AIP | Journal of Applied Physics

Influence of energy structure on recombination lifetime in GaAs/AlGaAs multilayers

B. G. M. Tavares, M. A. Tito, and Yu. A. Pusep

Citation: Journal of Applied Physics **119**, 234305 (2016); doi: 10.1063/1.4954161
View online: http://dx.doi.org/10.1063/1.4954161
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/119/23?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **119**, 234305 (2016)

Influence of energy structure on recombination lifetime in GaAs/AlGaAs multilayers

B. G. M. Tavares, M. A. Tito, and Yu. A. Pusep
São Carlos Institute of Physics, University of São Paulo, P.O. Box 369, 13560-970 São Carlos, SP, Brazil

(Received 5 April 2016; accepted 6 June 2016; published online 16 June 2016)

The processes of recombination of the photoexcited electron-hole pairs were studied in GaAs/AlGaAs weakly coupled multiple quantum wells, where the photoluminescence emission was composed of the contributions from the $\Gamma-\Gamma$ and $\Gamma-X$ conduction band minibands. Remarkable enhancement of the recombination time was observed when the magnetic field caused depopulation of the higher energy $\Gamma-X$ miniband. The observed effect is attributed to the magnetic field induced variation of the electron density of states. *Published by AIP Publishing.*
[http://dx.doi.org/10.1063/1.4954161]

I. INTRODUCTION

Recombination processes of photogenerated carriers fundamentally determine the performance of optoelectronic devices. The internal quantum efficiency of these devices, defined as the fraction of photogenerated electron-hole pairs that recombine and emit photons, depends on the quantity of electrons and holes which participate in the recombination processes. The number of recombining electron-hole pairs is defined by the exciton occupation probability, which in turn is determined by the joint density of states. In quantum wells, the relevant density of states consisting of the conduction and valence band states can be changed by appropriate choice of the quantum well structure. This allows for a desired modification of the temporal response of optoelectronic devices based on quantum wells. The effect of the band states occupancy on recombination time was analyzed in semiconductor lasers in Ref. 1. The influence of the carrier-density dependence of radiative and non-radiative recombinations was studied in nitride and GaAs based optoelectronic devices in Refs. 2 and 3. Moreover, the dynamic response of quantum wells and devices based on them was explored in Refs. 4–6. However, to the best of our knowledge, the effect of the density of states on recombination time was not yet demonstrated.

In the present work, we investigate the influence of the miniband energy structure of the populated electron states on the recombination time in GaAs/AlGaAs weakly coupled multiple quantum wells (MQW). The best method to study the effect of the energy structure is to measure the recombination time in the same sample subject to external influence which affects the energy structure. In such a case, the effect of the energy structure can be separated from influence of defects (different in different samples) on the recombination time. Application of an external electric field which changes concentration of carriers in a quantum well, and as a result, changes the energy structure of the populated electron states, presents such an external influence. However, the external electric field also causes modification of the quantum well potential profile, which in turn can alter the recombination time. Therefore, in order to control the occupancy of the electron minibands formed in the conduction band, we used the external magnetic field. Then, the evidence of a significant increase of both the radiative and the non-radiative recombination times, which accompanies a depopulation of the high energy miniband caused by the increasing cyclotron energy, was obtained using time-resolved photoluminescence (PL) measurements.

It should be mentioned that the influence of the magnetic field on optical recombination of high mobility GaAs/AlGaAs quantum wells was studied in the quantum Hall regime in Refs. 7 and 8. The increasing radiative recombination time observed at the filling factor $\nu=1$ was explained as a consequence of the screening and localization effects. This data are discussed in connection with our results.

II. EXPERIMENTAL DETAILS

$(GaAs)_n(Al_{0.18}Ga_{0.82}As)_m$ MQW consisting of $n=65$ML thick GaAs layers and $m=15$ML thick $Al_{0.18}Ga_{0.82}As$ layers, where the thicknesses are expressed in monolayers (ML), was grown on (100)-oriented semi-insulating GaAs substrate by molecular beam epitaxy. The barriers were selectively n-doped with *Si* ($N_{Si}=2\times10^{18}$ cm^{-3}), leaving 3ML thick undoped spacers on both sides. The total number of $N=30$ periods, each with thickness $D_{SL}=80$ML, was grown. The electron concentration and mobility obtained by standard Hall measurements at the temperature 1.6 K were $n=2\times10^{17}$cm^{-3} and $\mu=23{,}000$ cm^2/V s, respectively. The Fermi energy $E_F=15$ meV was determined by Shubnikov-de-Haas oscillations. The energy structure of the sample was calculated by the envelope function approximation taking into account the multi-valley band structure and nonparabolicity effects as in Ref. 9. According to the theory, the two lowest narrow minibands with the widths about 1 meV are formed by the $\Gamma-\Gamma$ and $\Gamma-X_z$ electron transfers. In the last case, to form the miniband, the electrons tunnel between the Γ minimum in the GaAs quantum well and the X_z valleys oriented along the growth direction z in the AlGaAs barrier, which are mapped onto the Γ point of the Brillouin zone of the multiple layers due to the zone-folding effect and give

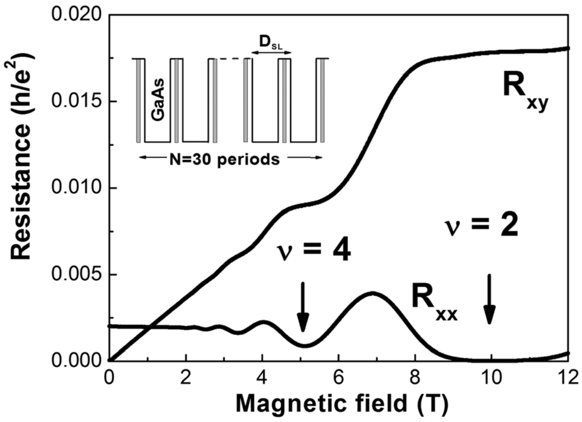

FIG. 1. Diagonal R_{xx} and Hall R_{xy} resistances measured in $(GaAs)_n$ $(Al_{0.18}Ga_{0.82}As)_m$ multiple quantum well at $T = 1.6$ K. Inset schematically demonstrates the layered structure of the sample. The shaded areas indicate the doped regions.

rise to the pseudodirect interband transitions. The results of the band structure calculations are shown in inset to Fig. 1.

PL and time-resolved PL measurements were performed at the temperature 1.6 K in the range of the magnetic field 0–10 T oriented perpendicular to the layers, using a liquid helium cryostat and a superconductive magnet (both by Oxford Instruments Inc.). The sample was pumped by a diode laser (Pico Quant LDH-P-C-470) emitting at 470 nm in a continuous mode for PL measurements. The same laser generated 90 ps pulses at the frequency 80 MHz for time-resolved PL measurements. The signal was dispersed by a SPEX 500M spectrometer and detected by a Pico Quant PMA Hybrid 50 photomultiplier tube. In the continuous mode, the signal was measured by a Ocean Optics Inc. HR4000 high-resolution spectrometer.

III. RESULTS AND DISCUSSION

A strong external magnetic field applied perpendicular to the plane occupied by the two-dimensional electron gas quantizes the electron kinetic energy into Landau levels. In such case, the single-particle electron states form a system of discrete Landau levels. Thus, the electron energy changes from continuous to discrete structure. The energy quantization manifests itself in the magneto-resistance oscillations an in the quantum Hall effect. The magneto-resistance data obtained in the studied MQW are depicted in Fig. 1. At the magnetic field 10 T, the diagonal R_{xx} and Hall R_{xy} resistances develop a clear zero-resistance state and a plateau, respectively. The magnetic fields corresponding to the magnetoresistance minima were used to determine the filling factors related to the quantized electron states. Accordingly, two neighboring magnetoresistance minima observed at the magnetic fields 5 T and 10 T correspond to the quantized Hall states with the filling factors $\nu = 4$ and $\nu = 2$, respectively. The plateau resistance of N quantum wells connected in parallel can be calculated as $R_{xy} = h/\nu N e^2$.[10] The plateau resistance 0.0179 h/e^2 related to the filling factor $\nu = 2$ implies that 28 periods of the MQW contribute to the measured resistance, while two of them placed near the surface of the sample are depleted. With a reasonable accuracy, the zero diagonal resistance was found at the magnetic field corresponding to the $\nu = 2$ quantized Hall state. Therefore, we conclude that the leakage currents are insignificant in the determination of the number of contributing quantum wells.

The PL spectra measured in different magnetic fields are shown in Figs. 2(a)–2(c). The best fits of the experimental spectra, achieved with a set of Gaussian lines, reveal contributions of four lines. The PL line observed at the zero magnetic field about the energy 1.495 eV is attributed to the recombination of the conduction band electrons with the holes residing at neutral acceptors, while the broad PL line around 1.52 eV is likely due to the recombination which involves neutral donor and valence band holes or exciton bound to neutral donor (DX).[11]

Two narrow PL lines at 1.527 eV and 1.532 eV are associated with the recombination of the electrons populating the $\Gamma - \Gamma$ and $\Gamma - X_z$ minibands with the photoexcited holes. The energy separation between these PL lines (5 meV) is in a good agreement with the calculated separation between the $\Gamma - \Gamma$ and $\Gamma - X_z$ minibands about 5 meV. The emission of the high energy $\Gamma - X_z$ miniband vanishes in high magnetic field due to depopulation of the corresponding miniband.

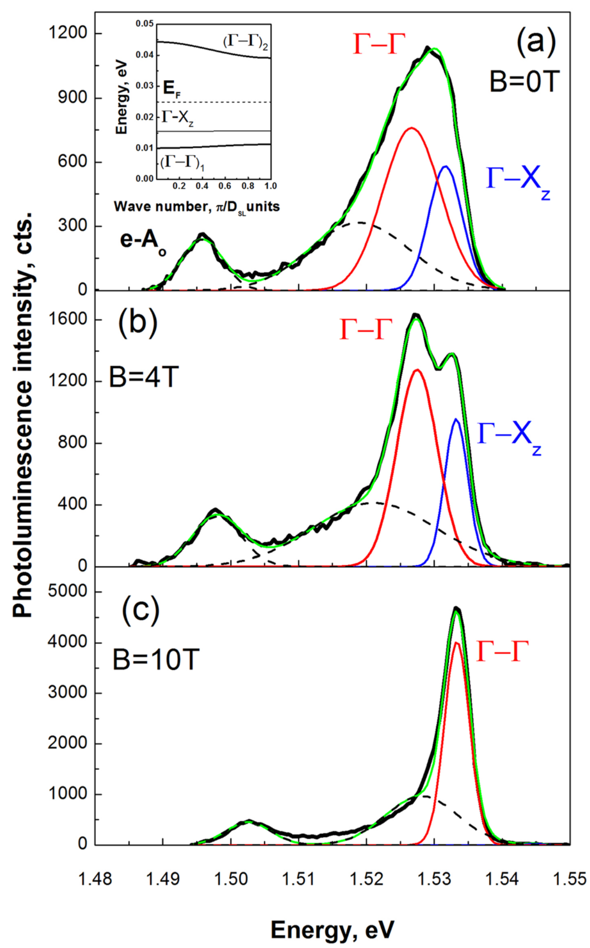

FIG. 2. Photoluminescence spectra measured in $(GaAs)_n$ $(Al_{0.18}Ga_{0.82}As)_m$ multiple quantum well in different magnetic fields at $T = 1.6$ K. Thick black lines are the experimental spectra. Dashed lines are contributions from neutral impurities, while red and blue thin lines are due to the $\Gamma - \Gamma$ and $\Gamma - X_z$ minibands. Green line shows the best fit to the experimental spectra. Inset shows the calculated miniband energy structure of the sample.

The energy peak positions, the integrated PL intensities, and the broadenings (full width at half maximum, FWHM) of the PL lines caused by the $\Gamma-\Gamma$ and $\Gamma-X_z$ minibands, determined by the fits of the experimental PL spectra, are presented in Figs. 4(a)–4(c), respectively. As it follows from Fig. 4(a), depopulation of the $\Gamma-X_z$ miniband takes place at the magnetic field 6 T when the energy gap between the $\Gamma-\Gamma$ and $\Gamma-X_z$ minibands reaches the value 8 meV, in a reasonable agreement with the Fermi energy obtained by the magneto-resistance measurements. The observed depopulation of the $\Gamma-X_z$ miniband takes place in the magnetic field corresponding to the transition between the quantum Hall states with the filling factors $\nu=4$ and $\nu=2$. The integrated PL intensities related to the recombination emissions from the $\Gamma-\Gamma$ and $\Gamma-X_z$ minibands shown in Fig. 4(b) demonstrate that the depopulation of the high energy $\Gamma-X_z$ miniband is accompanied by the corresponding increase in the occupancy of the low energy $\Gamma-\Gamma$ miniband. As expected, the increasing magnetic field causes a narrowing of the PL lines due to quantization of the electron energy into Landau levels; this effect is evident in Fig. 4(c). These results demonstrate magnetic field induced modification of the energy structure of the conduction band states participating in recombination processes. Two conduction band minibands contribute to the recombination in low magnetic field, while in the magnetic field higher than 6 T, the electrons residing in one miniband recombine with the holes.

The observed change in the miniband energy structure should result in the corresponding variation of the recombination time τ determined according to the Fermi golden rule

$$\frac{1}{\tau}=\frac{2\pi}{\hbar}|M_{cv}|^2\rho_{cv}, \tag{1}$$

where the square of the matrix element M_{cv} for the transition between the valence and the conduction band is defined by the spatial overlap of electrons and holes and the exciton occupation probability is determined by the joint density of states ρ_{cv}. In agreement with Eq. (1), one expects that the decreasing density of states leads to the increasing recombination time.

The PL transients were measured at the maximum PL intensity in different magnetic fields in the ranges where both $\Gamma-\Gamma$ and $\Gamma-X_z$ minibands and only one low energy $\Gamma-\Gamma$ miniband are populated. The PL intensity measured as a function of the time delay in the magnetic fields 5.5 T and 6.5 T around the critical magnetic field 6 T, when the high energy $\Gamma-X_z$ miniband becomes depopulated, is shown in Fig. 3.

In agreement with Eq. (1), the faster response was found in the low magnetic field where two electron minibands are populated, as compared to the higher magnetic field where only one miniband contributes to the recombination. The best fits of the PL transients were achieved with two recombination times, the short time τ_1 and a long one τ_2. Two characteristic lifetimes point to two independently recombining groups of photoexcited carriers. The short and long recombination times are assigned to non-radiative (Auger) recombination and radiative recombination, respectively.

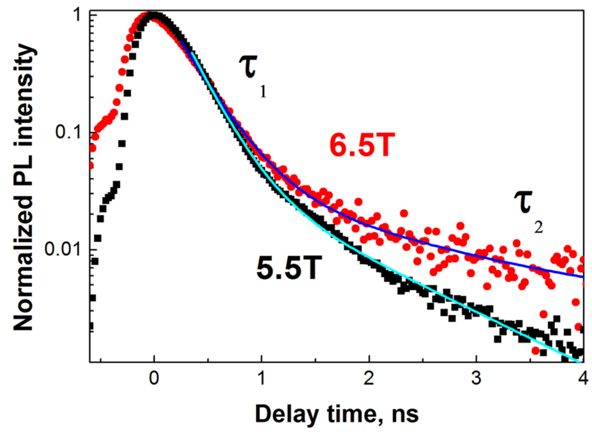

FIG. 3. Photoluminescence transients measured in $(GaAs)_n(Al_{0.18}Ga_{0.82}As)_m$ multiple quantum well at $T=1.6$ K. Black squares and red circles are the experimental data obtained in the magnetic fields 5.5 T and 6.5 T, respectively, while lines are the best fits obtained with two recombination times, the short time τ_1 and a long one τ_2.

The obtained characteristic recombination times are presented in Fig. 4(d) as a function of the magnetic field. Both times significantly increase at the critical magnetic field 6 T, when the contribution of the high energy $\Gamma-X_z$ miniband to

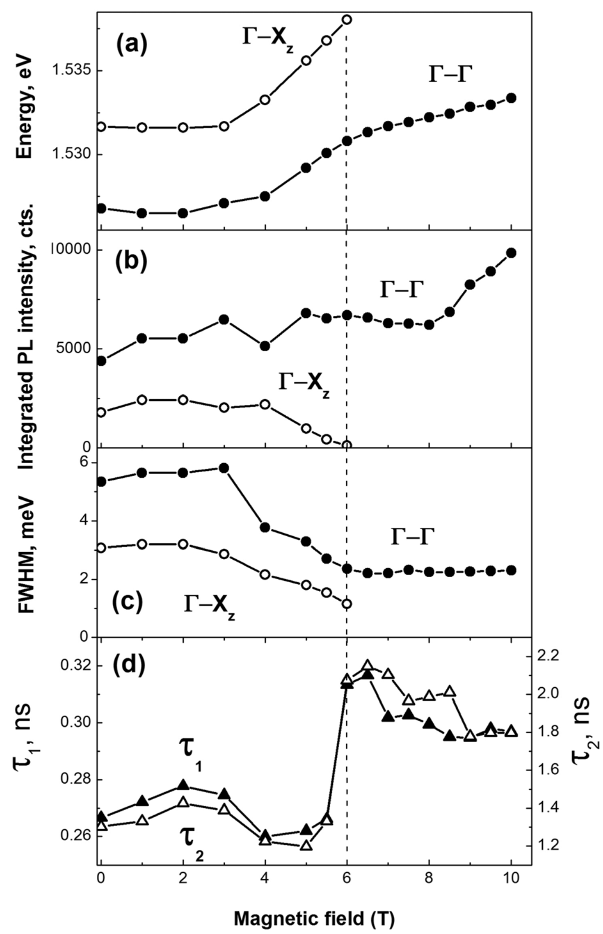

FIG. 4. The energy peak position (a), the integrated PL intensities (b), the broadenings (c), and the short τ_1 (full triangles) and long τ_2 (open triangles) recombination times (d) associated with the emissions due to the $\Gamma-\Gamma$ and $\Gamma-X_z$ minibands shown in Fig. 1, obtained as results of the best fits of the corresponding PL spectra and PL transients measured in different magnetic fields.

the PL emission vanishes. The fact that both the characteristic times reveal a similar behavior indicates that the energy structure is responsible for the observed effect. Indeed, as predicted by Eq. (1), the recombination times rise at the magnetic field when the density of the populated electron states decreases.

Similar behavior of the radiative recombination time was found in high mobility GaAs/AlGaAs quantum wells in the vicinity of the filling factor $\nu = 1$ in Refs. 7 and 8 and it was explained as a result of the screening and localization effects, which reduce the spatial overlap of electrons and holes and as a consequence, the matrix element M_{cv} for the transition between the valence and conduction band in Eq. (1). As a result, the recombination time increases. In high mobility quantum wells, the effect of the electron-hole overlap dominates the effect of the density of states. However, we presented the results obtained in the GaAs/AlGaAs MQW where the electron mobility was found about two orders of magnitude smaller than that in the high mobility quantum wells used in Refs. 7 and 8. At the critical magnetic field corresponding to the observed rise of the recombination time, the quantum Hall state with the filling factor $\nu = 4$ is not definitively formed. Therefore, in this range of the magnetic field, essential effects of the screening and localization are not expected. On the contrary, in such a case, changes in the density of states may be dominant. In addition, considerably stronger screening and localization effects are anticipated around the magnetic field 10 T at the filling factor $\nu = 2$ where in fact, no noteworthy changes in the recombination time were observed. Moreover, in the quantum Hall regime, the screening and localization result in peaks of recombination time at the magnetic fields corresponding to definite filling factors, as indeed was observed in Refs. 7 and 8. Whereas modification of the miniband structure causes a step-like increase of the recombination time, as it was found in our experiments. Based on these arguments, we conclude that the increasing recombination time observed in GaAs/AlGaAs MQW at the critical magnetic field when the occupancy of the high energy miniband vanishes is due to the changes in the miniband structure.

IV. CONCLUSION

The influence of the electron energy structure on dynamic optical response was studied in GaAs/AlGaAs weakly coupled multiple quantum wells. The modification of the energy structure induced by the quantizing magnetic field manifested itself in the magnetoresistance oscillations and in the variation of the spectroscopic characteristics of the photoluminescence emitted by the two-dimensional electrons confined in the multiple quantum wells, such as the emission energy, the integrated photoluminescence intensity associated with the occupancy of the corresponding electron states, and the photoluminescence line width. The effect of a significant change in the recombination time caused by the magnetic field induced variation of the miniband occupancy was demonstrated. The results of the presented study show a possibility of the band structure engineering to tailor the dynamic optical response of optoelectronic devices based on quantum wells.

ACKNOWLEDGMENTS

Financial supports from the Brazilian agencies FAPESP and CNPq are gratefully acknowledged.

[1]J. Hader, J. V. Moloney, and S. W. Koch, Appl. Phys. Lett. **87**, 201112 (2005).
[2]E. Kioupakis, Q. Yan, D. Steiauf, and C. Van de Walle, New J. Phys. **15**, 125006 (2013).
[3]D. Steiauf, E. Kioupakis, and C. G. Van de Walle, ACS Photonics **1**, 643 (2014).
[4]Y. Gao, C. S. Suchand Sandeep, J. M. Schins, A. J. Houtepen, and L. D. A. Siebbeles, Nat. Commun. **4**, 2329 (2013).
[5]J. Iveland, L. Martinelli, J. Peretti, J. S. Speck, and C. Weisbuch, Phys. Rev. Lett. **110**, 177406 (2013).
[6]M. Bernardi, D. Vigil-Fowler, C. S. Ong, J. B. Neaton, and S. G. Louie, PNAS **112**, 5291 (2014).
[7]M. Dahl, D. Heiman, A. Pinczuk, B. B. Goldberg, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **45**, 6957 (1992).
[8]S. A. Brown, A. G. Davies, A. C. Lindsay, R. B. Dunford, R. G. Clark, P. E. Simmonds, H. H. Voss, J. J. Harris, and C. T. Foxon, Surf. Sci. **305**, 42 (1994).
[9]D. Mukherji and B. R. Nag, Phys. Rev. B **12**, 4338 (1975).
[10]H. L. Störmer, J. P. Eisenstein, A. C. Gossard, W. Wiegmann, and K. Baldwin, Phys. Rev. Lett. **56**, 85 (1986).
[11]L. Pavesi and M. Guzzi, J. Appl. Phys. **75**, 4779 (1994).