Hole quantum Hall effect in stressed Ge–$Ge_{1-x}Si_x$ superlattices

O. A. Kuznetsov and A. L. Chernov
Scientific-Research Physicotechnical Institute, Nizhniĭ Novgorod University, 603003, Nizhiĭ Novgorod

L. K. Orlov and R. A. Rubtsova
Institute of Applied Physics, Academy of Sciences of the USSR, 603600, Nizhniĭ Novgorod

Yu. G. Arapov, N. A. Gorodilov, and G. L. Shtrapenin
Institute of Metal Physics, Academy of Sciences of the USSR, 620219, Sverdlovsk

(Submitted 19 July 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **54**, No. 6, 351–353 (25 September 1991)

The hole quantum Hall effect has been measured in a stressed multilayer Ge–$Ge_{1-x}Si_x$ heterostructure.

The quantum Hall effect is a new and unique physical phenomenon, and it has attracted considerable research interest.[1] Previous studies of this effect have focused for the most part on heterostructures based on III–V compounds. Much less attention has been paid to *p*-type structures than to heterostructures with a 2*D* electron gas, despite the fact that the complex dispersion of the valence band may give rise to distinctive features in the quantum Hall effect.[2]

The first indication of a possible manifestation of this effect in such structures came from a study by Mironov *et al.*[3] The structures which they studied were selectively doped superlattices grown by a hydride method, with a periodic alternation of layers of undoped Ge, with a thickness $d_{Ge} \sim 5$–25 nm, and of a boron-doped solid solution $Ge_{1-x}Si_x$ with $x \sim 0.05$–0.15, with a thickness $d_{GeSi} \sim 20$–30 nm, with spacers ~ 5 nm thick. The mobilities of the holes in these structures hold the record for the Ge–Si system, reaching 15 000 $cm^2/(V \cdot s)$ at $T = 4$ K and at a density $\sim (1$–$3) \times 10^{17}$ cm^{-3} (the average over the sample). The structure of these samples, the nature of the doping, and their electrical properties in a weak magnetic field are described in more detail in Refs. 4 and 5.

The Hall measurements were carried out in the van der Pauw geometry on a rectangular superlattice sample containing 90 periods with $x = 0.11$, $d_{Ge} \simeq 26$ nm, and $d_{GeSi} \simeq 18$ nm. An estimate of the discontinuity of the bands at the heterostructures of this structure yielded ~ 50 meV. The curvature of the bottom of the valence band in the quantum well of the Ge layer due to the accumulation of free holes was on the order of 5 meV. The hole subbands in the Ge layers in a zero magnetic field were split by the elastic strain ($\epsilon_{xy} \sim 5 \times 10^{-4}$) and by the quantum size effect. The splitting energy was about 20 meV.

Magnetotransport measurements were carried out over the temperature interval 4.2–1.5 K in a magnetic field up to 13 T, directed perpendicular to the plane of the superlattice layers. The resistivities ρ_{xx} and ρ_{xy} are shown as a function of the magnetic induction B at $T = 1.5$ K in Fig. 1a. On these curves we see all the characteristics of the quantum Hall effect, which indicate the presence of a $2D$ hole gas in the system. The upper plateau on the ρ_{xy} curve, which is referred, within an error $\sim 3\%$, to a single quantum layer of Ge, corresponds to a filling factor $\nu = 2$. This result corresponds to a hole surface density ($n_s = \nu eB/h$) of 5×10^{11} cm^{-2}. On the $\rho_{xx}(B)$ curve we can clearly see Shubnikov oscillations, whose minima occur at positions corresponding to the positions of the plateaus on the $\rho_{xy}(B)$ curve. The value found for the surface density from the period of the Shubnikov oscillations, $n_s = eB_1B_2/h(B_2 - B_1) = 5 \times 10^{-2}$ cm^{-2}, agrees well with the value given above. The hole mobility found from the relation $\sigma = en\mu$ in this sample is $\mu = 14\,000$ cm^2/(V·s).

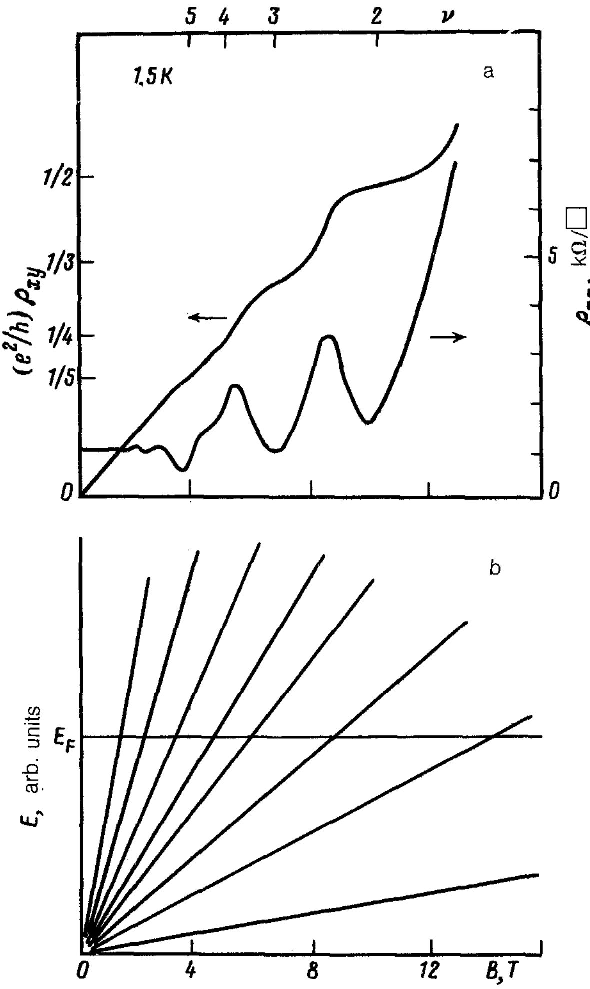

FIG. 1.

Note that ρ_{xx} does not vanish at the minima of the Shubnikov oscillations in these structures (for a filling factor $\nu = 2$ we have $\rho_{xx} = 870\ \Omega$). This result indicates a parallel metallic conductivity. An estimate of $\sigma^{\|}$ at the point $\rho_{xx}^{\min}$ yields $\sim 5.2 \times 10^{-6}$ S/cm. This value is lower than the limiting value for a metallic conductivity and indicates that a metal–insulator phase transition may be observed with increasing magnetic field and with decreasing temperature.

There are plateaus and oscillations on the $\rho_{xy}(B)$ and $\rho_{xx}(B)$ curves because of the quantization of the hole gas in the Ge layers of the superlattice. The positions of the energy levels are given by

$$E_{nj} = E_n + (j + \tfrac{1}{2})\hbar\omega_c \pm \tfrac{1}{2} g\mu_B B,$$

where n is the index of the quantum-size level, j is the level of the Landau subband, g is the Landé factor, μ_B is the Bohr magneton, and $\omega_c = eB/m$ is the cyclotron frequency. Calculations of the positions of the energy levels with respect to the Fermi energy E_F (Fig. 1c) indicate that only one upper quantum-size hole subband is filled in this sample ($E_1 < E_F < E_2$).

We thus see that heterosystems based on Ge and $Ge_{1-x}Si_x$, including superlattices, are extremely promising entities for research on the physics of 2*D* systems. On the other hand, a study of the quantum Hall effect can provide a wealth of information about the characteristics of samples with a 2*D* gas of free charge carriers.

We wish to thank E. A. Uskova and E. V. Kirillova for fabricating the contacts on the structures, B. A. Aronzon and O. A. Mironov for a fruitful collaboration, Yu. N. Drozdov for carrying out the x-ray study of the structures, and I. M. Tsidil'kovskiĭ and V. A. Volkov for a discussion of these results and for support.

[1]É. I. Rashba and V. B. Timofeev, Fiz. Tekh. Poluprovodn. **20**, 977 (1986) [Sov. Phys. Semicond. **20**, 617 (1986)].
[2]H. L. Stormer, Z. Schlesinger, A. Chang, *et al.*, Phys. Rev. Lett. **51**, 126 (1983).
[3]O. A. Mironov, S. V. Chistyakov, I. Yu. Skrylev, *et al.*, in: *Proceedings of the Fifth International Conference on Superlattices and Microstructures*, Berlin, 1990, P.Tu-Po-56.
[4]L. K. Orlov, O. A. Kuznetsov, Yu. N. Drozdov, *et al.*, Fiz. Tekh. Poluprovodn. **32**, 1933 (1990) [*sic*].
[5]L. K. Orlov, O. A. Kuznetsov, R. A. Rubtsova, *et al.*, Zh. Eksp. Teor. Fiz. **98**, 1028 (1990) [Sov. Phys. JETP **71**, 573 (1990)].

Translated by D. Parsons