# Magnetotransport in a wide parabolic well superimposed with a superlattice

Yu.A. Pusep,[1,a)] G. M. Gusev,[2] A. K. Bakarov,[3] A. I. Toropov,[3] and J. C. Portal[4,5,6]
[1]*Instituto de Fisica de Sao Carlos, Universidade de Sao Paulo, 13560-970 Sao Carlos, SP, Brazil*
[2]*Instituto de Física da Universidade de São Paulo, CP 66318 CEP 05315-970, São Paulo, SP, Brazil*
[3]*Institute of Semiconductor Physics, Novosibirsk 630090, Russia*
[4]*LNCMI-CNRS, UPR 3228, BP 166, 38042 Grenoble Cedex 9, France*
[5]*INSA Toulouse, 31077 Toulouse Cedex 4, France*
[6]*Institut Universitaire de France, 75005 Paris, France*

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The electron properties of artificially disordered superlattices embedded in a wide AlGaAs parabolic well were investigated in a strong magnetic field. We demonstrated that in the extreme quantum limit the interlayer disorder results in formation of a new correlated phase. A nearly uniform electron distribution over the superlattice wells was found in a weak magnetic field. However, a nonuniform phase with partially localized electrons, representing well-developed fractional quantum Hall effect features, was observed in high magnetic field (at the filling factor $\nu < 1$). A distinct magnetic field–induced transition separates these two phases. © *2011 American Institute of Physics*. [doi:10.1063/1.3576134]

Soon after the observation of the integer quantum Hall effect in a three-dimensional electron system[1] the question of whether the fractional quantum Hall effect may be extended to three dimensions was raised.[2] As was demonstrated in Ref. 1, semiconductor superlattices (SL) composed of alternate layers of different materials present an excellent electron system that can be changed from the two-dimensional case to the three dimensional one by tailoring layer widths. However, no observation of the fractional quantum Hall (FQH) effect in multilayers has yet been reported. The reason for this is the relatively low electron mobilities that may be achieved in semiconductor SLs where the quantum Hall effect is expected. In such SLs the barriers ought to be sufficiently thin (typically, not more that 5 nm) to satisfy the condition $\hbar\omega_c > W_{SL}$, which is indispensable to realizing the quantum Hall regime, where $\omega_c$ and $W_{SL}$ are the cyclotron frequency and the SL miniband width. Thin barriers do not allow for effective remote doping. Consequently, ionized impurities result in low mobilities. Successful remote doping may be obtained in a wide parabolic quantum well with an additional superlattice potential superimposed on it.[3,4]

We studied the magnetotransport properties of intentionally disordered $(Al_xGa_{x-1}As)_n(Al_y\ Ga_{y-1}As)_m$ SLs, where $n$ and $m$ are the thicknesses of corresponding layers expressed in monolayers (*ML*). 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 a gradual parabolic potential profile modulated by a square SL potential. Thus, the resulting structure presented a SL embedded in a wide parabolic well of width about 240 nm and height $h = 210$ meV. The randomization of the SL potential was achieved by a random variation of the layer thickness $m$ about the nominal value $m = 65$ *ML*, according to a probability distribution which is obtained from a Gaussian probability density for the electron energy in the isolated well. The Gaussian is centered at the value of the electron energy corresponding to the 65 *ML* well (well width of the nominally periodic SL) and is characterized by its full width at half-maximum, $\Delta$ (disorder energy). The random wells were separated by AlGaAs barriers of 15 *ML* thickness. The strength of the disorder was characterized by the ratio $\delta = \Delta/W_{SL}$, where the width of the miniband in the nominally periodic SL, $W = 1.5$ meV, was calculated by the effective mass approximation. Carriers were supplied by Si dopants set back 12.4 nm from the well edges, in $\delta$-doped sheets on either side of the well. The mobilities and the concentrations of the electrons collected in Table I, measured in four-terminal Hall bar structures at $T = 1.6$ K were $(140 - 200) \times 10^3\ \mathrm{cm^2/Vs}$ and $3.7 \times 10^{11}\ \mathrm{cm^{-2}}$, respectively. Redistribution of the electrons over the entire parabolic well results in a flat potential profile of the conduction band, while the valence band becomes bent 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. The samples with different disorder strengths in the range $\delta = 0 - 13.5$ were investigated. The effect of screening weakens the disorder strength by a factor of about 6.[5] Accordingly, the interlayer tunneling is

TABLE I. The sample parameters

| Sample | $\delta$ | $n_s (10^{11}\ \mathrm{cm^{-2}})$ | $\mu\ (\mathrm{cm^2/Vs})$ |
|---|---|---|---|
| A | no SL | 3.7 | 136000 |
| B | 0 | 3.7 | 200000 |
| C | 4.73 | 3.7 | 186000 |
| D | 8.5 | 3.7 | 156000 |
| E | 13.5 | 3.7 | 209750 |

[a)]Author to whom correspondence should be addressed. Electronic mail: pusep@if.sc.usp.br.

 

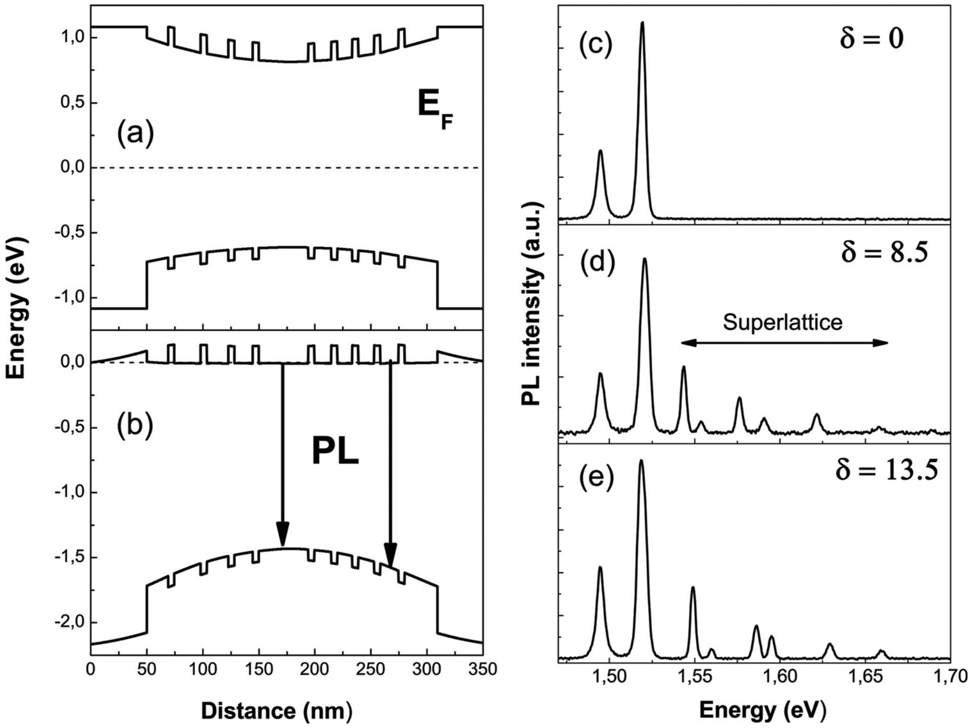


FIG. 1. Potential energy profiles of the conduction and valence bands calculated in the random superlattice ($\delta = 13.5$) embedded in a wide parabolic well. The (a) and (b) panels show the potentials in the undoped and doped ($n = 4 \times 10^{11}$ cm$^2$) samples, respectively. The different energies of the PL emission from different wells are shown by arrows. The (c), (d), and (e) panels demonstrate the photoluminescence spectra measured at $T = 1.6$ K in the random superlattices with different disorder strengths ($\delta$) embedded in wide parabolic wells.

considerably suppressed in samples D and E where the screened disorder energies are larger than the miniband width.

The PL measurements were carried out with an Ocean Optics Inc. HR2000 high-resolution spectrometer. The 514.5 nm line of an $Ar^+$ laser was used for excitation. The samples were cooled down in an Oxford Instruments optical cryostat with a superconducting magnet. The PL was measured in the temperature range $T = 1.6 - 50$ K and in a magnetic field with a range in magnitude equal to $B = 0 - 10$ T, oriented perpendicular to the sample surface. The magnetoresistance measurements were performed at the temperature $T = 80$ mK up to the magnetic field $B = 15$ T in the mixing chamber of a top-loading dilution refrigerator. The test samples were Hall bars with a distance between the voltage probes of 500 $\mu$m and a bar width of 200 $\mu$m. During the measurements an ac current did not exceed $10^{-7}$ A.

The potential energy profiles, calculated self-consistently using a one-dimensional, one-electron Schrödinger/Poisson equation, of the valence and conduction bands of the periodic and the disordered structures are shown in Figs. 1(a) and 1(b). According to the calculations performed with the Hall electron concentration, 6–7 of 10 wells are occupied, resulting in the effective width of the parabolic well $L_{eff} \approx 15$ nm. The function of the bow shape of the valence band potential, discussed above, is presented in the figure.

The PL spectra measured in the SLs with different disorder strengths are depicted in Figs. 1(c)–(e). The two PL lines at 1.49 eV and 1.52 eV are due to the GaAs substrate and GaAs epitaxial cap-layer of thickness 14 nm. No emission from the periodic SL embedded in the parabolic well was detected. This is because the total joint density of states in this SL is distributed over a wide energy range determined by the bowing of the valence band in the parabolic well (estimated as about 0.27 eV). As evident in the PL spectra of the disordered structures, up to six PL lines emerged in the random SLs. In this case, the electrons are localized in the random potential wells. This causes modulation of the joint density of states by the disorder and, as a consequence, local enhancement of the PL emission. The six observed PL lines correspond to six wells occupied by electrons. The first, low-energy PL line (closest 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 details of the PL measurements may be found in Ref. 6.

The low-field measurements are shown in Fig. 2. As in Ref. 1, in the SLs the integer quantum Hall effect was found

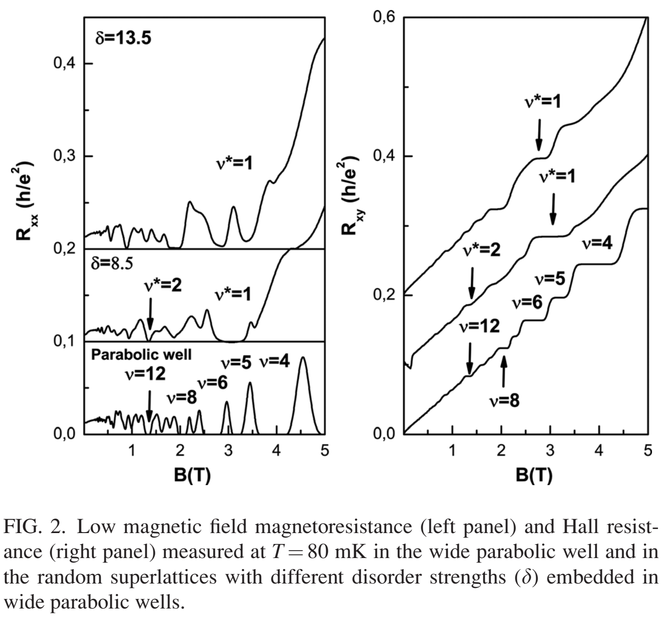


FIG. 2. Low magnetic field magnetoresistance (left panel) and Hall resistance (right panel) measured at $T = 80$ mK in the wide parabolic well and in the random superlattices with different disorder strengths ($\delta$) embedded in wide parabolic wells.

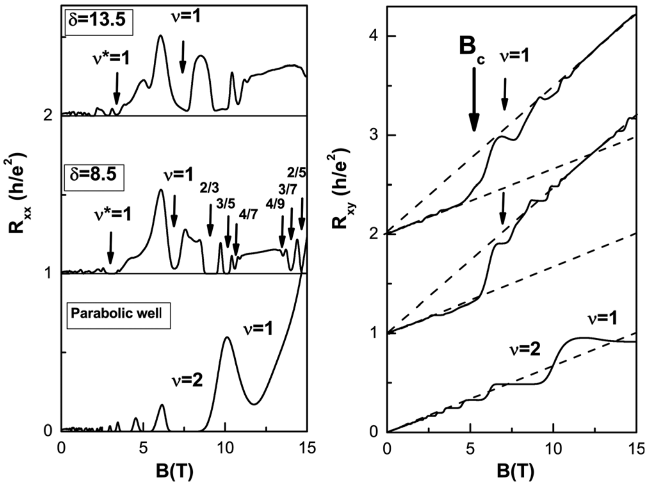


FIG. 3. High magnetic field magnetoresistance (left panel) and Hall resistance (right panel) measured at $T = 80$ mK in the wide parabolic well and in the random superlattices with different disorder strengths ($\delta$) embedded in wide parabolic wells.

shifted to the low magnetic fields according to the expression $B_{\nu^*} = hn_s/\nu^* N_{SL}$, where $n_s$, $\nu^*$, and $N_{SL}$ are the electron sheet density, filling factor of the quantum Hall miniband states, and the number of occupied layers, respectively. The value of $N_{SL} = 6$ well accounts for the observed quantum Hall states. A comparison between the quantum Hall states observed in the SLs embedded in a wide parabolic well and those found in an empty parabolic well prove that the six wells are occupied in the SLs. This number of occupied layers is in good accord with the PL data presented in Fig. 2.

Unexpectedly, in the high magnetic field range above the critical magnetic field $B_c$, the slope of the Hall resistance in the samples with SLs is enhanced by a factor of 2. Note that in both presented samples the electron density and the low-field Hall resistance are the same. Moreover, in the range of the magnetic field above the critical field, the samples with disordered SL reveal a well-developed FQH effect. It ought to be stressed that the quantum Hall state with the filling factor $\nu = 1$ was found on both sides of the critical field $B_c$. Below the critical magnetic field the filling factors ($\nu^*$) correspond to the integer quantum Hall miniband states. However, above the critical field the filling factors ($\nu$) are associated with the single two-dimensional layer. This is a manifestation of the quantum phase transition near the filling factor $\nu = 1$. The transition occurs in the narrow interval of magnetic field $\Delta B \sim 1.1$ T and is characterized by the striking mobility enhancement, the significant increase in the Hall resistance, and, consequently, by the decreasing total electron density. The high-field magnetoresistance data were discussed in Ref. 7.

The transition observed at $B_c$ may be caused by a magnetic field–induced change from a nearly uniform electron distribution over the SL wells to a nonuniform state with partially localized electrons.[8–12] We found that the interlayer disorder favors the observed transition. According to theory,[10] however, interlayer tunneling stabilizes the interlayer phase coherence. Therefore, the transition is likely due to a charge order and is not caused by the interlayer phase coherence. We suppose that the electrons experiencing high mobilities, which contribute to the observed FQH effect, occupy the central GaAs well, while the electrons in the AlGaAs lateral wells are localized. In turn, the artificial interlayer disorder supports a spatial separation of electrons resulting in a predominant occupation of the central well and in localization of electrons in the lateral wells.

It is worth mentioning that a similar but much weaker increase of the Hall resistance with the magnetic field was found in wide parabolic wells in Ref. 13. The stronger enhancement of the Hall slope observed in SLs is in accord with the conclusions of Ref. 11, which affirms that the amplitude of the charge-density waves is enhanced by the additional charge localized by the SL potential.

## ACKNOWLEDGMENTS

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