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Transition from a single- to double-quantum-well magnetotransport in the p-GeSi/Ge/p-GeSi heterosystem

M. V. Yakunin†, G. A. Alshanskii†, Yu. G. Arapov†, O. A. Kuznetsov‡ and V. N. Neverov†
† Institute of Metal Physics RAS, Ekaterinburg, GSP-170, 620219, Russia
‡ Scientific-Research Institute at Nizhnii Novgorod State University, Russia
e-mail: yakunin@imp.uran.ru

Abstract. As revealed from the high field low temperature magnetotransport measurements, the joint quasi two dimensional hole gas with the density $p_s = (3-5) \times 10^{15}$ m^{-2} exists in a p-GeSi/Ge/p-GeSi quantum well up to the Ge layer widths $d_w \lesssim 25$ nm, but it separates in two sublayers located at the well's sidewalls at $p_s \approx 5 \times 10^{15}$ m^{-2} and $d_w \gtrsim 35$ nm. The sublayers have approximately equal resistances indicating similarity of the normal and inverted interfaces in this heterosystem. The recently discovered quantized Hall insulator phase was detected here only in the intermediate range of sublayer separations, yielding evidence that the intersublayer correlations are important to stabilize this state.

A system of two closely spaced two-dimensional (2D) layers — a double quantum well (DQW) — creates an intriguing new physics since the distance between the layers can be made comparable or less than an average distance between free carriers within a single layer. Under these conditions the interlayer correlation effects may be stronger than the intralayer ones. A picture of Landau levels in a DQW system differs considerably from that in a single 2D layer reflecting the following essentials.

(1) If the two layers are close enough, the tunneling between them results in a gap (Δ_{SAS}) between the generalized DQW symmetric and antisymmetric levels; each of these levels generating its own fan of Landau levels.

(2) The combination of intra- and interlayer correlations modifies the gap; this effect depends on magnetic field. The tunneling and correlations, acting in concert, can either enhance or destroy the gap. Consequently, the Landau levels of a single 2D layer would be split in the DQW system into doublets each presenting a combination of symmetric and antisymmetric levels. In high enough magnetic fields, such that the orbital and Zeeman splittings exceed Δ_{SAS}, and in sufficiently perfect samples able to satisfy the condition that the level width is smaller than the gap, the first integer quantum Hall (QH) state would relate to the gap between the lowest split-off levels, i.e. to the resultant gap in a DQW, the same being for all the odd numbered QH states. Thus the odd QH states can serve as a tool for exploring the gap in a DQW system. The situation is unique in that the gaps between magnetic split-off levels do not necessarily increase with field. Just this case was observed in [1] where the odd numbered QH states, although quite distinct in the intermediate field range, collapsed in the high fields. On the other hand, the interlayer correlations may create a gap even when the single electron gap Δ_{SAS} is absent (the case of infinitely high but narrow barrier), although this gap is easily destroyed by the increasing temperature or by the in-plain magnetic field [2].

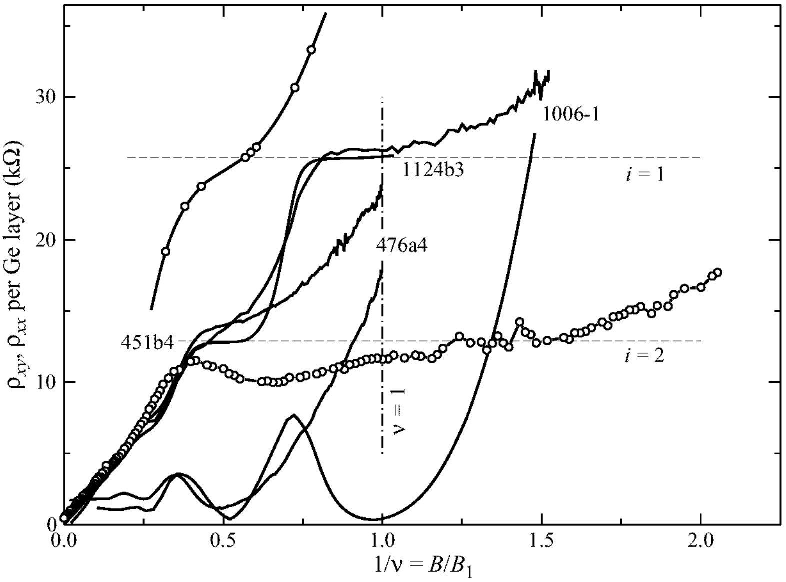

Fig. 1. The Hall and longitudinal magnetoresistances *vs* inverse filling factor.

The other feature of the DQW is the ability to stabilize the hardly achievable or even forbidden states of 2D electron gas (2DEG) due to additional degree of freedom stemming from the possibility for the carrier to locate in each of the coupled wells. So the $\nu = 1/2$ fractional QH effect state, a forbidden state in a single 2DEG, was observed in a DQW [3]. Also a transition into an insulating phase, probably into a Wigner crystal, was achieved in a DQW under conditions for which it has never been observed in a single 2DEG [4].

Deliberately introducing a barrier into the well is not the only way to create a DQW system. A similar physics can be realized in a sufficiently wide and intensively populated single well [5]. The idea is when electrons are introduced in a wide QW, the electrostatic repulsion between the electrons forces them into a stable configuration in which two 2DEG's are formed at the wall wells. A major advantage of this system over a conventional DQW is the minimization of alloy scattering since the barrier between the two 2DEG's is of the same material, it's not a heterointerface. Also, both Δ_{SAS} and inter-sublayer distance can be changed with varying the carrier density in the well.

So far almost all of the researches in the DQW were performed in the electron systems. The hole system offers some new properties in the DQW, particularly the large value of the heavy hole mass allows to achieve easily the configuration with Coulomb coupled hole gases without tunneling between them.

We performed low temperature high magnetic field ($B \leq 30$ T) measurements of the resistivity and Hall voltage in a series of multilayered p-$Ge_{1-x}Si_x$/Ge heterostructures differed by the Ge layer width (which is the QW for holes) in the range $d_w = 12{-}40$ nm, and by the hole densities per single Ge layer $p_s = (1{-}6) \times 10^{15}$ m^{-2}. The structures were grown by the vapor deposition and selectively doped with boron in the central parts of the $Ge_{1-x}Si_x$ barriers. The barriers were sufficiently wide to avoid the inter-Ge-layer tunneling. The low temperature hole mobilities were in the range 1–1.4 m^2/V·s.

Data for four samples are presented in the Fig. 1. The sample parameters are depicted in Fig. 2, additionally for the sample 1124b3: $p_s = 2.8 \times 10^{15}$ m^{-2}, $d_w = 20$ nm. For the

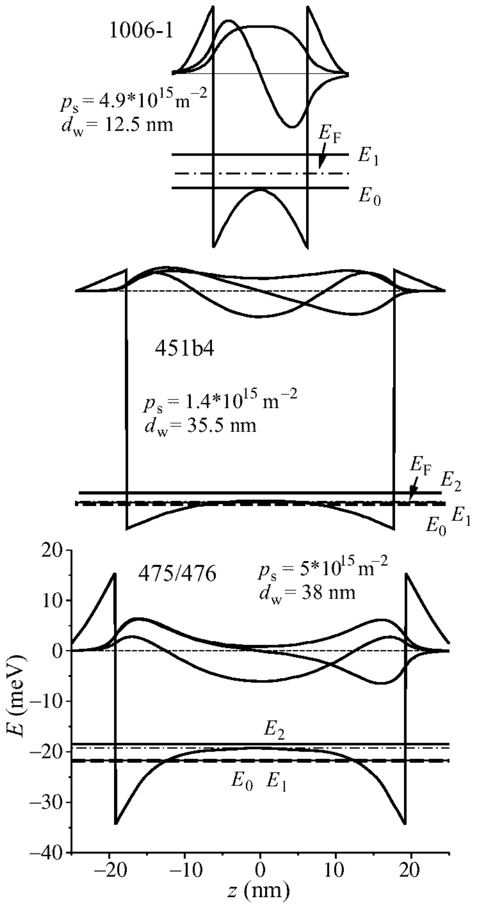

Fig. 2. Calculated potential profiles, energy levels and wave functions of the samples researched.

samples 1006 and 1124, with the narrowest Ge layers (12.5 and 20 nm), a usual QH picture was obtained: the plateaus in $\rho_{xy}(B)$ at integer filling factors $i \geq 1$ (per single Ge layer) and concomitant minima in $\rho_{xx}(B)$. A similar picture was obtained for the samples with the widest Ge layers and highest hole densities: $d_w = 38$ nm and $p_s = 5 \times 10^{15}$ m^{-2} (sample 476 in Fig. 1; we have examined a group of 4 similar samples and obtained similar results), but with an essential difference: the QH state for $i = 1$ was absent here. Considering that the spin splitting in the valence band of 2D Ge is as high as nearly a half of the orbital one [6] and that the $i = 1$ QH state is well resolved in the narrow well samples, the missing of the $i = 1$ QH state in the wide wells means unambiguously that conductivity in each Ge layer is via two parallel 2D sublayers here. That the first plateau on the high field side is close to the fundamental value $\rho_{xy} \approx h/2e^2$ means that the two sublayers in a Ge layer have approximately *equal* resistances $\rho_{xy} \approx h/e^2$. This result is surprising on the background of similar researches in a wide GaAs/Ga$_{1-x}$Al$_x$As QW [7] where up to 40 times difference in mobility was obtained for electron sublayers located at the normal and inverted interfaces. Bad mobility near the inverted interface was attributed to the scattering on Si dopands floated up from the lower Ga$_{1-x}$Al$_x$As barrier during the growth. Our results on the QH effect indicate that it is possible to grow a $Ge_{1-x}Si_x$/Ge system so that the effects of the boron dopant floating up are negligibly weak and both the normal and inverted interfaces of the Ge layer are similar. The multilayered structure of our samples may help the high symmetry of the wells [8]. Although some deviations of the $\rho_{xy}(B)$ plateau from the $i = 2$ horizontal and its finite slope may be attributed to some inequality of sublayers. Also approximately 20% positive magnetoresistance in the weakest fields has been observed only in this group of samples indicating the participation of two kinds of carriers with slightly different mobilities and densities.

The most unusual results were obtained on a group of three samples within the intermediate range of sublayer separations: $d_w = 34$–41 nm, comparable with the previously described sample group, but with lower hole densities $p_s = (1$–$2) \times 10^{15}$ m^{-2}. Each of these samples exhibited bistable behavior. In one of their two metastable states a weak $i = 1$ QH peculiarity was present (see sample 451b4 in Fig. 1) concomitant with the weak $\rho_{xx}(B)$ minimum, while an extremely wide plateau was revealed in the second metastable state in $\rho_{xy}(B)$ close to the value 13 kΩ, which corresponds to $i = 2$. We interpret the latter as a manifestation of a double layer quantized Hall insulator state stabilized by the interlayer correlations [9].

The potential profile of the QWs together with the energy levels and wave functions were calculated self consistently from a system of Schrödinger and Poisson equations — see Fig. 2. In general, these results confirm our explanations. For the sample 1006 all the levels are higher than the bottom bending amplitude, and the ground wave function is uniformly distributed within the well. On the contrary, in the samples 475/476 the two lowest levels E_0 and E_1 coincide and their wave functions are confined within triangular wells close to the well walls. Only the third level E_2 corresponds to the state extended through the whole layer width, but the Fermi energy is lower than this level.

In the intermediate case, for the sample 451, the first two levels E_0 and E_1, as well as the Fermi level, are lower but very close to the bottom bending amplitude. Even for the level E_0 the wave function Ψ_0 is far from zero in the center of the well. The differences from the samples 475/476 are due to much lower hole density in the well. All these features indicate the possibility for existence of two coupled hole sublayers in the Ge layer. Considering the big hole mass, even a lowest barrier suppresses tunneling that is reflected in the small splitting between E_0 and E_1 levels. But a small depth of a Ψ_0 minimum in the center of the well indicates that the effective distance between the sublayers might be small enough for the interlayer correlations were substantial.

Acknowledgements

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