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Citation: [Applied Physics Letters](#) **96**, 113106 (2010); doi: 10.1063/1.3364138

View online: <http://dx.doi.org/10.1063/1.3364138>

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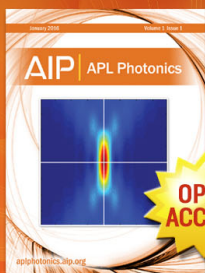
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## A study of disorder effects in random $(\text{Al}_x\text{Ga}_{1-x}\text{As})_n(\text{Al}_y\text{Ga}_{1-y}\text{As})_m$ superlattices embedded in a wide parabolic potential

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(Received 8 January 2010; accepted 24 February 2010; published online 17 March 2010)

A photoluminescence (PL) study of the individual electron states localized in a random potential is performed in artificially disordered superlattices embedded in a wide parabolic well. The valence band bowing of the parabolic potential provides a variation of the emission energies which splits the optical transitions corresponding to different wells within the random potential. The blueshift of the PL lines emitted by individual random wells, observed with increasing disorder strength, is demonstrated. The variation of temperature and magnetic field allowed for the behavior of the electrons localized in individual wells of the random potential to be distinguished. © 2010 American Institute of Physics. [doi:10.1063/1.3364138]

Photoluminescence (PL) spectroscopy is widely used to study effects of disorder in semiconductors. An analysis of position and shape of the PL lines provides comprehensive information about an electron system subject to the disorder, such as the energy distribution of the electron states and the electron state broadening.<sup>1,2</sup> However, this information concerns characteristic electron parameters averaged over all the states of a disordered system, which contribute to the PL. In this work we report a method which allows for a spectroscopic separation of the individual electron states in disordered systems. As a result, the behavior and characteristics of individual electrons localized in the quantum wells of a random potential may be explored.

Our studies focus on the PL spectra of intentionally disordered  $(\text{Al}_x\text{Ga}_{x-1}\text{As})_n(\text{Al}_y\text{Ga}_{y-1}\text{As})_m$  superlattices (SL), where  $n$  and  $m$  are the thicknesses of corresponding layers expressed in monolayers. The samples were grown by molecular-beam epitaxy. The compositions of the wells ( $x$ ) and of the barriers ( $y$ ) were controlled independently by two Al cells in order to achieve the parabolic potential profile modulated by a square SL potential. The correspondence between the alloy composition and energy was taken from Ref. 3. The randomization of the SL potential was achieved by a random variation of the layer thickness  $n$ . The strength of disorder was characterized by the ratio  $\delta = \Delta/W$ , where  $\Delta$  is the width of a Gauss distribution of the energy of the noninteracting electrons calculated in the isolated quantum wells and the width of the miniband in the nominally periodic SL  $W = 1.5$  meV was calculated by the effective mass approximation. Details of the disordered SLs can be found in Ref. 4 where a quantitative control of the disorder strength ( $\delta$ ) was demonstrated. Carriers were supplied by Si dopants situated 12.4 nm from the well edges, in  $\delta$ -doped sheets on either side of the well, within a short-period AlAs/GaAs SL. The mobilities and the concentrations of the electrons measured in four-terminal Hall bar structures at  $T = 1.6$  K were  $(140\text{--}200) \times 10^3$  cm<sup>2</sup>/V s and  $3.7 \times 10^{11}$  cm<sup>-2</sup>, respectively. According to the analysis of the low-field Shubnikov-

de-Haas oscillations, this electron density corresponds to a Fermi energy of 4.3 meV. Redistribution of the electrons over the entire parabolic well results in a flat potential profile of the conduction band, while the valence band bends according to the variation of the compositional profile in the growth direction. The bow shape of the valence band of the parabolic well provides spectroscopic separation of the PL energies of the individual SL wells. In such a case, the PL of the random SL splits into individual peaks each emitted by the corresponding well. Thus, the behavior of the electrons localized in individual wells of the one-dimensional random potential may be studied. Samples with different disorder strengths in the range  $\delta = 0\text{--}13.5$  were investigated. Here, values of  $\delta > 1$  imply the localization of electrons in the wells of the random SL potential. It should be mentioned that remotely doped periodic SLs embedded in wide parabolic wells were first proposed in Refs. 5 and 6, where magnetotransport measurements were performed. However, no effects of disorder and PL emission were demonstrated in such structures to date.

The PL measurements were carried out with an Ocean Optics Inc. HR2000 high-resolution spectrometer. The 514.5 nm line of an Ar<sup>+</sup> laser was used for excitation. The samples were cooled in an Oxford Instruments optical cryostat with a superconducting magnet. The PL was measured in the temperature range  $T = 1.6\text{--}50$  K and in a magnetic field, ranging in magnitude from  $B = 0$  to 10 T, oriented perpendicular to the sample surface.

The potential energy profiles of the valence and conduction bands of one of the disordered structures calculated self-consistently using a one-dimensional, one-electron Schrödinger/Poisson equation solver<sup>7</sup> are shown in Fig. 1. According to the calculations performed with the Hall electron concentration, eight of ten wells are occupied. The Fermi energy, calculated as the average value from the bottoms of all the occupied wells, gives 5.5 meV and is in good agreement with the experimental value. The function of the bow shape of the valence band potential, discussed above, is clearly presented in the figure.

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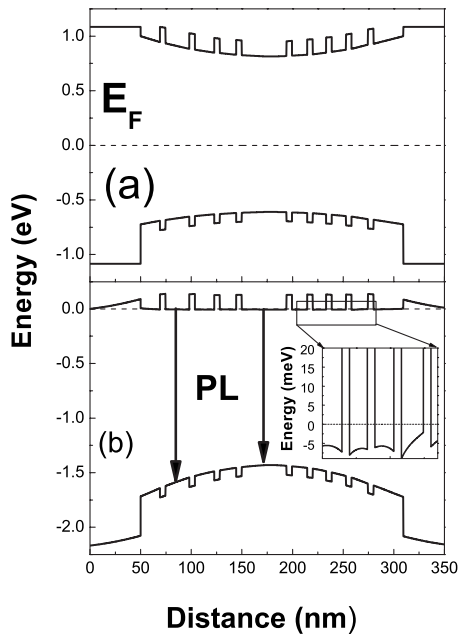


FIG. 1. Potential energy profiles of the conduction and valence bands calculated in the random superlattice ( $\delta=13.5$ ) embedded in a wide parabolic well. The (a) and (b) panels show the potentials in the undoped and doped ( $n=4 \times 10^{11} \text{ cm}^{-2}$ ) samples, respectively. The different energies of the PL emission from different wells are shown by arrows.

The PL spectra measured in the SLs with different disorder strengths are depicted in Fig. 2. The two PL lines at 1.49 and 1.52 eV are due to the GaAs substrate and GaAs epitaxial cap-layer of 14 nm thickness, respectively. The emission from the substrate is caused by the recombination of free electrons in the conduction band with neutral carbon acceptors ( $e-A^0$ ). The low density of defects resulted in intrinsic exciton emission in the epitaxial layer.<sup>8</sup> Owing to weak fluctuations of the cap-layer thickness and strain, the spectral position of this exciton line is slightly different in

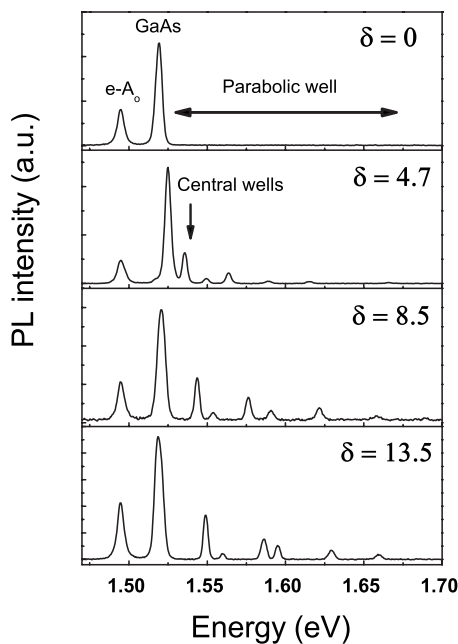


FIG. 2. Photoluminescence spectra measured at  $T=1.6 \text{ K}$  in the random superlattices with different disorder strengths ( $\delta$ ) embedded in wide parabolic wells.

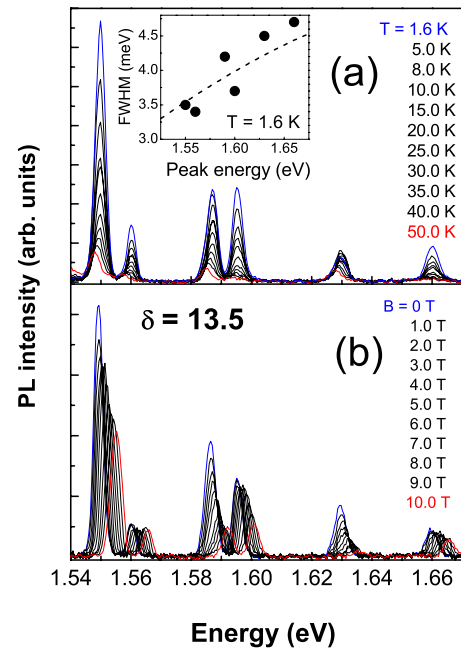


FIG. 3. (Color online) Photoluminescence emission from the random SL with  $\delta=13.5$  measured as functions of the (a) temperature and (b) magnetic field. The inset of (a) shows the widths of the individual peaks measured at  $T=1.6 \text{ K}$ .

various samples. No emission from the periodic SL embedded in the parabolic well was detected because the total joint density of states in this SL is distributed over the wide energy range determined by the bowing of the valence band in the parabolic well (estimated as about 0.27 eV). Identical PL emission was found from the parabolic well without a SL structure. As evident in the PL spectra, up to six PL lines emerged in the random SLs where the electrons are localized in the wells of the random potential. The localization causes the modulation of the joint density of states by the disorder and, as a consequence, local enhancement of the PL emission. The first low energy PL line, found around 1.54 eV (close to the GaAs emission), is due to the central well. The weak lines observed in the range of 1.65 eV are emitted by the peripheral wells. The decrease in line intensities when approaching the parabolic well boundary obviously shows the effect of the electron scattering due to the variation of the alloy composition (the concentration of Al increases toward the peripheral wells). Consequently, our data demonstrate the effect of dispersion caused by the valence band bending in the parabolic well.

The energy positions of the PL lines from the disordered SLs revealed a blueshift of approximately 20 meV with increasing disorder. This blueshift is associated with the increasing energy of the localized states in the random SL with respect to the bottom of the miniband in the periodic SL. An analogous blueshift of the PL, although caused by the integral effect of disorder on electron energy, was observed in intentionally disordered SLs in Ref. 9.

The temperature dependence of the PL emission from the individual wells of the disordered potential with  $\delta=13.5$  is demonstrated in Fig. 3(a). The effect of the alloy scattering potential mentioned above is demonstrated in the inset of Fig. 3(a), where the widths of all the PL peaks from the SL are shown. The increasing peak width associated with transitions in wells situated closer to the parabolic well

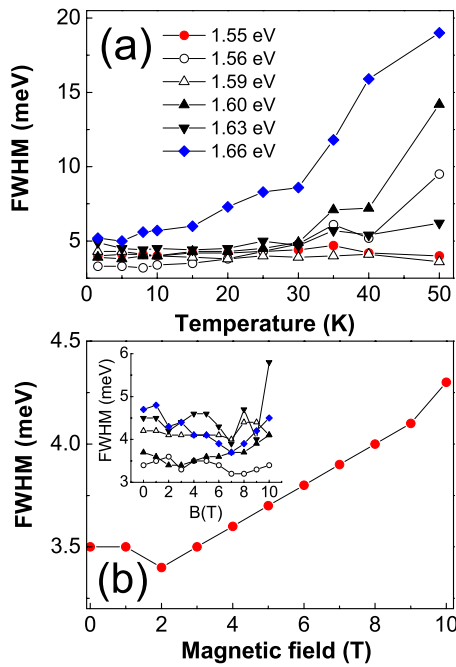


FIG. 4. (Color online) (a) Widths of the individual PL lines measured in the random SL with  $\delta=13.5$  as functions of temperature. (b) The magnetic field dependence of the width of the PL line emitted by the central well; the widths of the remaining lines are shown in the inset.

boundary is due to the corresponding increase in Al composition. The dependence of the PL linewidth on alloy composition ( $x$ ) may be calculated according to the formula derived for the exciton linewidth ( $\Gamma_{\text{exc}}$ ) in quantum wells composed of alloys<sup>10</sup>

$$\Gamma_{\text{exc}} \approx 0.17 \frac{Nx(1-x)a_0^6 M}{\hbar^2 L} \Delta U_{\text{all}}^2, \quad (1)$$

where  $N$  is the number of alloy sites per unit volume,  $a_0$  is the lattice constant,  $M = m_e^* + m_h^*$  is the sum of the electron and hole masses,  $L$  is the well width, and  $\Delta U_{\text{all}}$  is the difference of the alloy scattering potentials of the conduction and valence bands. In the absence of an available value for the AlGaAs alloy valence band scattering potential, we used a reasonable value  $\Delta U_{\text{all}} = 0.2$  eV to fit the experimental data. The PL linewidth calculated in this way is shown by a dashed line in the inset of Fig. 3(a).

The widths of the PL lines measured at different temperatures are shown in Fig. 4(a). They are attributed to the broadening of the corresponding electron states localized in the wells of the random SL potential. The electron state broadening is composed of the broadenings parallel and perpendicular to the SL layers. All the parallel broadenings are identical, while the perpendicular broadenings depend on the sample structure. The observed dissimilar temperature dependences exhibited by the various spectral lines are attrib-

uted to the distinct occupation of the corresponding wells, caused by the disorder. The electrons tend to occupy broad wells, while narrower wells are less occupied. According to the sample structure, the central well is the widest one in all the disordered SLs. Therefore, most of the electrons are localized in the central well, where a Fermi energy higher than in the case of the periodic SL (4.3 meV) is expected. Indeed, the broadening of the PL line from the central well does not reveal a remarkable temperature variation (metallic behavior), while the broadenings of the PL lines from the peripheral wells increased with temperature.

The influence of the magnetic field on PL from the individual wells measured in the random SL is shown in Fig. 3(b). All the lines revealed blueshifts due to the magnetic field quantization (at  $B=10$  T, the expected blueshift is  $0.5\hbar\omega_c \approx 8$  meV). The broadening of the PL from the central well clearly increased with the magnetic field, as shown in Fig. 4(b). However, this dependence was found to be stronger than the square-root dependence predicted for the Landau level broadening in Ref. 11. In contrast, no regular influence of the magnetic field was found on the broadenings of the PL lines from the peripheral wells. Again, this may be caused by the particular occupation of each well because the Landau levels are well pronounced in the most occupied metalliclike central well.

In conclusion, we have demonstrated that the bowed valence band potential of the parabolic well provides the dispersion of the electron interband transition energies, which may be considered as an “internal spectrometer.” As a result, the PL from an intentionally disordered SL embedded within a remotely doped wide parabolic well presents an excellent tool for the analysis of properties of individual electron states in disordered systems.

Y.A.P. thanks G. Gusev for helpful discussions. Financial support from the Brazilian agencies, FAPESP and CNPq, and of the Canadian Institute for Photonic Innovations, is gratefully acknowledged.

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