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Quantum bistability in a quasi bilayer hole system formed in wide potential wells of p-GeSi/Ge MQW heterostructure

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Abstract. Spontaneous switching between two stable states has been observed in the high field low temperature magnetotransport of wide potential well p-GeSi/Ge multilayered heterostructures in which the Fermi energy is comparable to the amplitude of the well bottom bending. These two states exist in broad ranges of temperatures and currents and look like the quantum Hall state for double layer system and the classical single layer state.

A system of two interacting 2D layers is an intriguing object for investigation of the quantum Hall regime magnetotransport in view of an additional degree of freedom arising here. On the other hand, such an object is closely connected with the problem of wide potential wells in selectively doped heterosystems since the well bottom bending that exist in these structures may lead to separation of the quasi-2D gas in the well into two gases located at the opposite potential walls. This may happen when the Fermi level lies lower than the bottom bending amplitude.

In our previous works [1] the quantum magnetotransport has been studied in the quasi 2D hole gas of wide potential well p-GeSi/Ge multilayered heterostructures and the quasi-two-dimensionality was manifested in that the second heavy hole confinement subband participated in kinetics leading to considerable changes in the structure of quantum Hall and magnetoresistivity curves. These heterostructures were selectively doped but there was a moderate value of the bottom bending so that the hole gas in the well could be treated as undivided. The latter manifested particularly in the existence of a wide quantum Hall plateau at $\rho_{xy} = 25.8 \text{ K}\Omega$ corresponding to the filling factor $\nu = 1$ for the whole gas in the well. In this communication we describe the results obtained in a similar p-GeSi/Ge multi-quantum-well (MQW) heterostructure, but with wider wells, that we cannot explain in terms of a single hole gas.

We measured longitudinal $\rho_{xx}(B)$ and Hall $\rho_{xy}(B)$ magnetoresistances in a set of CVD grown multilayer samples with a following structure: substrate Ge(111)/buffer Ge $\sim 1.8 \mu\text{m}$ /buffer $\text{Ge}_{1-y}\text{Si}_y$, $0 \div 1.6 \mu\text{m}/\text{N} \times (\text{Ge}/\text{Ge}_{1-x}\text{Si}_x\text{B})$. Thickness' of Ge and GeSi layers in a multilayer region were approximately equal and varied from sample to sample in a range of $d = 100 \div 400 \text{ \AA}$. The GeSi layers were doped with boron in the central part with undoped spacers of $\sim 1/4$ the total layer thickness left on theirs both sides. In the range of $d = 100 \div 300 \text{ \AA}$, $y \approx 0.07$, $x = 0.07 \div 0.10$, hole densities $p_s = (2.8 \div 5) \cdot 10^{11} \text{ cm}^{-2}$ and mobilities $\mu = 10000 \div 15000 \text{ cm}^2/\text{V}\cdot\text{s}$ a single stable state was observed with distinct manifestations of integer quantum Hall effect (QHE) [1].

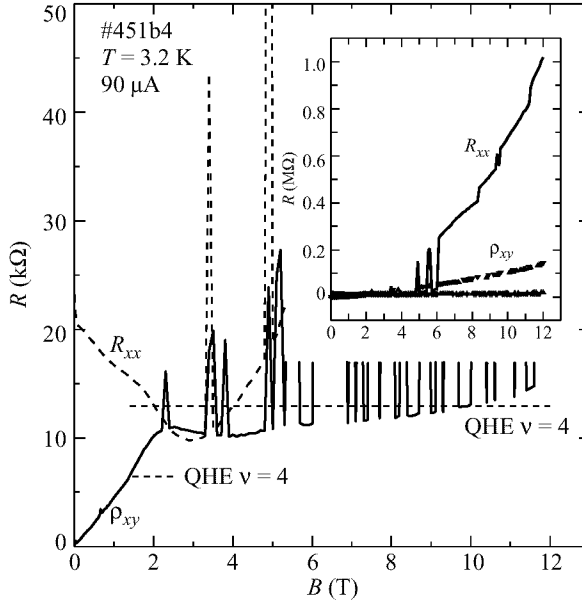


Fig 1.

Just another result was observed recently in a sample 451b4 with a wider well $d = 355 \text{ \AA}$ and notably lower 2D hole density $p_s = 1.4 \cdot 10^{11} \text{ cm}^{-2}$ (other parameters: number of repetitions $N = 36$, $y \approx 0.087$, $x = 0.097$, and $\mu = 14000 \text{ cm}^2/\text{V}\cdot\text{s}$): Fig. 1. In the weak field region again the single state is observed with features of the QHE: weak plateau $\rho_{xy} \approx 6.5 \text{ K}\Omega$ (close to the value for $\nu = 4$) and corresponding minimum in $\rho_{xx}(B)$ at $\sim 1.3 \text{ T}$. Then in $B \gtrsim 2 \text{ T}$ the strong plateau shows up in $\rho_{xy}(B) \approx 11 \div 13 \text{ K}\Omega$ (close to the value of $12.9 \text{ K}\Omega$ for $\nu = 2$) concomitant with the deep minimum in ρ_{xx} at $B = 3 \text{ T}$. At fields $B > 2 \div 3 \text{ T}$ the unstable behavior of experimental data begins. The most exiting feature (to our minds) is that the experimental points in this region are apparently grouped on two smooth curves: see Fig. 2. The first curve is the prolongation of the QH plateau that started at $\sim 2 \text{ T}$ with very weak magnetic field dependence slightly enhanced in the highest fields region. The second curve is the prolongation of the weak field curve, which extrapolates to zero with $B \rightarrow 0$ and monotonously depends on field with a slope much higher than that of the first curve. In the experiment the cause of the switching from one state to another is the change in polarity of dc current. Important is that data for both current polarities exist on each of the two split-of curves (see up and down triangles on the figure). Therefore the splitting of the data is not a manifestation of any asymmetry in the sample (e.g. in contacts) but switching the current polarity is simply an impact transforming the sample from one stable state to another one. Grouping of the points on the *smooth* curves means that the sample is in a stable state during measurements in a fixed field at a fixed current polarity. Then the current polarity is changed and the sample changes into another state or remains in the same state. In the field range where the intensive instabilities in $\rho_{xy}(B)$ exist the magnetoresistivity curve $\rho_{xx}(B)$ also reveals bistable behavior which transforms into sharp stepwise increase (see the insert in the Fig. 1) implying the break

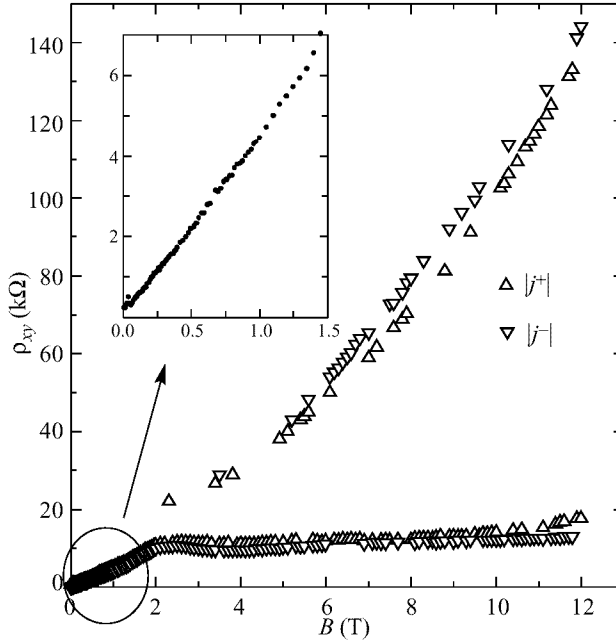


Fig 2.

up of the QHE. But we observed this bistable behavior at the current densities as low as ~ 45 mA/m that seems too low for the break up effect. The effect was observed without considerable changes in the range of currents $0.1 \div 100 \mu\text{A}$ and temperatures $1.6 \div 4.2$ K.

Among the samples we investigated earlier [1] simple estimations predicted that for one of them, #1003, the Fermi level must be close to the well bottom bending amplitude u_0 . Let's compare estimations for the sample #451b4 and those for #1003. For the simplest case of the uniform hole gas distribution in the infinite well: $u_0 \propto p_s d$. For #1003: $p_s = 4.8 \cdot 10^{11} \text{ cm}^{-2}$ and $d = 220 \text{ \AA}$. So in the sample #451b4 u_0 is approximately $(1.4/4.8)(355/220) \approx 0.5$ of the value for #1003. The first confinement level E_1 in the well in the energy range outside the band edge relief is roughly $\propto d^{-2}$ that is 0.4 and the Fermi level $E_F - E_1 \propto p_s$ is 0.3 of that for #1003. On the basis of these estimations we can anticipate that in the sample #451b4 the Fermi level drops lower than the bending amplitude does. Therefore probable becomes the situation that the Fermi level falls into the energy range corresponding to two potential wells in a single Ge layer and some quasi-double-layer behavior of the whole sample might be expected.

While the QH plateau for $\nu = 2$ is distinctly observed in #451b4 there is not a hint for the existence of the $\nu = 1$ peculiarity. Neither there is a minimum in $\rho_{xx}(B)$ at $B > 3$ T [in spite of instabilities the monotonous background in $\rho_{xx}(B)$ is still seen at $B \approx 6$ T where the minimum for $\nu = 1$ is expected] nor a plateau in $\rho_{xy}(B) > 13 \text{ K}\Omega$ exist. On this basis we conclude that the plateau in $\rho_{xy}(B)$ and the minimum in $\rho_{xx}(B)$ at $B \approx 3$ T are the manifestations of the number one peculiarity of the Integer QHE (counting from the high field side). In other words, this is the manifestation of QHE for the filling factor $\nu = 1$ but for twice the number of 2D layers: not for 36 layers

(= the number of Ge layers in the sample), but for $2 \times 36 = 72$ layers. Another evidence that the plateau corresponds to $\nu = 1$ is its big length, that is an indication of the delayed transition into a high field insulating phase. The value of the hole density $p_s = 1.4 \cdot 10^{11} \text{ cm}^{-2}$ in a Ge layer was obtained from the slope of $\rho_{xy}(B)$ in extremely low fields (see the insert in the Fig. 2). The position of ρ_{xx} minimum at 3 T yields the density of $\sim 0.7 \cdot 10^{11} \text{ cm}^{-2}$ in a single 2D layer (implying that it correspond to $\nu = 1$) indicating that there are two 2D sublayers in a Ge layer.

Some additional informational that may be useful in interpreting the phenomena observed. Investigations of the sample #399 of the same family as #451b4 but with narrow wells $d = 145 \text{ \AA}$ and lower hole density in a Ge layer $p_s \approx 0.5 \cdot 10^{11} \text{ cm}^{-2}$ have revealed that it is in the insulating phase at low temperatures (although in conducting state at temperatures $T \gtrsim 15 \text{ K}$). Therefore we can expect that separation of the hole gas inside the Ge layer of the sample #451b4 into two 2D sublayers may switch the sample into insulating phase since the effective thickness of a sublayer is less than a half the Ge layer thickness ($< 180 \text{ \AA}$) and a hole density in it is $\sim 0.7 \cdot 10^{11} \text{ cm}^{-2}$. We believe that transition into two-sublayer state when the Fermi level becomes lower than the band bending amplitude may be rather sharp for holes since their tunneling through the barrier will be weak due to big effective masses.

As it follows from our experiment, this transition as a matter of fact goes not into the insulating state but is limited by appearing of another conducting state. The monotonous, stemming from zero course of $\rho_{xy}(B)$ for this new state implies classical Hall effect and its slope in the weakest fields yields the hole density which is the double value obtained for the sublayer from the QHE in a first state. So we can establish that the sample in the fields $B \gtrsim 3 \text{ T}$ can exist in two states: (i) quantum Hall state with holes divided into two 2D sublayers in each Ge layer and (ii) classical state with undivided hole gas in a layer. As both of these states are metastable there must exist some self-stabilizing mechanism. Probably its essence is connected with the double sublayer potential structure itself. While the sublayers in a Ge layer are in balance with each other the first state exist. Going out of this balance drives the system into the state of a single conducting gas in a Ge layer and to destruction of the QH regime. This implies the change of the potential profile in the well probably due to the hole gas redistribution in the direction normal to the interface. The superlinear course of $\rho_{xy}(B)$ in the classical state indicates that some part of the hole gas is in the insulating phase and this part increase with field. The switching between two states must bear a collective character, i.e. to happen simultaneously in all the Ge layers otherwise the points would scatter far outside the smooth curves.

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References

- [1] Yu.G. Arapov et. al., *Proc. 11-th Internat. Conf. "High magnetic fields in the physics of semiconductors"*, Cambridge, USA, 1994, p. 632; *Semiconductors* (in press).