows a bimodal behavior, having a certain behavior up to a critical temperature and, starting from this temperature, seems to follow the dependence of the AlAs energy gap. Pseudodirect transitions were observed for all directions.

1. INTRODUCTION

The development of molecular-beam epitaxy (MBE) has permitted the growth of short period superlattices (SLs) of high quality. There has been great interest in these SLs because they often possess tunable electronic properties and, hence, are suited to a variety of applications [1]. The $(GaAs)_m/(AlAs)_n$ (001) superlattices, in particular, have received enormous attention as they show a variety of electronic structures depending on the choice of the layer thicknesses [2]. In SLs, where the coupling through penetrable barriers plays an important role, a miniband is formed because of delocalization of the wave function. Electrons in the states at the Γ point of the Brillouin zone of $(GaAs)_n/(AlAs)_m$ SLs tend to be confined in either GaAs (Γ-like state) or AlAs (X_z-like state) layers. The Γ-like conduction state associated with the Γ conduction-band edge of GaAs, while the X_z-like state is associated with the X conduction-band edge of AlAs because the X conduction valleys of AlAs is lower than those of GaAs due to to valence-band offset. Only the X_z minima are mapped onto the Γ point of the Brillouin zone of the SLs due to the zone-folding effect, while the X_{xy} minima are at the M point of the Brillouin zone of the SL (X_{xy}-like state). Since holes at the Γ maximum of the Brillouin zone of the SLs tend to be confined in GaAs layers, the transition associated with the Γ-like conduction state has a large transition probability, while that associated with the X_z-like state has a small transition probability. Therefore, the Γ-like, X_{xy}-like, and X_z-like states give the direct, indirect, and *pseudodirect* (weakly allowed direct) transitions, respectively [3].

Growth directions also play an important role in the optical properties of semiconductor structures. The (n11)A surfaces have a mixed nature which is determined by the existence of both single and double dangling bond sites [4]. This (n11)A family contents a high concentration of non-reactive, empty single dangling bond reducing the overall background of impurities and a highly stepped surface. The latter enhances a step flow growth mode which is important for producing sharp surface and interfaces.

Exciton binding energies in semiconductor nanostructures are much stronger as compared to bulk material, due to the confinement. However, the interfaces between well and barrier material are never ideally on atomic scale. Even in advanced MBE growth, fluctuations of a few monolayers occur.

In this paper, we have studied the optical properties of photoluminescence signal of $(GaAs)_5/(AlAs)_5$ SLs grown on (111)A, (311)A and (001) GaAs substrates. We have investigated the behavior of PL signal as function of the sample temperature. We have measured an enhanced exciton binding energy and demonstrated efficient exciton localization and lateral confinement in the SL grown on (311)A plane. The (111)A surface has shown a better interface quality.

2. EXPERIMENTAL PROCEDURE

The samples were grown by the MBE technique, using a MECA 2000 system, on GaAs (001), (111)A and (311)A semi-insulating substrates (GaAs growth rate of 1 μm/h).

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Growth process was monitored in situ by a reflection high-energy electron diffraction (RHEED) system operated at 15 kV. The samples were simultaneously grown at 620 ^oC without interruptions at the interfaces. The residual pressure of As_4 in the growth chamber was 9,0 x 10^{-6} Pa. To avoid the formation of defects in the main SL, i. e., to trap impurities and to prevent non-equilibrium carrier spreading into the semi-insulating substrate, a layered buffer with the following parameters was grown between the substrates and the main SL: a GaAs/AlAs SL (10 periods with 20 Å thickness of both layers) and a 0.5 μm GaAs layer on the top. The main SL consists of 40 periods of five monolayers of GaAs and AlAs. In GaAs and AlAs a monolayer (ML) corresponds to a thickness of about 0.283 nm in [001] direction. The growth rates were 0.5 ML/s for both GaAs and AlAs. To complete the structure, a 15 nm GaAs thick cap layer was deposited. The photoluminescence (PL) measurements were carried out in a cryostat, at a pressure of 6,7 x 10^{-2} Pa allowing a temperature variation between 10 K and room temperature. The samples were excited by about 80 W of the 514.5 nm line of an Ar^+ ion laser. The PL spectral analysis was carried out by a 0.5m monochromator and the detection was made by a photomultiplier, using standard lock-in techniques. The PL lines were fitted to Gaussian curves to obtain their respective position, intensity, and full width at half maximum (FWHM).

3. RESULTS AND DISCUSSION

The normalized PL spectra of the studied SLs, taken at 10 K, are shown for all directions in Fig 1. The PL peaks are assigned to as a *pseudodirect* transition. One can observe an orientation effect on the peak position of the GaAs/AlAs superlattice. A nonmonotonic redshift of the PL peak have a maximum for the (311)-oriented sample. Different phenomena, as a buildup piezoelectric field and effective mass anisotropy could be responsible for this shift, when orientation changed from (001) to a (111) plane. Since piezoelectric effects and effective mass anisotropies monotonically increase from a (001) plane to a (111) plane, we suppose that another effect, like surfaces properties, can be responsible for this phenomenon. The atomic steps and kink position for adatom incorporation increase for high index planes having the maximum value for the (311) planes. We believe that this peak position dependence is mainly related to interface roughness due to surface step density [5].

In order to obtain additional information about SL properties, measurements of PL temperature dependence were carried out. In Fig. 2 the PL peak position of the three surfaces are plotted as a function of temperature for the GaAs/AlAs superlattice. The temperature dependence of the exciton transition seems to be bimodal for our sample. In the low temperature range they are well fitted (solid lines) to the following Bose-Einstein expression

$$E_g(T) = a - b\left(1 + \frac{2}{\exp(\Theta_B/T) - 1}\right), \qquad (1)$$

proposed by Viña *et al.* [6] In Eq. (1) *(a – b)* is the band gap energy at 0 K, and *b* represents the strength of the exciton-average phonon interaction. Θ_B indicates the average frequency of acoustic and optical phonons. Above a critical temperature (T_C), the temperature-induced change in the band-gap energy seems to follow the AlAs band gap variations (shaded lines). The T_C values are about 95 K, 135 K e 140 K for (111)A, (001) and (311)A planes, respectively. The parameters obtained from the fits to Eq. (1) are listed in Table I. The Θ_B values for the (001) and (311)A surfaces is almost the same, and for (111)A are smaller as compared with the others.

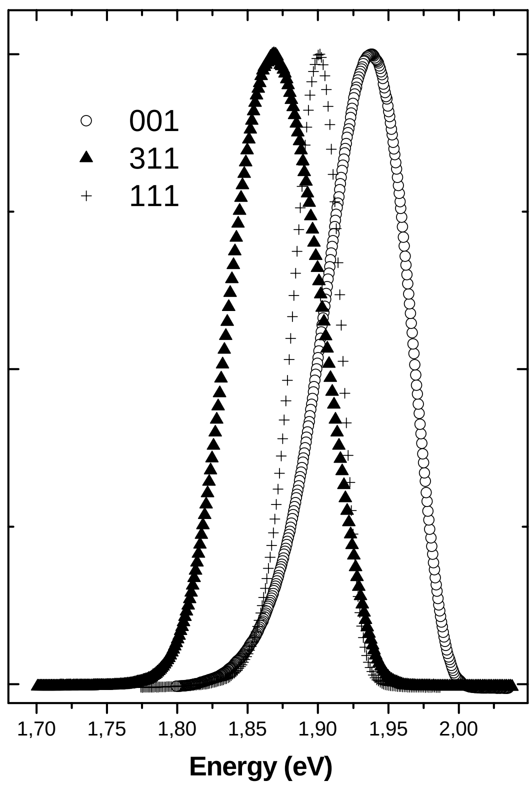

Figure 1 - Normalized PL spectra for (001), (311)A and (111)A GaAs/AlAs superlattice at 10 K.

Fig. 3 shows the broadening, i.e., the FWHM of the PL lines as a function of temperature for all directions. The PL FWHM also depends on the crystallographic orientation as noted above for the PL peak position. The SL grown on (111)A plane exhibits a smaller FWHM as compared with the other surfaces, suggesting a superior interfaces and energy levels narrower. The behavior of PL FWHM as a function of temperature is the usual for the (111)A surface. Conversely, an unusual decrease was detected for Gaussian-shaped emissions from 10 K to about 70 K und 130 K for planes (001) and (311)A, respectively.

The PL lineshape reflects the distribution of local minimum states. As the temperature increases, localized excitons in the SL at shallow potential minima can be easily thermally activated, getting them out of energy barriers produced by interface mono-steps, and then they recombine nonradiatively, transfer and relax into low-lying energy states. Components in the Gaussian-shaped PL spectrum decrease much faster than the low-energy components, resulting in the redshift of the PL peak energy and a reduction of the FWHM [4]. In the (311)A plane there is also a contribution to this anomalous behavior because of an additional lateral confinement due to the corrugation of this surface. This confinement produces a more accentuate decrease for the (311)A surfaces. The atypical FWHM decrease was first reported for InAs self-assembled quantum dots [7]. The temperature dependence of linewidth of exciton transitions of semiconductors can be expressed as:

$$\Gamma(T) = \Gamma(0) + \frac{\Gamma_{ep}}{\exp(\Theta_{LO}/T) - 1} \tag{2}$$

Where Γ (0) represents the broadening due to temperature-independent mechanisms, such surface scattering, impurity and dislocation, and Γ_{ep}, the strength of the exciton-LO phonon coupling. Θ_{LO} is the average frequency of the longitudinal optical phonons. The full curves are fits to Eq. (2). The parameters deduced from these fits are listed in Table II. As expected, the Θ_{LO} value is greater than Θ_B one for each direction, as a consequence of their definitions.

Table I - Values for the parameters *a*, *b* and Θ_B obtained by fitting the exciton transition energy versus temperature to Eq. (1).

Orientation	a (eV)	b (eV)	Θ_B (K)
(001)	2.042 ± 0.014	0.108 ± 0.014	160 ± 11
(311)A	1.932 ± 0.007	0.065 ± 0.007	158 ± 10
(111)A	1.917 ± 0.003	0.018 ± 0.003	67 ± 9

Table II - Values of the parameters Γ (0), Γ_{ep} e Θ_{LO} obtained by fitting the PL linewidth (full-width at half maximum) versus temperature to Eq. (2).

Orientation	Γ (0) (meV)	Γ_{ep} (meV)	Θ_{LO} (K)
(001)	62 ± 1	1605 ± 972	565 ± 83
(311)A	56 ± 1	2528 ± 1794	982 ± 159
(111)A	40 ± 1	2374 ± 324	665 ± 26

The energy-integrated PL intensity of SL for all directions is exhibited in Fig. 4. There are clearly two different regions of dependence on temperature. The energy-integrated intensity remains nearly constant between 10 and ~35 K for (001) and (111)A surfaces and decays by approximately three orders of magnitude above 40 K, as illustrated by Fig. 4. For the (311)A plane, the integrated intensity is almost constant up to 50 K and reduces its value by four orders of magnitude above 60 K. The decrease of the integrated PL emission at higher temperature is related to exciton dissociation, and consequent electron-hole pairs escape from SLs. The thermal PL quenching in our samples can be approximately fitted by to the following formula [8], presuming the presence of two thermally activated nonradiative recombination channels with activation energies E_A and E_B, respectively:

$$I(T) = \frac{I_0}{1 + A\exp\left(-\frac{E_A}{k_B T}\right) + B\exp\left(-\frac{E_B}{k_B T}\right)} \tag{3}$$

The A and B coefficients measure the strengths of both quenching mechanism, i. e., the relative number of nonradiative recombination centers within the respective temperature-dependent carrier diffusion lengths. Equation (3) fits the experimental data points in the whole temperature range as illustrated by solid lines in Fig. 4. The parameters obtained from fits to Eq. (3) are listed in Table III. Using these results, we estimated the values for thermal quenching energy E_A, which is reminiscent of an exciton binding energy. The (311)A plane shows an increase by a factor of almost three, evidencing an additional lateral confinement. The thermoativation energy E_B for electron-hole pair emissions was also estimated by the Arrhenius plot. E_B value calculated for (311)A surface is about two times greater than for the others, suggesting a suppression of electron-hole emission due to a binding energy increase.

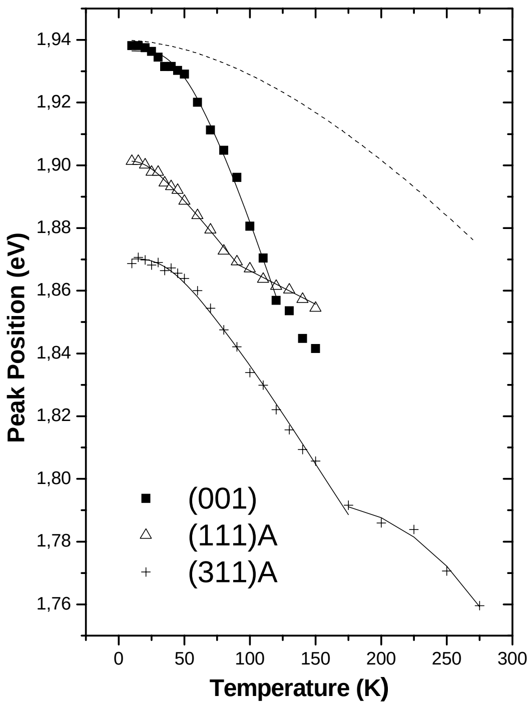

Figure 2 - PL peak energy as function of the temperature for all orientations. The solid curves are fits to Viña's expression (Eq. (1)), where the dashed curve is the temperature-dependence band-gap energy of AlAs. This (dashed) curve has been vertically shifted for clarity.

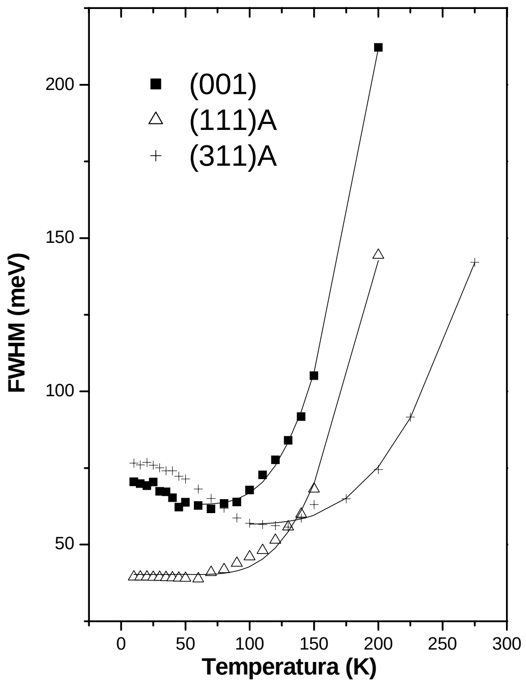

Figure 3 - FWHM versus temperature for all planes. The solid lines are fits to Eq. (2).

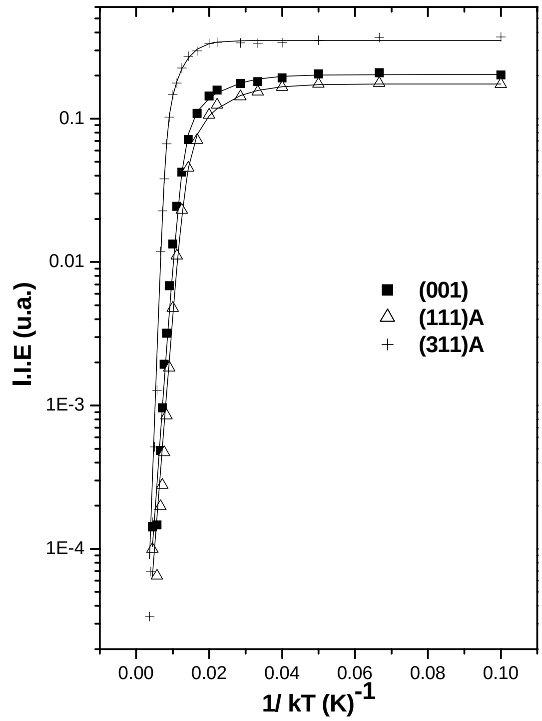

Figure 4 - Arrhenius Plot of the energy-integrated PL intensity. The solid lines are fits to Eq. (3).

Table III - Values of the parameters I_0, A, E_A, B e E_B obtained by fitting the energy-integrated PL intensity data versus temperature to Eq. (3).

Orientation	(001)	(311)A	(111)A
I_0	0.205±0.003	0.350±0.003	0.175±0.002
A	5.11±1.60	35.2±11.7	8.6±2.3
E_A (meV)	10±1	28±2	11±1
B (x 10^6)	0.081±0.014	2.56±0.68	0.083±0.014
E_B (meV)	71±4	146±6	66±4

4. CONCLUSIONS

We have investigated the optical properties of $(GaAs)_5/(AlAs)_5$ superlattices grown by MBE on (111)A, (311)A and (001) GaAs surfaces. This investigation was carried out by PL as a function of temperature. The results point to a dependence of SL's peak position, FWHM and intensity of PL signal on substrate orientation. Our results also illustrate an unusual decrease of PL FWHM with temperature for the (311)A surface, suggesting a localization of excitons because of interface roughness. The thermoativation energy shows a value two times larger for the [311}A orientation in relation to the others, indicating an additional lateral confinement as a consequence of the natural interface corrugation.

ACKNOWLEDGEMENTS

The authors would like to thank CNPq- and FAADCT-Brazil for financial support.

REFERENCES

1. For a review see, for instance KELLY, M.J.; NICHOLAS, R.J., *Rep. Prog. Phys.* 48 (1985) 1699.
2. MU, X.; DING, Y.J.; WANG, Z.; SALAMO, G.J., *IEEE Journal of Quantum Electronics **41(2005)** 3.*
3. GLUKHOV, K.E.; BERCHA, A.I.; KORBUTYAK, D.V.; LITOVCHENKO, V.G., *Low-Dim. Sys.* 38 (2004) 4.
4. MAREGA JR., E.; OLIVEIRA, R.M.; SOUZA, C.A.; ARAKAKI, H.; GONZÁLEZ-BORRERO, P.P., *Microel. Journal* 35 **(**2004) 41.
5. GONZÁLEZ-BORRERO, P.P.; LUBYSSHEV, D.I.; MAREGA JR., E.; PETITPREZ, E.; BASMAJI, P., *J. Cristal Growth* 169 (1996) 424.
6. VIÑA, L.; LOGOTHETDIS, S.; CARDONA, M.; *Phys. Rev. B* 30 (1984) 1979.
7. LUBYSHEV, D.I.; GONZÁLEZ-BORRERO, P.P.; MAREGA JR., E.; PETITPREZ, E.; LA SCALA JR., N.; BASMAJI, P., *Appl. Phys. Lett.* 68 (1996) 205.
8. GOLDYS, E.; GODLEWSKI, M.M.; LANGER, R.; BARSKI, A.; BERGMAN, P.; MONEMAR, B., *Phys. Rev. B* 60 (1999) 5464.