Hall effect and characteristics of the energy band structure of selectively doped Ge–$Ge_{1-x}Si_x$ superlattices

L. K. Orlov, O. A. Kuznetsov, R. A. Rubtsova, A. L. Chernov, V. I. Gavrilenko, O. A. Mironov, V. V. Nikanorov, I. Yu. Skrylev, and S. V. Chistyakov

Physicotechnical Research Institute at the N.I. Lobachevski State University, Gorki and Institute of Radiophysics and Electronics, Academy of Sciences of the Ukrainian SSR, Kharkov
(Submitted 19 March 1990)
Zh. Eksp. Teor. Fiz. **98**, 1028–1034 (September 1990)

Selectively doped Ge–$Ge_{1-x}Si_x$ superlattices with ultrathin (down to 10 nm) layers were grown and investigated for the first time. The best (for the time being) values of the hole mobilities, reaching $\sim 15\,000\ cm^2 \cdot V^{-1} \cdot s^{-1}$, and bulk hole density $\sim 10^{17}\ cm^{-3}$ were attained in these heterostructures at $T \sim 1.6$–10 K. The dependences of the mobility on the Si content in $Ge_{1-x}Si_x$ films and on the external magnetic field revealed different types of carriers participating in the conduction process. For the first time it was shown experimentally that the p-type conduction along the planes of the superlattice layers in stressed heteroepitaxial Ge–$Ge_{1-x}Si_x$ structures was dominated by light carriers localized in Te. The results obtained for these heterostructures were compared with the data obtained by the Hall effect measurements carried out on homogeneous germanium superlattices with δ-like boron doping (also realized for the first time).

Studies of the Hall effect in selectively doped periodic heterostructures revealed a number of unique (from the point of view of technical applications) features of the behavior of the electron–hole gas in the system as a function of the applied magnetic field, of temperature, and of the type and nature of the dopant in the superlattice layer.[1]

The effect of a considerable increase in the electron mobility in selectively doped n^+-type Si–$Si_{1-x}Ge_x$ superlattices grown by the molecular beam epitaxy method was first investigated experimentally by Abstreiter *et al.*[2] They also proposed a method for using the Hall effect measurements to determine the nature of modulation of the edges of the energy bands in the periodic structure and, in particular, they showed for the first time that superlattices based on Si and $Si_{1-x}Ge_x$ have a covariant energy band structure, i.e., they belong to type II superlattices.[3]

The energy structure band in stressed Ge–$Ge_{1-x}Si_x$ superlattices was first discussed in Ref. 4. The earliest reports of an increase in the mobility of holes in these superlattices at $T \geqslant 77$ K were given in Refs. 5 and 6. The mobility of a two-dimensional hole gas localized in the vicinity of the heterojunctions in an n-Ge/p^+–$Ge_{0.5}Si_{0.5}$/n-Ge structure, grown by the molecular beam epitaxy method, was determined at temperatures $T = 4$–10 K (Ref. 7). However, relatively low values of the hole mobility $\lesssim 3200\ cm^2 \cdot V^{-1} \cdot s^{-1}$ were reported in Ref. 7.

We shall give the first results of an investigation of the Hall mobility of holes μ_H in selectively doped stressed Ge–$Ge_{1-x}Si_x$ superlattices at temperatures $1.6 \leqslant T \leqslant 77$ K. These superlattices were grown by the vapor hydride method on an n-type Ge sublayer of thickness ~ 2–3 μm deposited on a (111) n^+-type Ge substrate; their period was from 10 to 50 nm and the number of layers was up to 200. The solid-solution layers contained up to 20 at.% of silicon and were doped with boron atoms to a concentration $N_a \sim 10^{17}$–$10^{18}\ cm^{-3}$. The dopant was introduced to approximately half their thickness d_{GeSi}. The doped solid-solution regions in the superlattice were separated from the undoped Ge layers by spacers whose thickness was $\sim d_{GeSi}/4$. Such selective penetration of the impurity into the solid-solution layers was confirmed by a mass-spectrometric investigation.

The mobilities μ_H and the densities $\bar{p} = p_s / N d_{SL}$ of holes were determined using rectangular samples in a six-probe method described in Ref. 8. (Here, $d_{SL} = d_{Ge} + d_{GeSi}$ is the superlattice period and Nd_{SL} is the superlattice thickness.) The size-quantized magnetoresistance was allowed for in accordance with Ref. 9. The parameters of the investigated superlattices are listed in Table I.

TABLE I.

Parameter	Sample No.								
	1	2	3	4	5	6	7	8	9
x	0,108	0,18	0	0,09	0,06	0,028	0,022	0	0,137
$\bar{x}$	0,054	0,09	0	0,045	0,03	0,014	0,011	0	0,085
d_{SL}, nm	44	50	18	36	38	35	34	4200	29
p, $10^{17}\ cm^{-3}$ (77 K)	1,2	2,1	5,5	0,87	1,0	1,2	1,3	1,5	1,9
N	90	15	40	50	50	50	50	1	90
ΔE_v, meV	53	116	0	40	27	13	10	0	84

Note. Here, n is the number of superlattice periods and ΔE_v is the discontinuity of the valence band at the Ge–GeSi heterojunction.

 0038-5646/90/090573-04$03.00

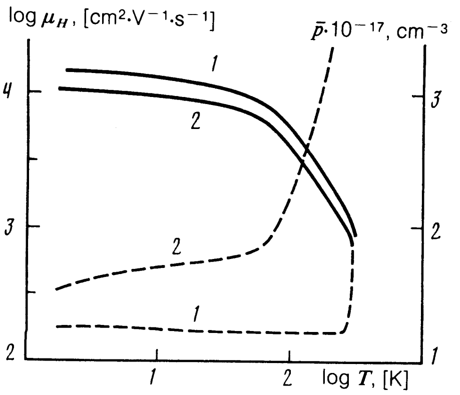

FIG. 1. Temperature dependences of the Hall mobility μ_H (continuous curves) and of the total density $\bar{p}$ (dashed curves) of holes in samples 1 (curves labeled 1) and 2 (curves labeled 2).

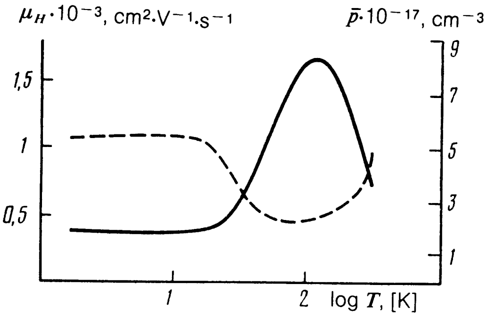

FIG. 2. Temperature dependences of the Hall mobility μ_H (continuous curve) and of the total density $\bar{p}$ (dashed curve) of holes in sample 3.

The temperature dependences of the hole mobilities and densities in heteroepitaxial superlattices (samples 1 and 2) were determined in the range 1.6–295 K (Fig. 1). The structure of sample 2 differed from the other superlattices because of the presence of a buffer n-type $Ge_{1-y}Si_y$ layer between the substrate and the p-type superlattice; the composition of this buffer layer was characterized by $y = xd_{GeSi}/d_{SL}$ and its thickness was $\sim 2\ \mu$m.

Free holes localized mainly in undoped Ge layers of the superlattice were scattered by impurity atoms, fluctuations of the potential, and lattice vibrations (mixed scattering). At temperatures above 77 K the scattering by the lattice vibrations was however predominant and it was responsible for the considerable rise of the Hall mobility of holes as a result of cooling. At temperatures below 77 K the rise of the Hall mobility in all the samples slowed down and this was due to an increasing role of other scattering mechanisms. The density of holes in the investigated structures (dashed curves in Fig. 1) remained practically constant below 200 K, manifesting the effectiveness of the mechanism of separation of mobile carriers from acceptor centers within one superlattice period.

A considerable increase in the density of holes at temperatures $T > 250$ K could be possibly due to the appearance of leakage currents flowing into the substrate because of a reduction of the barrier in the region of the p^+-n junction, or because of the presence of additional hole states in the region of localization of a dislocation network. This network formed in the vicinity of the p-n junction on the substrate side. The appearance of an additional conducting p^+-type channel near the p-n junction resulted in an underestimate of the values obtained near room temperature. In the range $T < 250$ K the holes were frozen out in this particular model and no longer participated in the conduction process.

The temperature dependences $\mu_H(T)$ and $\bar{p}(T)$ were of fundamentally different nature (Fig. 2) in the case of a homogeneous germanium superlattice of the p^+-i-p^+-i-... type, which was formed by introducing a periodic sequence of narrow ($\sim$1–10 nm) impurity (boron) layers into the growing i-type (intrinsic conduction) Ge film. Cooling in the range 100–300 K resulted in a monotonic reduction in the density of holes in such a homogeneous superlattice by a factor of approximately 2. Between 100 and 15 K the density of holes rose again and then remained constant up to 1.6 K. Estimates indicated that the amplitude of the potential barrier in this homogeneous superlattice was just 4 meV at 295 K and that it decreased as a result of cooling.

In the range 77–300 K the temperature dependence of the mobility of holes in such a homogeneous superlattice resembled the dependence $\mu_H(T)$ for homogeneously doped Ge, indicating that the mechanisms of carrier scattering were the same in both cases. The presence of undoped channels in a superlattice did however affect the mobility of holes in it. For a given density of holes the mobility in the homogeneous superlattice was slightly higher than in a thick homogeneous epitaxial Ge film. In the range 20–1.6 K the density of holes and their mobility along the layers in the homogeneously doped superlattice remained constant at the same values as found for the superlattice at room temperature. The temperature dependence $\mu_H(T)$ was typical of two-dimensional homoepitaxial structures with δ-like doping.[10]

Figures 1 and 2 show the averaged (over all the carriers in the superlattice) mobilities μ_H and the total densities of holes $\bar{p}$, given by

$$\mu_H = \frac{\sum_i p_i \mu_{Hi}^2 d_i}{\sum_i p_i \mu_{Hi} d_i}, \qquad \bar{p} = \sum_i p_i, \tag{1}$$

where $i = \{(l,h),j\}$ is the index used the label the charge carriers participating in the conduction process; $l(h)$ is the index of the hole subband; j is 1 and 2 for the Ge or GeSi layers, respectively; μ_{Hi} and p_i are the mobility and density of holes in a given modification; d_j is the thickness of the relevant layer.

In the case of the investigated structures when $x \sim 0.01$ and $N_a \sim 10^{17}$–10^{18} cm^{-3} we found that carriers in the solid-solution layers ($p_{(l,h),2} > p_{(l,h),1}$) predominated and that an important role was played by the scattering on impurity atoms. An increase in x reduced the density of holes in $Ge_{1-x}Si_x$ layers (and increased in the Ge layers) because of the change in the shape of the potential relief (Fig. 3b), which (at a given temperature) increased the mobility μ_H in the investigated structure. This was manifested clearly in the experiments at lower temperatures (see Fig. 3a; the experimental points are numbered in the same way as samples in Table I).

Calculations carried out for superlattices with the pa-

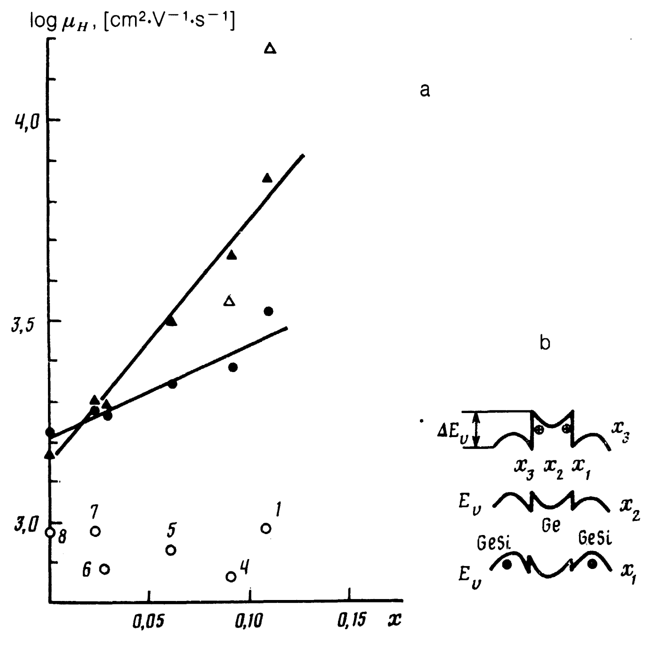

FIG. 3. a) Dependences of the mobility of holes μ_H on the Si content in solid-solution layers in $Ge-Ge_{1-x}Si_x$ superlattices (samples 1 and 4–8) recorded at different temperatures: ○) 295 K; ●) 150 K; ▲) 77 K; △) 4.2 K. b) Qualitative shapes of the top of the valence band of superlattices with different values of x.

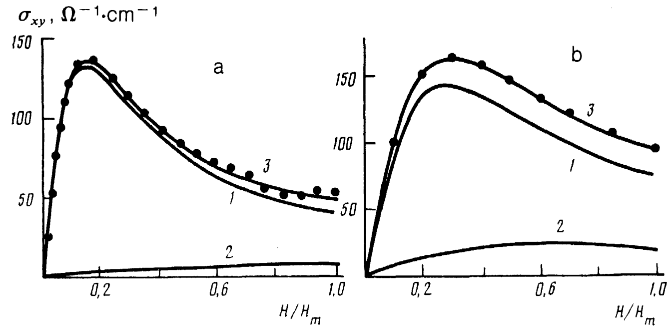

FIG. 4. Dependences of the transverse component of the conductivity σ_{xy} of samples 1 (a) and 9 (b) on the magnetic field (H_m is the maximum magnetic field applied to a given sample). The experimental results are represented by the points and the continuous curves are theoretical.

rameters $d_{Ge} = d_{GeSi} \approx 10$ nm, $N_a = 10^{18}$ cm^{-3}, and $0 < x < 0.2$ at 295 K demonstrated that practically right up to $x \sim 0.1$ the density of holes in the $Ge_{1-x}Si_x$ layers predominated over the density of holes in the Ge layers. This was due to the fact that the value of ΔE_v for a superlattice with $x \lesssim 0.1$ did not exceed $2kT$. In particular, in the case of sample 1 the amplitude of the potential relief was approximately 50 meV. Therefore, a slight change in the superlattice parameters and of the spacer thickness in $Ge_{1-x}Si_x$ layers resulted in a considerable scatter of the hole density in neighboring superlattice layers, which varied from one sample to another, so that there was a corresponding large scatter in the mobility μ_H averaged on the basis of Eq. (1). This, together with possible leakage at high temperatures to the lightly doped n-type Ge sublayer, prevented us from observing the above-mentioned dependence of μ_H on x at room temperature (Fig. 3).

The $Ge-Ge_{1-x}Si_x$ superlattices are structures with stressed layers whose characteristic feature, distinguishing them from the structures used in Ref. 7, is the splitting of the hole subbands in the Ge layers.[11] The number of carriers participating in the conduction process and differing in respect of the effective mass generally depends not only on the Si content in the $Ge_{1-x}Si_x$ layers, on the dopant concentration, and on the temperature of a sample, but also on the degree of degeneracy of the carrier gas and on the splitting energy of the subbands.

Different modifications of holes with different values of μ_{Hi} and p_i can be revealed at low temperatures by investigating the dependence of the conductivity component σ_{xy} of a superlattice on an external magnetic field H (Ref. 12). Figure 4 shows the experimental values of σ_{xy} obtained for samples 1 and 9 (see Table I) at $T = 4.2$ K. The continuous curves (curve 3 is the sum of curves 1 and 2) were obtained by optimization of the experimental data with the aid of the expression

$$\sigma_{xy} = \sum_i \frac{ep_iH}{H_i^2 + H^2}, \tag{2}$$

where $H_i \propto 1/\mu_{Hi}$. Curves 1 and 2 in Fig. 4 represent the h and l hole subbands[6] in the Ge layers of the superlattice. The densities and mobilities of holes p_i and μ_{Hi}, and the total density $\bar{p}$ as well as the average mobility μ_H, measured in a weak magnetic field, are all listed in Table II. Our results indicated that at low temperatures the holes in $Ge-Ge_{1-x}Si_x$ superlattices with $x \geqslant 0.1$ are localized in the solid-solution layers and do not contribute to the mobility μ_H of the system as a whole.

At liquid helium temperatures the longitudinal transport of the charge involves two types of carrier: light and heavy holes localized in the Ge layers (Fig. 4). The holes with the heavy (light) effective mass (l subband) along (across) the superlattice layers are shifted downward on the energy scale relative to the subband h with light (heavy) holes because of lifting of the degeneracy due to deformation.[6] The light (along the superlattice layer planes) holes dominate the conduction process in the system and are responsible for the relatively high values of the mobility of the hole gas at low temperatures.

The slight discrepancy between curve 3 in Fig. 4a and the experimental values of σ_{xy} is due to superposition of weak Shubnikov–de Haas oscillations on a classical curve; these oscillations appeared in the case of sample 1 even in magnetic fields which were not too strong. The oscillations were manifested more clearly in the dependence of the electrical resistivity ρ_{xx} on the magnetic field plotted in Fig. 5.

The stressed $Ge-Ge_{1-x}Si_x$ superlattices are characterized by much higher values of the mobility in the two-dimensional hole gas than the mobility in heterostructures with unstressed Ge layers.[7] In the absence of deformation the size quantization of holes in narrow channels near the heterojunctions lifts the hole subband degeneracy. Consequently, at low temperatures the longitudinal transport involves mainly heavy holes and this is the reason why the electrical characteristics of the system are relatively poor.

The strong deformation of the Ge layers in the superlattice (in our case the influence of the substrate was weakened by the presence of a plastic deformation region at the super-

TABLE II.

Sample No.	H_m, T	$\bar{p}\cdot10^{-17}$, cm^{-3}	μ_H, cm$^2\cdot$V$^{-1}\cdot$s^{-1}	$p_{hl}\cdot10^{-17}$, cm^{-3}	μ_{Hhl}, cm$^2\cdot$V$^{-1}\cdot$s^{-1}	$p_{ll}\cdot10^{-17}$, cm^{-3}	μ_{Hll}, cm$^2\cdot$V$^{-1}\cdot$s^{-1}
1	4,73	1,21	14 400	1,21	14 200	0,137	1060
9	2,78	1,88	12 100	1,44	12 900	0,44	6500

lattice/Ge heterojunction on the substrate side) not only results in splitting of the hole subbands, but is also responsible for a strong anisotropy of the effective masses of the carriers.[13] Holes in the upper h subband of the valence band of Ge have a mass which is almost an order of magnitude heavier across the layer planes than holes in the lower l subband. Therefore, size quantization should increase even more the splitting of the hole subbands. However, our results indicate that the mass of holes in the upper h subband in Ge layers along the planes of growth of the structure is relatively small (it is close to the mass of light holes in unstressed Ge). This explains why the mobility of holes observed by us at liquid helium temperature is considerably higher than the values reported in Ref. 7.

We thus demonstrated experimentally for the first time that holes, more mobile along the layer planes in a stressed Ge–Ge$_{1-x}$Si$_x$ superlattice, are localized in the upper (h) valence subband of the Ge layers. The splitting energy of the subbands considered as a function of the structure is estimated to range from 1 meV to several tens of millielectron-volts. The heating of holes by an electric field directed along the superlattice layers can redistribute them between the h and l subbands,[6] which results—as found for uniaxially deformed Ge (Ref. 14)—in the appearance of a falling region in the current-voltage characteristics.

Such a negative differential conductance region in the current-voltage characteristics for a current flowing along the superlattice layers may appear also because of transverse diffusion of carriers out of the high-mobility Ge layers to the neighboring doped solid-solution layers characterized by a low hole mobility.[15,16]

The authors are grateful to V. M. Vorotyntsev for supplying high-purity germanium, to A. V. Kozhukhov for mass-spectrometric investigations, and to I. A. Elipashev for his help in numerical calculations.

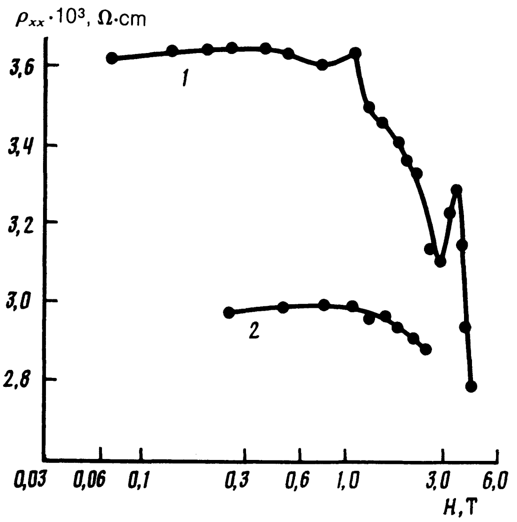

FIG. 5. Dependences of the electrical resistivity ρ_{xx} on the magnetic field applied to samples 1 (curve 1) and 9 (curve 2).

[1] A. C. Gossard, IEEE Trans. Electron Devices **ED-29**, 1659 (1982).
[2] G. Abstreiter, H. Brugger, T. Wolf *et al.*, Phys. Rev. Lett. **54**, 2441 (1985).
[3] M. A. Herman, *Semiconductor Superlattices* [Russian translation], Mir, Moscow (1989)
[4] Z. F. Krasilnik, O. A. Kuznetsov, and L. K. Orlov, Proc. Nineteenth Intern. Conf. on Physics of Semiconductors, Warsaw, 1988 (ed. by W. Zawadzki), Vol. 1, Institute of Physics, Polish Academy of Sciences, Warsaw (1988), p. 503.
[5] L. K. Orlov, O. A. Kuznetsov, G. N. Gorshenin, R. A. Rubtsova, and A. L. Chernov, Proc. First All-Union Conf. on Physical Basis of Solid-State Electronics, Leningrad, 1989 [in Russian], p. 214.
[6] L. K. Orlov, O. A. Kuznetsov, and R. A. Rubtsova, Pis'ma Zh. Tekh. Fiz. **15**(21), 77 (1989) [Sov. Tech. Phys. Lett. **15**, 863 (1989)].
[7] G. R. Wagner and M. A. Janocko, Appl. Phys. Lett. **54**, 66 (1989).
[8] V. L. Kon'kov, Fiz. Tverd. Tela (Leningrad) **6**, 304, 308 (1964) [Sov. Phys. Solid State **6**, 244, 247 (1964)].
[9] N. I. Pavlov and Yu. I. Yakunin, Fiz. Tekh. Poluprovodn. **12**, 1577 (1978) [Sov. Phys. Semicond. **12**, 930 (1978)].
[10] K. Ploog, M. Hauser, and A. Fischer, Appl. Phys. A **45**, 233 (1988).
[11] L. K. Orlov, O. A. Kuznetsov, and Yu. N. Drozdov, Fiz. Tekh. Poluprovodn. **21** 1962 (1987) [Sov. Phys. Semicond. **21**, 1188 (1987)].
[12] D. L. Leslie-Pelecky, D. G. Seiler, M. R. Lololee, and C. L. Littler, Appl. Phys. Lett. **51**, 1916 (1987).
[13] G. L. Bir and G. E. Pikus, *Symmetry and Strain-Induced Effects in Semiconductors*, Israel Program for Scientific Translations, Jerusalem; Wiley, New York (1975).
[14] A. A. Kastal'skiĭ and S. M. Ryvkin, Fiz. Tekh. Poluprovodn. **1**, 632 (1967) [Sov. Phys. Semicond. **1**, 523 (1967)].
[15] Z. S. Gribnikov, Fiz. Tekh. Poluprovodn. **6**, 1380 (1972). Sov. Phys. Semicond. **6**, 1204 (1973)].
[16] K. Hess, Proc. Eighteenth Intern. Conf. on Physics of Semiconductors, Stockholm, 1986, in Physica B + C (Utrecht) **118**, 723 (1983).

Translated by A. Tybulewicz