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Magnetic field induced charge redistribution in artificially disordered quantum Hall superlattices

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Abstract – The photoluminescence from individual quantum wells of artificially disordered weakly coupled multi-layers embedded in wide AlGaAs parabolic wells was investigated in a strong magnetic field. We show that the response of the individual wells is very different from the average response of the multi-layers studied by transport measurements and that photoluminescence represents a local probe of the quantum Hall state formed in three-dimensional electron system. The observed magnetic field induced variations of the in-layer electron density demonstrate the formation of a new phase in the quasi-three-dimensional electron system. The sudden change in the local electron density found at the Landau filling factor $\nu = 1$ by both the magneto-transport and the magneto-photoluminescence measurements was assigned to the quantum phase transition.

Electron-electron interactions play a fundamental role in the behavior of high-mobility many-body electron systems. They were found to determine a vast number of different quantum phenomena, including metal-to-insulator transition, magnetic ordering, fractional quantum Hall effect (QHE) and many others, observed in two-dimensional electron systems. A variety of fascinating new effects due to the electron-electron interaction were also predicted to occur in uniform three-dimensional electron gas (3DEG) subjected to magnetic field, such as spin and charge density waves, excitonic insulators and Wigner crystals [1,2]. However, impurity scattering strongly limits the carrier mobilities in the 3DEG, which makes the observation of interaction effects difficult. In order to achieve high mobilities, the remotely doped wide parabolic quantum wells (PQW) have been proposed [2]. In such systems dopants are spatially separated from the electrons considerably reducing the electron impurity scattering. The electrons screen the bare parabolic potential and form a wide slab with uniform electron density, which may be considered as the 3DEG [3,4].

Additional controlled degrees of freedom in the growth direction may be introduced into the problem by fabrication of the multiple-well quantum Hall systems, where the density of 3DEG is modulated by a periodic potential which breaks the translational crystal symmetry resulting in new gaps [5]. Diverse broken-symmetry phases such as spontaneous interlayer phase coherent and charge-ordered states were demonstrated to occur in such multiple-well systems in the presence of a strong magnetic field as a result of both the electron density modulation and many-body effects [6–11]. Their predominance is established by the well separation. In coupled multiple wells (superlattices, SLs), due to relatively thin barriers indispensable for noteworthy interlayer tunneling, remote doping does not work properly. Therefore, mobilities of semiconductor superlattices are drastically limited by impurity scattering. In order to increase the mobilities, SLs were suggested to grow within wide parabolic wells, see refs. [12–14]. In such case remote dopants may be set in the barriers of the parabolic well and high mobilities may be achieved.

Recently, magnetotransport properties of such high-mobility multiple-layer systems embedded in wide parabolic wells were investigated in ref. [15], where the magnetic field induced transition separating two phases with different distributions of the electron density over the layers was found. The observed transition manifested

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itself in a corresponding change of the slope of the Hall resistance and it was understood as a kind of quantum phase transition leading to a spatial redistribution of the charge in a multi-component electron system predicted in refs. [7–9,11]. A mostly straightforward observation of charge distribution can be obtained by measurements of the local electron density. However, an integral charge due to contributions of all the wells of a multiple-layer system is measured by transport experiments. Consequently, spatial variation of the electron density cannot be deduced from the magneto-transport measurements. Therefore, this work was motivated by a research of a magnetic field induced redistribution of the electrons over the quantum wells, which is fundamental in order to confirm origin of the observed quantum phase transition. As was demonstrated in ref. [16], the valence band bowing of the parabolic potential provides an internal spectrometer which splits off the optical transitions corresponding to different wells embedded in a PQW. In this way, photoluminescence (PL) emission determined by the occupied one-particle density of states [17] presents an adequate method to explore the spatial charge distribution. Thus, *individual responses of each layer* may be examined and a mapping of the charge distribution onto the growth direction can be obtained. Here we use the method developed in ref. [16] to probe the spatial characteristics of the ground electron state of the quasi-3DEG in the regime of the QHE.

In this letter, we report on the observation of the magnetic field driven distribution of the density of electron states which results in a new phase of the quasi-3DEG multiple-well quantum Hall system. The electron density of a wide PQW was modulated by a SL potential. In order to increase the charge localization and consequently, to separate the emissions from individual quantum wells, the interlayer disorder was introduced during the growth. Additionally, the charge localization enhances the interaction effects [7]. We found that the magnetic field considerably influences the charge distribution in the PQW. At the Landau filling factor $\nu = 1$ an abrupt change in the local electron density attributed to a quantum phase transition was found.

We studied magneto-PL from intentionally disordered $(\mathrm{Al}_x\mathrm{Ga}_{x-1}\mathrm{As})_n(\mathrm{Al}_y\mathrm{Ga}_{y-1}\mathrm{As})_m$ SLs embedded in wide PQWs, where n and m are the thicknesses of corresponding layers expressed in monolayers (ML). Ten weakly coupled quantum wells composing a SL 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. Electrons were supplied by Si dopants set back 12.4 nm from the well edges in δ-doped sheets on either side of the well. In order to avoid an in-built electric field, one more δ-doped sheet was placed close to the sample surface. The electron concentration and mobilities in the studied samples, measured at $T = 90\,\mathrm{mK}$, were $3.7 \times 10^{11}\,\mathrm{cm}^{-2}$ and about $2 \times 10^5\,\mathrm{cm}^2/\mathrm{Vs}$, respectively. The details of the sample structure and the electrical characterization may be found in ref. [15]. The randomization of the SL potential was achieved by a deliberate random variation of the well thickness n about the nominal value $n = 65\,\mathrm{ML}$. The energy of the disorder Δ was determined as the width of the Gaussian distribution of the single-electron energies corresponding to individual wells. The random wells were separated by AlGaAs barriers of $m = 15\,\mathrm{ML}$ thickness. The strength of the disorder was characterized by the ratio $\delta_0 = \Delta/W$, where the width of the miniband in the nominally periodic SL $W = 1.5\,\mathrm{meV}$ was calculated by the effective mass approximation as in ref. [18]. According to the calculations, unavoidable monolayer fluctuations of the well width cause the disorder energy $\Delta \simeq 0.23\,\mathrm{meV}$. As demonstrated in ref. [18], the as-grown intentional disorder dominates the electron properties of the samples reported here. The strongest perturbation by the disorder potential (the widest well) was set in the center of the parabolic well where the highest mobility is expected. It ought to be stressed that any failure happening during a growth may cause a deviation of the PQW potential from the parabolic shape. As a consequence, weak interlayer coupling might be broken. Therefore, special care (cautious analysis of the PL line positions, especially that from the central well) should be taken to distinguish a proper effect of the interlayer disorder. For this reason some of the samples used in ref. [16] were discarded.

The PL measurements were performed with an Ocean Optics Inc. HR4000 high-resolution spectrometer. The 514.5 nm line of an Ar+ laser with power $\leqslant 0.2\,\mathrm{mW}$ was used for excitation. The samples were cooled down in an Oxford Instruments optical cryostat with a superconducting magnet. The PL was measured at the temperature $T = 1.6\,\mathrm{K}$ in the range of the magnetic field $B = 0$–$10\,\mathrm{T}$, oriented perpendicular to the sample surface.

In the presence of free electrons screening reduces the random potential of weakly coupled multi-layers according to [19]

$$\delta = \frac{\delta_0}{1 + 2\pi e^2 \rho_0 d/\epsilon}, \tag{1}$$

where the unscreened (as grown) disorder parameter δ_0 is reduced by the factor $\alpha = 1 + 2\pi e^2 \rho_0 d/\epsilon$, with ρ_0, d, and ϵ being the density of states in a subband, the interlayer distance and the dielectric constant, respectively. For the multi-layers studied here the calculated screening factor is $\alpha \approx 6$.

The samples with different disorder strengths in the range $\delta = 0$–2.3 were investigated. The interlayer tunneling is expected to be considerably suppressed in the samples with $\delta > 1$ where the calculated screened disorder energy is larger than the miniband width. The energy profiles of the valence and conduction bands shown in fig. 1 were calculated self-consistently as in ref. [16] with the electron concentrations determined by Hall measurements.

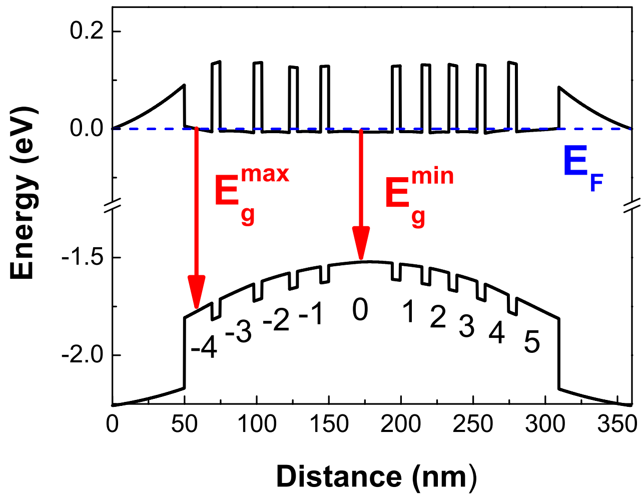

Fig. 1: (Color online) The potential energy profiles of the conduction and valence bands calculated in the superlattice with $\delta = 2.3$. The numbers (l) indicate corresponding quantum well.

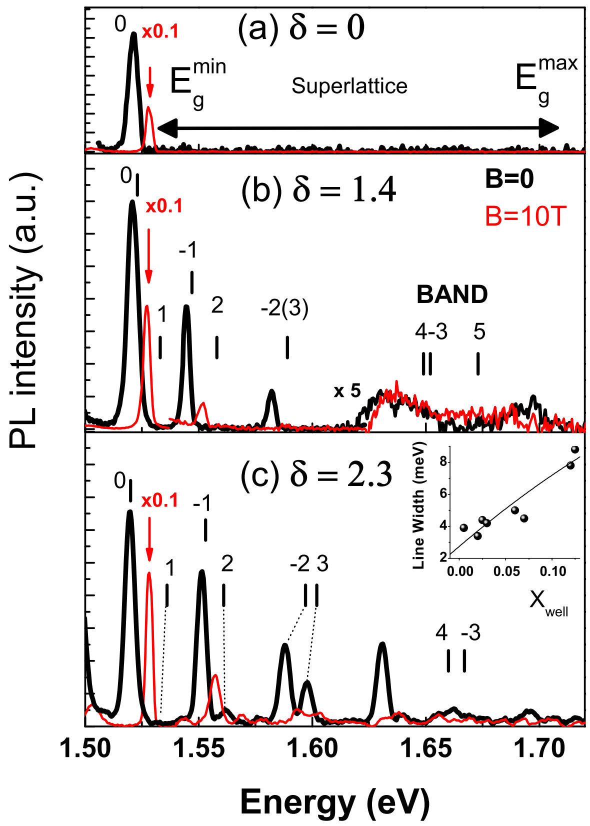

Fig. 2: (Color online) Photoluminescence spectra measured in the superlattices with different disorder strength ($\delta: 0$ (a), 1.4 (b), 2.3 (c)) without magnetic field (thick black line, magnified by 2) and in the magnetic field $B = 10\,\mathrm{T}$ (thin red line). Inset shows the PL line widths determined without magnetic field. The black line is the calculated line width determined by alloy scattering.

The numbers (l) indicate the corresponding quantum wells. The energies $E_g^{\min}$ and $E_g^{\max}$ indicate the interval (estimated as about 0.27 eV) where the emission from a SL is expected. According to the calculations performed with the Hall electron concentrations, 8 of 10 wells are occupied. The emissions from all eight occupied wells were detected by PL measurements. Besides, the calculated Fermi energy equal to 5.5 meV was found in good agreement with the Fermi energy of 4.3 meV obtained by the low-field Shubnikov-de-Haas oscillations. The agreement observed between the results of the self-consistent calculations and the experimental data proves accuracy of the calculations.

The PL spectra measured in the SLs with different disorder strengths are depicted in fig. 2. In the periodic SL the single line at 1.52 eV corresponding to the emission from the central well was detected. The interlayer disorder causes modulation of the joint density of states and, as a consequence, a local enhancement of the PL emission. Eight PL lines were observed in the mostly disordered SL ($\delta = 2.3$). They correspond to eight isolated wells. The first, low energy PL line is due to the central well. The weak high energy lines are emitted by the peripheral wells. In the SL with an intermediate disorder strength ($\delta = 1.4$) the central wells are isolated by the disorder, while the peripheral wells are still coupled ensuing a pseudo-miniband which exhibits the broad spectral band. The emission energies from all the wells calculated self-consistently are shown by vertical dashes. Reasonable agreement between the positions of the PL lines and the calculated emission energies was observed.

With the increasing energy the PL line intensities decrease, whereas the line widths increase due to the alloy scattering which raises toward the peripheral wells. The PL line widths obtained in the SL with $\delta = 2.3$ by the fits of the Gaussian lines, together with those calculated due to the alloy scattering according to ref. [20] are shown as functions of the alloy composition in the wells in the inset to fig. 2(c). When the magnetic field is applied, the intensity of the PL line from the central well (shown for all the samples in the larger scale) increases much more rapidly than those from the peripheral wells. Below we demonstrate that this is caused by the magnetic field induced redistribution of the electron charge over the wells of a SL. Identical behaviors of the PL lines in the magnetic field were obtained in both disordered SLs.

In multiple layers the interlayer disorder may lead to the breakdown of the QHE. The quantization of the Hall conductivity is destroyed when the disorder energy is large compared to the spacing between the Landau levels (LLs). The integer QHE was studied in similar disordered uniformly doped SLs in ref. [18]. It was shown to survive even in the mostly disordered SL ($\delta \simeq 2$). The Hall resistance measured in the SL with $\delta = 1.4$ as a function of the magnetic field is depicted in fig. 3(a). Depending on the magnetic field, two quantum phases with different distributions of the electron density over

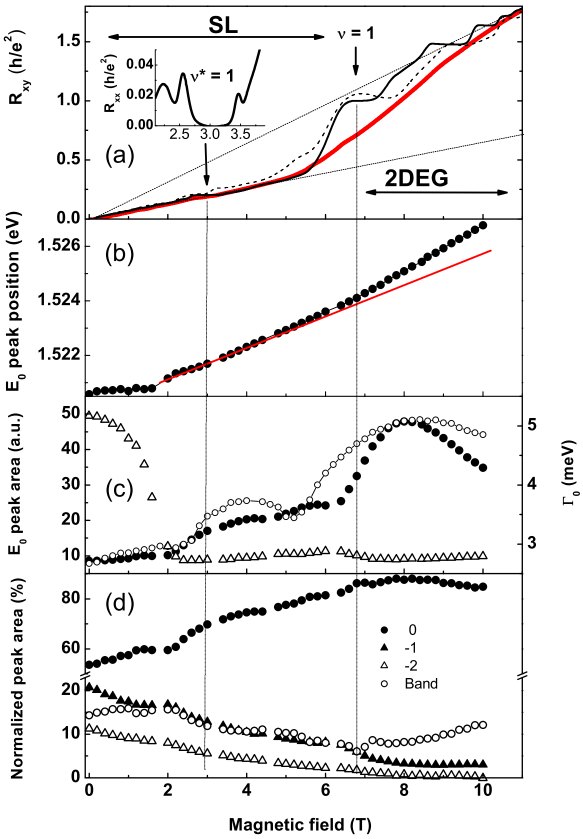

Fig. 3: (Color online) (a) Hall resistances measured in the superlattice with $\delta = 1.4$ at $T = 0.08\,\mathrm{K}$ (black line) and $T = 0.95\,\mathrm{K}$ (thick red line) and in the superlattice with $\delta = 2.3$ at $T = 0.08\,\mathrm{K}$ (black dashed line). Indicated are the quantized Hall states $\nu^* = 1$ and $\nu = 1$ formed in the superlattice and in the central well, respectively; insert shows resistance R_{xx} in the range of $\nu^* = 1$. (b) Energy position of the PL line from the central well (E_0) measured as a function of the magnetic field. Red straight lines show the Landau level slopes in different magnetic field ranges. (c) Width (triangles), integrated peak intensity (solid circles) of the PL line from the central well and integrated intensity of the PL line from the central well of the superlattice with $\delta = 2.3$ (open circles) measured as functions of the magnetic field. (d) Normalized integrated PL peak intensities from the lateral wells measured as functions of the magnetic field. The peak labels correspond to the well numbers l in fig. 1.

the wells were distinguished in this sample [15]. In a low magnetic field the SL responds as a stack of independent quantum wells connected in parallel [18]. In this case, the miniband quantum Hall state $\nu^* = 1$ with nearly uniform distribution of the electron density over eight wells is formed. The zero resistance R_{xx} corresponding to this state shown in insert to fig. 3(a) proves uniform occupation of the quantum wells. The quantum Hall state observed in a strong magnetic field at $\nu = 1$ corresponds to a single quantum well. The transition between these two phases is manifested in a change of the slope of the Hall resistance, which shows that in the high-field phase 50% of conducting electrons are confined in the central well. At the same time, the rest of the electrons is localized in the peripheral wells and do not contribute to the conductivity. The conclusion about the existence of two quantum phases was based on the observation of two distinct slopes of the Hall resistance. Identical Hall resistance data were observed in both disordered SLs [15]. However, the interlayer disorder resulted in a broader transition between two quantum Hall phases.

The energy of the PL peak from the central well (E_0) associated with the lowest LL, measured in the SL with $\delta = 1.4$, is shown in fig. 3(b). The slope of the LL increases when the magnetic field is increased past the filling factors $\nu = 1$. Several reasons may result in the observed LL slope change. The increasing LL slope may be caused by decreasing the effective mass associated with the formation of new quantum Hall phase. Also, the Coulomb energy of the electron-electron interaction significantly contributes to the energy of a correlated ground state and it is defined by the magnetic length. Therefore, the observed raise in the PL peak energy may be a manifestation of a correlated state. Similar changes in the slopes of the energies of the PL peaks from the wells neighbor to the central well were found.

In order to examine the density of electron states in each well, the integrated PL line intensities (the PL peak areas) were determined. It is worth mentioning that the integrated intensities cannot be attributed to absolute values of electron densities because of the different alloy scattering in the wells. However, relative variations of the electron densities may be evaluated. The width of the PL line from the central well (Γ_0) depicted in fig. 3(c) drops with the increasing magnetic field due to the Landau quantization. In a strong magnetic field, when the LLs are well separated, the line width remains almost unchanged. Therefore, in this range of the magnetic field a variation of the integrated PL intensity may be related to the corresponding variation of the density of the occupied electron states. As shown in fig. 3(c), the occupation of the central well shows a non-monotonic behavior with the magnetic field. The integrated PL intensity rises at the magnetic field $B = 2T$, related to the beginning of the Landau quantization. This rise is likely due to the redistribution of the electrons over the quantized density of states. The second stronger rise of the integrated PL intensity takes place at the magnetic field corresponding to the range where the transition between two slopes of the Hall resistance was found (fig. 3(a)). Following ref. [15], we suggest that in the low-field phase (below 6 T) the electrons are nearly uniformly distributed over the wells and, therefore, all eight wells connected in parallel contribute to the conductivity of the sample. In the high-field phase only the electrons in the central well determine the conductivity of the sample, while in the lateral wells the electrons are localized and do not contribute to the conductivity. According to the magneto-PL data, in the high-field phase the electron density in the central well increases by a factor of five. Consequently, in the high-field phase the total conductivity of the sample should roughly decrease by a factor of 8/5 = 1.6. This estimation is in reasonable agreement with the two-fold changes in the observed slope of the Hall resistance.

The relative distribution of the electron density over the wells is represented by the integrated peak intensities normalized to the total area of all the PL lines shown in fig. 3(d). They demonstrate a magnetic field induced redistribution of the electrons from the peripheral wells to the central well, with a subsequent charge buildup established within the wells in the quantum limit ($\nu = 1$). As shown above, the large enhancement of the electron density in the central quantum well, observed at the filling factor $\nu = 1$, associated with the corresponding increase in the PL intensity, matches well the related variation of the slope of the Hall resistance. This is the manifestation of the same origin of both effects observed in PL and in magnetoresistance. In a strong magnetic field, enhancement of the electronic charge in the centre of a wide PQW caused by the exchange-correlation effects was indeed predicted by the theory [21]. Apparently, as postulated in refs. [6–11], the observed magnetic field driven redistribution of the electron density relies on the negative exchange and correlation energies being larger that the positive kinetic and Hartree energies, which is favorable in the quantum limit. Moreover, the magnetic field driven interwell charge transfer caused by exchange-correlation energy has been observed in double and triple quantum wells in refs. [22,23]. We believe that forces driving the interwell charge transfer observed in our multiple wells have the same origin. According to theory, the exchange-correlation energy is anticipated to determine the ground state of multiple wells when $d/l_B \simeq 1$ [11], where l_B is the magnetic length. Indeed, in the structures studied here this ratio is about unit at $\nu = 1$.

It ought to be mentioned that the electrostatic fields may cause the redistribution of the electrons over the random quantum wells due to the accommodation of the Fermi level in the magnetic field. Such effect must result in a stronger redistribution of the charge in more disordered SLs. However, as shown in fig. 3(c), the integrated intensities of the PL lines from the central wells in SLs with the disorder strengths $\delta = 1.4$ and $\delta = 2.3$ demonstrate the same variations with the magnetic field. This agrees with the equal variations of the slopes of the Hall resistances observed in both SLs in ref. [15]. Furthermore, as shown in fig. 3(a), the transition between two phases determined by the different Hall resistance slopes becomes broader with the increasing interlayer disorder. As a consequence, the onset of the peak intensity increase observed at $\nu = 1$ shifts to the lower magnetic field. Thus, the magneto-PL data were found consistent with the results of magneto-transport measurements and again, this points to the same origin of the changes in the slope of Hall resistance and of the magnetic field induced PL intensity, that is the exchange-correlation energy.

In summary, the wide PQWs modulated by artificially disordered SL potentials were studied to probe the ground electron state of the quasi-3DEG in a strong perpendicular magnetic field. We demonstrated that the PL peak intensities emitted by the individual quantum wells can be used to directly observe a spatial distribution of the density of electron states within the 3DEG. As a result, the magnetic field induced redistribution of the electron charge confined in the wells of the weakly coupled multi-layers was observed. As expected, in a weak magnetic field the multiple electronic layers respond as a stack of isolated wells, representing the miniband quantum Hall state $\nu^* = 1$. However, a higher magnetic field forces the electrons to occupy the central well resulting in the formation of the new quantum phase. According to the theory, in a strong magnetic field, the electrons in the coupled multiple-layer electron systems undergo a quantum phase transition at $\nu = 1$, caused by the exchange and correlation energies. Such transition manifests itself in additional modulation of the charge in the direction of the magnetic field. The presented results show that the observed magnetic field driven redistribution of the charge density over individual wells of the SL may be attributed to this additional charge modulation. The agreement observed between PL and transport measurements supports this conclusion. The demonstrated quantum phase transition may be of some type of the above-discussed transitions predicted in multiple quantum wells. At last, we propose the multi-component electron system with tunable parameters, which can be successfully used to study the effects of electron-electron interactions in the 3DEG.

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