Longitudinal conductivity in Si/SiGe heterostructure at integer filling factors

I. Shlimak, V. Ginodman, and M. Levin
Minerva Center and Jack and Pearl Resnick Institute of Advanced Technology, Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel

M. Potemski and D. K. Maude
High Magnetic Field Laboratory, Max-Planck-Institut für Festkörperforschung/CNRS, F-38042 Grenoble Cedex 9, France

K.-J. Friedland
Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, 10117 Berlin, Germany

D. J. Paul
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom
(Received 3 February 2003; revised manuscript received 13 May 2003; published 29 August 2003)

We have investigated temperature dependence of the longitudinal conductivity σ_{xx} at integer filling factors $\nu = i$ for Si/SiGe heterostructure in the quantum Hall effect regime. It is shown that for odd i, when the Fermi level E_F is situated between the valley-split levels, $\Delta\sigma_{xx}$ is determined by quantum corrections to conductivity caused by the electron-electron interaction: $\Delta\sigma_{xx}(T) \sim \ln T$. For even i, when E_F is located between cyclotron-split levels or spin-split levels, $\sigma_{xx} \sim \exp[-\Delta_i/T]$ for $i=6,10,12$ and $\sim \exp[-(T_{0i}/T)]^{1/2}$ for $i=4,8$. For further decrease of T, all dependences $\sigma_{xx}(T)$ tend to almost temperature-independent residual conductivity $\sigma_i(0)$. A possible mechanism for $\sigma_i(0)$ is discussed.

DOI: 10.1103/PhysRevB.68.075321 PACS number(s): 73.43.−f, 72.20.−i, 72.20.Ee

I. INTRODUCTION

The measurement of the temperature dependence of two-dimensional (2D) conductivity $\sigma(T)$ in the quantum Hall effect regime is a very useful tool for the analysis of the density of states (DOS) of carriers at different filling factors ν. At integer filling factors, $\nu = i$ $(i=1,2,3,\dots)$, the Fermi level E_F lies in the middle of two Landau levels (LL's) where the DOS is minimal and electron states are localized. In this case, the character of longitudinal conductivity $\sigma_{xx}(T)$ is determined by the ratio between the energy distance between the two adjacent LL's E_i and the temperature within the measuring interval. If $E_i \leqslant T$, one expects a weak nonexponential dependence for $\sigma_{xx}(T)$, while for $E_i \gg T$, the conductivity has to be strongly temperature activated (see, for example, Refs. 1–3 and references therein),

$$\sigma_{xx}(T) = \sigma_0 \exp(-\Delta/T). \quad (1)$$

Here, Δ is the energy of activation and 2Δ reflects the mobility gap, which is less than E_i because of the nonzero width of the band of delocalized states in the center of each LL, the prefactor σ_0 is equal to $2e^2/h$.[1] (The coefficient 2 appears because the conductivity is due to electrons excited into the upper LL and holes in the lower LL.) For $\Delta \gg T$, direct excitations of electrons to the mobility edge is unlikely, and the conductivity is due to the variable-range-hopping (VRH) mechanism via localized states in the vicinity of E_F:[4–6]

$$\sigma_{xx}(T) \propto \exp(-T_0/T)^m, \quad (2)$$

where $m=1/2$ because of the existence of a Coulomb gap in the DOS at E_F.[7,8] The parameter T_0 is connected with the localization radius $\xi(\nu)$ of the states for given ν: $T_0 = C_1 e^2/\kappa\xi(\nu)$. Here $C_1 \approx 6$ for two dimensions and κ is the dielectric constant of the host semiconductor.

Most previous measurements of $\sigma_{xx}(T)$ were performed on GaAs/AlGaAs heterojunctions. Increased interest in the study of the Si/SiGe heterostructure is motivated by the application of thin $Si_{1-x}Ge_x$ layers as the base of a heterojunction bipolar transistor with increased mobility,[9] resonant interband tunneling diodes,[10] as well as by possible future application of this heterostructure for quantum computing.[11,12] The special feature of n-type Si/SiGe in comparison with GaAs/AlGaAs heterostructures lies in the appearance of an additional splitting of energy levels due to lifting of twofold valley degeneracy in a strong perpendicular magnetic field. As a result, in n-type Si/SiGe heterostructures, odd filling factors correspond to the location of E_F between valley-splitting LL's.

In Ref. 13 measurements of $\sigma_{xx}(T)$ in tilted magnetic fields were used for determining the valley splittings in $Si/Si_{1-x}Ge_x$ heterostructure. It was found that the values of Δ for odd $i=3,5,7,9$, as determined from the Arrhenius plot, Eq. (1), do not agree with the values of E_i estimated theoretically in Refs. 14,15. However, the values obtained for Δ (0.2–0.4 K) were of the order of T, which makes doubtful the use of the Arrhenius law for data processing. In the same work,[13] the coincidence method in tilted magnetic fields was used to determine spin splitting and the effective g factor g^*. It was found that $g^* = 3.4$ for filling factors $16 \leqslant \nu \leqslant 28$ and increases for lower ν. The spin- and valley-split energy levels were also determined in strained Si quantum wells using Shubnikov–de Haas oscillation measurements.[16] It was found that for a perpendicular magnetic field of ~ 2.8 T which corresponds to $\nu = 7$, a valley splitting is of the order

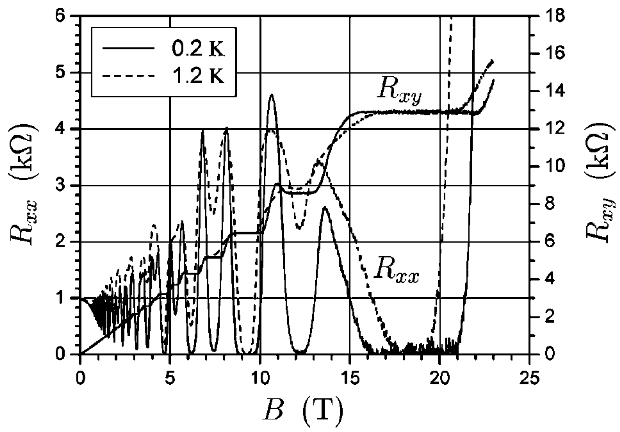

FIG. 1. Transverse resistance R_{xy} and longitudinal resistance R_{xx} of $Si/Si_{0.7}Ge_{0.3}$ heterostructure at $T=0.2$ K and 1.2 K.

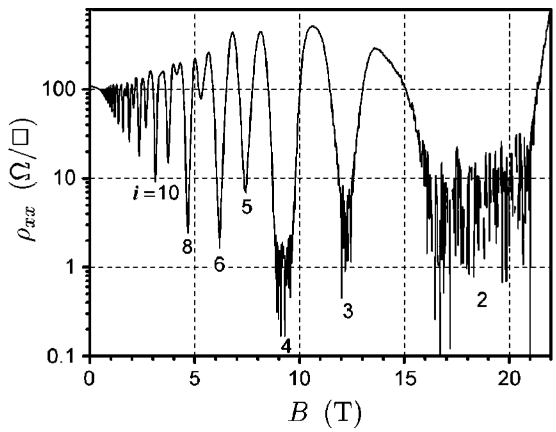

FIG. 2. Longitudinal resistivity $\rho_{xx}=R_{xx}/\Box$ on logarithmic scale at $T=0.2$ K. The values of i are shown near the minima.

of 52 μeV≈0.6 K. This value is in agreement with the data obtained in Ref. 13 for $Si/Si_{1-x}Ge_x$ heterostructure, but is much less than those determined for strained inverse layer in Si–metal-oxide-semiconductor structures in strong magnetic fields: $\Delta\approx 12$ K for $B=14.6$ T,[17] or $\Delta[\mathrm{K}]=2.4+0.6B[\mathrm{T}]$ at 2 T$<B<$8 T.[18] It was also shown in Ref. 16 that $g^*\approx 3.5$ at $\nu\geqslant 10$ and g^* oscillates between 2.6 and 4.2 with decreasing ν. To summarize, the character of $\sigma_{xx}(T)$ for different i in Si/SiGe heterostructure remains vague, which motivated this work.

II. EXPERIMENT

The sample investigated was Hall-bar patterned n-type $Si/Si_{0.7}Ge_{0.3}$ double heterostructure, a 7-nm i-Si quantum well was situated between 1-μm i-$Si_{0.7}Ge_{0.3}$ layer and 67-nm $Si_{0.7}Ge_{0.3}$ layer with 17-nm spacer followed by 50-nm $Si_{0.7}Ge_{0.3}$ heavily doped with As. A 4-nm silicon cap layer protects the surface. The electron concentration n and mobility μ at 1.5 K were $n=9\times 10^{11}$ cm^{-2}, and $\mu=80\,000$ cm^2/V s. The sample resistance was measured using a standard lock-in technique, with the measuring current being 20 nA at a frequency of 10.6 Hz.

Figure 1 shows the longitudinal R_{xx} and transverse R_{xy} resistances of the sample investigated when measured at $T=1.2$ and 0.2 K in magnetic fields up to $B=23$ T. The plateaus in R_{xy} are clearly seen at values which are a portion of a quantized resistance $h/e^2=25.8$ kΩ. At some magnetic fields B_i when the filling factor ν achieves an integer value $\nu=i$, longitudinal resistance R_{xx} exhibits a deep minimum, these fields correspond approximately to the midpoint of each R_{xy} plateau.

Figure 2 shows the two-dimensional resistivity $\rho_{xx}=R_{xx}/\Box$ on a logarithmic scale for $T=0.2$ K. At ν around $i=2,3,4$, huge fluctuations of ρ_{xx} are seen. These fluctuations of longitudinal voltage (ΔV_{xx}) do not reflect fluctuations of the sample resistivity or sample inhomogeneity, but can be explained by the fact that in strong magnetic fields and for small integers i, both 2D resistivity ρ_{xx} and conductivity $\sigma_{xx}=\rho_{xx}/(\rho_{xx}^2+\rho_{xy}^2)$ are close to zero, which leads to decoupling of the bulk of 2D electron system from the contacts at the edges.[19] These fluctuations are also not connected with the scan rate of the magnetic field, because they were observed in experiments when the magnetic field is fixed and only temperature is variable (Fig. 3). The magnitude of ΔV_{xx} increases with decreasing ν: for ν around $i=4,3,2$, the maximal values of ΔV_{xx} achieved are 0.5 μV, 1 μV, and 4 μV correspondingly. These fluctuations of the voltage signal prevent from determination of σ_{xx} at $i=2$. For the same reason, we will not discuss $\sigma_{xx}(T)$ for $i=3,4$ below $T=0.2$ K.

III. RESULTS AND DISCUSSION

Odd integers ($i=3,5,7,9$). In the case of n-Si/SiGe heterostructure, odd filling factors correspond to the location of E_F between the valley-split LL's. The valley splitting of strained Si layers has been theoretically investigated in Refs. 14,15,20. It was shown in Ref. 15 that valley splitting could be observed only in the presence of a high magnetic field normal to the interface and is given approximately by

$$\varepsilon_v[\mathrm{K}]\approx 0.174(N+1/2)B[\mathrm{T}]. \quad (3)$$

Here the valley-splitting energy ε_v is measured in Kelvin, magnetic field B in Tesla, and $N=0,1,2,\ldots$ is the Landau

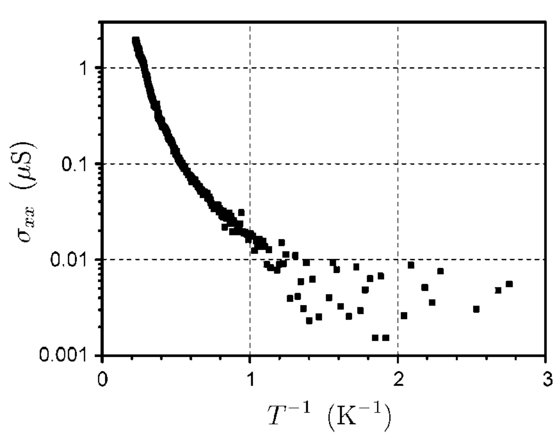

FIG. 3. $\sigma_{xx}(T)$ for $\nu=4$ for magnetic field fixed at $B_4=9.1$ T.

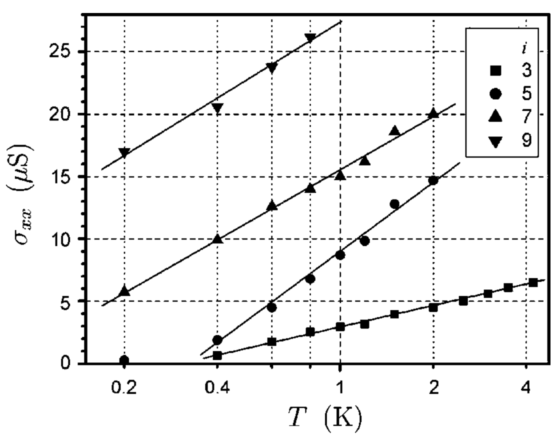

FIG. 4. σ_{xx} for odd integers $i=3,5,7,9$ as a function of $\ln T$.

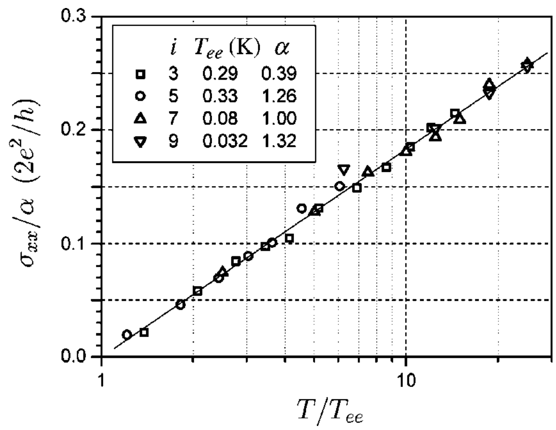

FIG. 5. $\sigma_{xx}(T)/\alpha$ for odd integers plotted in dimensionless units $\sigma_{xx}/\alpha(2e^2/h)$ vs $\ln(T/T_{ee})$. The inset shows the values of the adjustable parameter α and T_{ee}.

index. Because increase of B is accompanied by decrease of N, the values of the valley splitting weakly depend on B. Numerical estimation based on Eq. (3) showed that the values of ε_v for magnetic fields 4 T$<B<$12 T are about 1 K. Therefore, one cannot expect an activated character of $\sigma_{xx}(T)$ within the experimental temperature interval ($T=4.2$–0.2 K).

In contrast, in Ref. 18 much larger values of ε_v have been reported with a significant energy of the valley-splitting even without magnetic field, it was emphasized that these data agree well with theoretical calculations:[20]

$$\varepsilon_v[\mathrm{K}] \approx 2.4 + 0.6B[\mathrm{T}]. \tag{4}$$

In accordance with Eq. (4), the value of ε_v for $i=3$ in the case of our sample ($B\approx 12$ T) should be about 10 K providing strong activated character of conductivity. However, the analysis shows that $\Delta\sigma_{xx}$ weakly depends on T, there is no activation process, the best fit of experimental data is achieved by logarithmic law: $\Delta\sigma_{xx}(T)\sim\ln T$ (Fig. 4). This result agrees with the model of Ohkawa and Uemura.[15]

Logarithmic temperature dependence of conductivity at low temperatures is usually interpreted as a manifestation of corrections to the conductance due to quantum interference effects.[21,22] In strong perpendicular magnetic fields, weak localization corrections to the conductivity are suppressed and $\Delta\sigma_{xx}$ is determined by quantum corrections due to the electron-electron interaction, which occurs both in weak and in strong magnetic fields (see, for example, Ref. 23 and references therein). This leads to the following expression for the temperature correction to the conductivity:[24]

$$\Delta\sigma_{ee}(T) = \left(\frac{\alpha p e^2}{2\pi h}\right)\ln\left(\frac{T}{T_{ee}}\right), \tag{5}$$

where α is a constant of order unity and p is the exponent in the temperature dependence of the phase-breaking time $\tau_\varphi \sim T^{-p}$. At low T, the phase used to be broken by the electron-electron interaction, leading to $p\approx 1$.[21] This gives

$$(1/\alpha)\frac{\Delta\sigma_{xx}}{(e^2/h)} = \frac{1}{2\pi}\ln\left(\frac{T}{T_{ee}}\right). \tag{6}$$

In Fig. 5, the dimensionless conductivity is plotted as a function of dimensionless temperature T/T_{ee}, the values of T_{ee} being determined from the intersection with the x axis for each curve in Fig. 4. The solid line in Fig. 5 corresponds to the slope $(1/2\pi)$. Having α as the only adjustable parameter, one can merge all curves. The inset shows the values obtained for α which are indeed of order unity. Thus, $\sigma_{xx}(T)$ for odd integers can be successfully described in terms of quantum corrections to the conductivity in strong magnetic fields caused by the electron-electron interaction.

Even integers ($i=4,6,8,10,12$). For even integers, there are two possibilities for the location of E_F: between cyclotron LL's (four-multiple integers $i=4,8,12$) and between spin-split levels ($i=6,10$). Taking into account that for the strained Si well, $m^*=0.195m_0$,[25] the cyclotron energy is given by

$$\hbar\omega_C\,[\mathrm{K}] = 6.86B\,[\mathrm{T}]. \tag{7}$$

The energy of spin splitting $g^*\mu_B B$ depends on the effective g factor g^*. As mentioned earlier, the value of g^* increases for lower ν oscillating between 2.6 and 4.2.[16] For numerical estimates, we assume $g^*\approx 3.8$, giving

$$g^*\mu_B B\,[\mathrm{K}] \approx 2.55B\,[\mathrm{T}]. \tag{8}$$

In Ref. 26, a similar value ($g^*\mu_B B\approx 2.6$ K/T) was used for estimating spin splitting in Si-inversion layers in high-mobility Si–metal-oxide-semiconductor field-effect transistors. In the calculation of E_i, all relevant splitting energies are taken into account. For example, $E_4=\hbar\omega_C - g^*\mu_B B - \frac{1}{2}[\varepsilon_V^{N=0}+\varepsilon_V^{N=1}]$. Substituting $B_4=9.1$ T in Eqs. (3), (7), and (8), we obtain $E_4\approx 40$ K. Similarly, $E_6=g^*\mu_B B - \varepsilon_V^{N=1}$. Substituting $B_6=6.07$ T in Eqs. (3) and (8), one gets $E_6\approx 12$ K, and so on. These energies are shown in the inset of Fig. 6. Because all E_i are larger than T within the experimental interval of temperatures, it is expected that $\sigma_{xx}(T)$ will be determined by the temperature-activated excitation of electrons to the mobility edge and characterized, therefore, by the constant energy of activation $\Delta \lesssim 1/2E_i$, Eq. (1). In Fig. 6, the dependences $\sigma_{xx}(T)$ for even integers

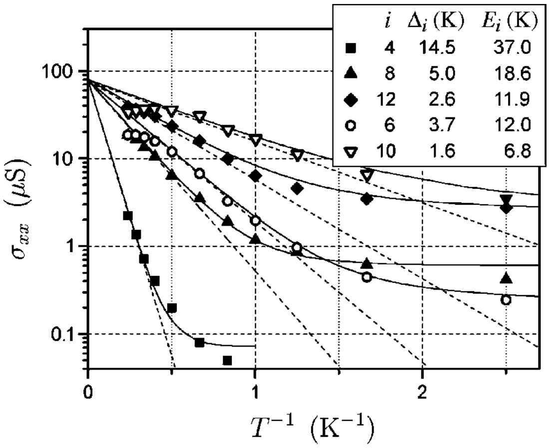

FIG. 6. σ_{xx} for even integers $i=4,8,12$ and 6,10, plotted on Arrhenius scale of $\ln \sigma_{xx}$ vs $1/T$. The inset shows the values of the experimentally determined Δ_i and the calculated values of E_i. Solid curves represent the calculated dependences $\sigma_{xx}(T)=(2e^2/h)\exp(-\Delta_i/T)+\sigma_i(0)$, with $\sigma_i(0)$ as the only adjustable parameter. The values of $\sigma_i(0)$ are shown in inset in Fig. 7.

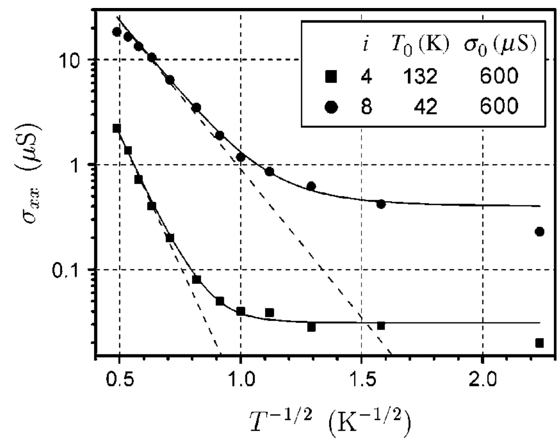

FIG. 8. $\sigma_{xx}(T)$ for $i=4,8$ plotted in the VRH scale $\ln \sigma_{xx}$ vs $T^{-1/2}$. Solid curves correspond to the calculated dependences $\sigma_{xx}(T)=\sigma_0\exp(-T_{i0}/T)^{1/2}+\sigma_i(0)$, with the values of T_{i0} and σ_0 shown in the inset. The values of $\sigma_i(0)$ are shown in the inset in Fig. 7.

are plotted on the scale $\ln \sigma_{xx}$ vs $1/T$. One sees that at high temperatures, the experimental points are in agreement with Eq. (1), which allows to determine the values of Δ_i. The prefactor σ_0 for all curves is close to 78 μS$\approx 2e^2/h$, in accordance with the theoretical prediction.[1] It is seen, however, that with decrease of temperature, all dependences tend towards the residual, almost temperature-independent, conductivity $\sigma_i(0)$. Having $\sigma_i(0)$ as the only adjustable parameter in expression $\sigma_{xx}(T)=(2e^2/h)\exp(-\Delta_i/T)+\sigma_i(0)$, the values of $\sigma_i(0)$ were determined from fitting the calculated σ_{xx} (solid lines in Fig. 6) to the experimental points. Subtraction of $\sigma_i(0)$ allows us to merge all curves into one straight line on the dimensionless scale, $\ln\{[\sigma_{xx}(T)-\sigma_i(0)]/(2e^2/h)\}$ vs Δ_i/T (Fig. 7).

It follows from Figs. 6 and 7 that the low-temperature experimental points for $i=4$ and 8 do not fit well to the calculated curves. This can be explained by the fact that the

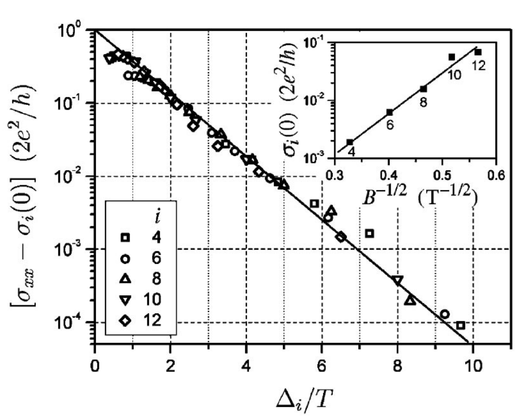

FIG. 7. $\sigma_{xx}(T)-\sigma_i(0)$ for even integers in dimensionless units as a function of a dimensionless reciprocal temperature Δ_i/T. The inset shows the residual conductivity $\sigma_i(0)$ in units of $(2e^2/h)$ as a function of magnetic fields B for different even i shown near the points, with the straight line corresponding to $\sigma_i(0)\propto\exp(B^{-1/2})$.

values of Δ_i for $i=4$ and 8 are substantially larger than for $i=6$, 10, 12. As a result, direct thermal excitation of electrons to the mobility edge is unlikely, and it is more probable that electron transport is due to VRH conductivity via localized states in the vicinity of E_F, Eq. (2). To summarize, one can write the general expression for the longitudinal conductivity at even filling factors,

$$\sigma_{xx}(T)=(2e^2/h)\exp(-\Delta_i/T)+\sigma_0\exp(-T_{0i}/T)^{1/2}, \quad (9)$$

where the first term corresponds to activation of localized electrons from the Fermi level E_F to the mobility edge, while the second term corresponds to VRH in the vicinity of E_F. If $\Delta_i \gg T$, the first term is very small and the second term dominates in σ_{xx}.

To check this assumption, we plot $\sigma_{xx}(T)$ for $i=4$ and 8 in the VRH scale of Eq. (2): $\ln\sigma_{xx}$ vs $T^{-1/2}$ (Fig. 8). On this scale, all experimental points for $i=4,8$ coincide with the calculated curves $\sigma_{xx}(T)=\sigma_0\exp(-T_{i0}/T)^{1/2}+\sigma_i(0)$, where σ_0 and T_{i0} are determined from experiment and $\sigma_i(0)$ is the only adjustable parameter. [As expected, experimental data on $\sigma_{xx}(T)$ for $i=6$, 10, and 12 do not fit well to the VRH scale and therefore are not shown in Fig. 8.] The inset of Fig. 7 shows $\sigma_i(0)$ obtained for different i as a function of magnetic field B_i. It is found that the best fit corresponds to the exponentially strong dependence $\sigma_i(0)\propto\exp(B_i^{-1/2})$.

The question arises about the origin of residual conductivity $\sigma_i(0)$. It worth to emphasize that the low-temperature saturation of longitudinal conductivity (or resistivity) in the quantum Hall effect regime is not a new phenomenon; it had been observed earlier in modulated doped GaAs/AlGaAs (Ref. 3) and Si/SiGe (Ref. 13) heterostructures. However, we are not aware of any discussion of the origin of this effect. Let us enumerate the experimental features of the residual conductivity: (i) The values of $\sigma_i(0)$ are much smaller than the minimal quantum for 2D conductivity $e^2/h\approx 39$ μS, (ii) $\sigma_i(0)$ decreases strongly with increasing magnetic field

B: $\sigma_i(0) \propto \exp(B_i^{-1/2})$, (iii) $\sigma_i(0)$ exists in all investigated temperatures, which means that this mechanism of conductivity occurs in a parallel conductive channel.

Both features (i) and (ii) suggest that $\sigma_i(0)$ is a sort of hopping conductivity. Indeed, e^2/h is the minimal value of metallic conductivity in 2D, while $\sigma_i(0) \ll e^2/h$. Moreover, there is no mechanism of exponentially strong magnetoresistance for metallic conductivity. By contrast, in strong magnetic fields, hopping resistivity ρ_3 increases exponentially: $\rho_3 \propto \exp[\mathrm{const} \cdot B_i^{1/2}]$.[8] However, weak temperature dependence of $\sigma_i(0)$ contradicts the hopping model and needs additional assumptions. We believe that this can be explained by the nonequilibrium character of $\sigma_i(0)$, which means the absence of thermal equilibrium in the distribution of electrons across the localized states, as was observed earlier in electron glasses.[27] A very slow rate of relaxation can be caused, for example, by an exponential decay of the DOS in the vicinity of E_F. In this case, relaxation to the lower states with decreasing temperature requires hopping over long distances and therefore is very unlikely. If the regions with such modified DOS form a continuous path along the voltage probes, a parallel conductive channel will appear, which explains feature (iii). At low temperatures, a weakly temperature-dependent residual conductivity will override the activated conductivity of the bulk 2D plane.

ACKNOWLEDGMENTS

We are thankful to B. I. Shklovskii for discussion, A. Belostotsky for the help with data analysis, and to the Eric and Sheila Samson Chair of Semiconductor Technology for financial support. V.G. and M.L. acknowledge the "KAMEA" Program for support.

[1] D.G. Polyakov and B.I. Shklovskii, Phys. Rev. Lett. **74**, 150 (1995).
[2] M.M. Fogler, D.G. Polyakov, and B.I. Shklovskii, Surf. Sci. **361/362**, 255 (1996).
[3] M. Furlan, Physica B **249-251**, 123 (1998).
[4] D.G. Polyakov and B.I. Shklovskii, Phys. Rev. Lett. **70**, 3796 (1993).
[5] F. Hohls, U. Zeitler, and R.J. Haug, Phys. Rev. Lett. **88**, 036802 (2002).
[6] D.-H. Shin *et al.*, Semicond. Sci. Technol. **14**, 762 (1999).
[7] A.L. Efros and B.I. Shklovskii, J. Phys. C **8**, L49 (1975).
[8] B.I. Shklovskii and A.L. Efros, *Electronic Properties of Doped Semiconductors* (Springer, Berlin, 1984).
[9] J.D. Cressler, IEEE Trans. Microwave Theory Tech. **46**, 572 (1998).
[10] S.L. Rommel *et al.*, Appl. Phys. Lett. **73**, 2191 (1998).
[11] R. Vrijen *et al.*, Phys. Rev. A **62**, 012306 (2000).
[12] I. Shlimak, V.I. Safarov, and I.D. Vagner, J. Phys.: Condens. Matter **13**, 6059 (2001).
[13] P. Weitz, R.J. Haug, K. von Klitzing, and F. Schäffler, Surf. Sci. **361/362**, 542 (1996).
[14] T. Ando, A.B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
[15] F.J. Ohkawa and Y. Uemura, J. Phys. Soc. Jpn. **43**, 917 (1977).
[16] S.J. Koester, K. Ismail, and J.O. Chu, Semicond. Sci. Technol. **12**, 384 (1997).
[17] R.J. Nicholas, K. von Klitzing, and T. Englert, Solid State Commun. **34**, 51 (1980).
[18] V.M. Pudalov, S.G. Semenchinskii, and V.S. Edel'man, JETP Lett. **41**, 325 (1985).
[19] J. Weis, Y.Y. Wei, and K. von Klitzing, Physica B **256-258**, 1 (1998).
[20] H. Köhler, Surf. Sci. **98**, 378 (1980).
[21] B.L. Altshuler and A.G. Aronov, in *Electron-Electron Interaction in Disordered Systems*, edited by A.L. Efros and M. Pollak, (North-Holland, Amsterdam, 1987).
[22] P.A. Lee and T.V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).
[23] S.S. Murzin, JETP Lett. **67**, 216 (1998).
[24] S. Hikami, Phys. Rev. B **24**, 2671 (1981).
[25] S.Q. Murphy *et al.*, Appl. Phys. Lett. **63**, 222 (1993).
[26] V.M. Pudalov, A. Punnoose, G. Brunthaler, A. Prinz, and G. Bauer, cond-mat/0104347 (unpublished).
[27] A. Vaknin, Z. Ovadyahu, and M. Pollak, Phys. Rev. B **65**, 134208 (2002).