Longitudinal conductivity in Si/SiGe heterostructure at integer filling factors

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We have investigated temperature dependence of the longitudinal conductivity $\sigma_{xx}$ 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 $\sim \exp[-(T/T_0)/T]^{1/2}$ 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.

INTRODUCTION

The measurement of the temperature dependence of 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 $\nu$. At integer filling factors, $\nu = i$ ($i = 1, 2, 3...$), the Fermi level $E_F$ lies in the middle of two Landau levels (LL) where the DOS is minimal and electron states used to be 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 LLs $E_i$ and the temperature within the measuring interval. If $E_i \ll T$, one expects a weak non-exponential dependence for $\sigma_{xx}(T)$, while for $E_i \gg T$, the conductivity has to be strongly temperature-activated (see, for example, [1] [2] [3] and references therein).

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

(1)

Here, $\Delta$ is the energy of activation and $2\Delta$ reflects the mobility gap, which is less than $E_i$ because of the non-zero width of the band of delocalized states in the center of each LL, the prefactor $\sigma_0$ 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 large $\Delta \gg T$, 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 $E_F$: [1] [5] [6]

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

(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 $\nu$: $T_0 = C_1e^2/\kappa\xi(\nu)$. Here $C_1 \approx 6$ for two dimensions and $\kappa$ 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 two-fold 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 LLs.

In Ref. [13] measurements of $\sigma_{xx}(T)$ in tilted magnetic fields were used for determining the valley-splitting in Si/Si$_{1-x}$Ge$_x$ heterostructure. It was found that the values of $\Delta$ 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 Ref. [14, 15]. However, the values obtained for $\Delta$ (0.2–0.4 K) were of order $T$, 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 $16 \leq \nu \leq 28$ and increases for lower $\nu$. The spin- and valley-split energy levels were also determined in strained Si quantum wells using Shubnikov-de Haas oscillations measurements [10]. It was shown that for a perpendicular magnetic field of $\sim 2.8$ T which corresponds to $\nu = 7$, a valley splitting is of order of $52 \mu eV \approx 0.6$ K. This value is in agreement with the data obtained in [13] for Si/Si$_x$Ge$_{1-x}$ heterostructure, but is much less than those determined for strained inverse layer in Si-MOS structures in strong magnetic fields: $\Delta \approx 12$ K for $B = 14.6$ T, Ref. [17] or $\Delta [K]= 2.4 + 0.6 \cdot B [T]$ at $2T < B < 8$T, Ref. [18]. It was also shown in Ref. [10] that $g^*$ $\approx 3.5$ at $\nu \geq 10$ and $g^*$ oscillates between 2.6 and 4.2 with decreasing $\nu$. To summarize, the character of $\sigma_{xx}(T)$ for different $i$ in Si/SiGe heterostructure remains vague, which motivated this work.

**EXPERIMENT**

The sample investigated was Hall-bar patterned n-type Si/Si$_{0.7}$Ge$_{0.3}$ double heterostructure, 7 nm i-Si quantum well was situated between 1 nm 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$_{0.3}$ layer heavily doped with As. A 4 nm silicon cap layer protects the surface.

**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 $\rho_{xx} = R_{xx}/\square$ on logarithmic scale at $T = 0.2$ K. The values of $i$ are shown near the minima.

The electron concentration $n$ and mobility $\mu$ at 1.5 K were $n = 9 \cdot 10^{11}$ cm$^{-2}$, $\mu = 80,000$ 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 plateau 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 $i$ 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 $\rho_{xx} = R_{xx}/\square$ on a logarithmic scale for $T = 0.2$ K. At $\nu$ around $i = 2, 3, 4$, huge fluctuations of $\rho_{xx}$ are seen. These fluctuations of longitudinal voltage $\Delta V_{xx}$ do not reflect fluctuations of the sample resistivity or sample inhomogeneity, but can be explained by the fact that in strong magnetic fields and small integers $i$, both 2D resistivity $\rho_{xx}$ 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 $\Delta V_{xx}$ increases with decreasing $\nu$: for $\nu$ around $i = 4, 3, 2$, the maximal values of $\Delta V_{xx}$ achieved to 0.5 µV, 1 µV and 4 µV correspondingly. These fluctuations of the voltage signal prevent from determination of $\sigma_{xx}$ at $i = 2$. For
FIG. 3: \( \sigma_{xx}(T) \) for \( \nu = 4 \) for magnetic field fixed at \( B_4 = 9.1 \, \text{T} \).

the same reason, we will not discuss \( \sigma_{xx}(T) \) for \( i = 3, 4 \) below \( T = 0.2 \, \text{K} \).

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 LLs. The valley splitting of strained Si layers has been theoretically investigated in Ref. [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

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

Here the valley splitting energy \( \varepsilon_v \) is measured in Kelvin, magnetic field \( B \) in Tesla, \( N = 0, 1, 2 \ldots \) is the Landau 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 \( \varepsilon_v \) for magnetic fields \( 4T < B < 12T \) are about 1 K. Therefore, one cannot expect an activated character of \( \sigma_{xx}(T) \) within the experimental temperature interval \( (T = 4.2 \, \text{K}) \).

In contrast, in [13] much larger values of \( \varepsilon_v \) 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]:

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

In accordance with Eq. (4), the value of \( \varepsilon_v \) for \( i = 3 \) in the case of our sample \( (B \approx 12T) \) 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 \( \alpha \) is a constant of order unity and \( p \) is the exponent in the temperature dependence of the phase-breaking time \( T_{ee} \) \( \sim T^{-p} \). At low \( T \), the phase used to be broken by the electron-electron interaction, leading to \( p \approx 1 \) [21]. This gives

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

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 $\alpha$ as the only adjustable parameter, one can merge all curves. The insert shows the values obtained for $\alpha$ 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 LLs (four-multiple integers $i = 4, 8, 12$) and between spin-split levels ($i = 6, 10$). Taking into account that for the strained Si well, $m^* = 0.195 m_0$ [24], the cyclotron energy is given by:

$$h\omega_C[K] = 6.86 B[T].$$

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 $\nu$ oscillating between 2.6 and 4.2 [10]. For numerical estimates, we assume $g^* \approx 3.8$, giving

$$g^*\mu_B B[K] \approx 2.55 B[T].$$

In Ref. [24], 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-MOSFETs. In the calculation of $E_i$, all relevant splitting energies are taken into account. For example, $E_4 = h\omega_C - g^*\mu_B B - \frac{1}{2}\varepsilon_{N=0}^V + \varepsilon_{N=1}^V$. Substituting $B_4 = 9.1$ T in Eqs. (3), (7), (8), we obtain $E_4 \approx 40$ K. Similarly, $E_8 = g^*\mu_B B - \varepsilon_{N=1}^V$. Substituting $B_8 = 6.07$ T in Eqs. (3) and (8), one get $E_8 \approx 12$ K and so on. These energies are shown in the insert in 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 are plotted on this 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 $\Delta_i$. The prefactor $\sigma_0$ for all curves is close to $78 \mu S \approx 2e^2/h$, in accordance with the theoretical prediction [11]. 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 $\sigma_{xx}$ (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. $\Delta_i/T$ (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 values of $\Delta_i$ 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 probably that electron transport is due to variable-range-hopping (VRH) conductivity via localized states in the vicinity of $E_F$.
The question arises about the origin of residual conductivity \( \sigma_i(0) \). To check this assumption, we plot \( \sigma_{xx}(T) \) for \( i = 4 \) and \( 8 \) in the VRH scale of Eq. (2): \( \ln \sigma_{xx}(T) = T^{-1/2}(i) = \frac{2}{T} \). On this scale, all experimental points for \( i = 4, 8 \) coincide with the calculated curves \( \sigma_{xx}(T) = \sigma_0 \exp(-T_\text{m}/T)^{1/2} + \sigma_i(0) \), where \( \sigma_0 \) and \( T_\text{m} \) are determined from experiment and \( \sigma_i(0) \) is the only adjustable parameter. (As expected, experimental data \( \sigma_{xx}(T) \) for \( i = 6, 10 \) and 12 do not fit well to the VRH scale and therefore are not shown in Fig. 8). The insert in Fig. 7 shows \( \sigma_i(0) \) obtained for different \( i \) as a function of magnetic field \( B \). It is found that the best fit corresponds to the exponentially strong dependence \( \sigma_i(0) \propto \exp(B_\text{m}^{1/2}) \).

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 phenomena, it had been observed earlier in modulated doped GaAs/AlGaAs \(^3\) and Si/SiGe \(^13\) 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 \( e^2/h \approx 39 \, \mu\text{S} \); (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 (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 \( \rho_3 \) increases exponentially: \( \rho_3 \propto \exp(\text{const} \cdot B_i^{1/2}) \). However, weak temperature dependence of \( \sigma_i(0) \) contradicts to the hopping model and needs additional assumptions. We believe that this can be explained by the non-equilibrium 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 \(^24\). 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

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

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 \( \sigma_{xx} \).

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

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unlikely. If the regions with such modified DOS form a continuous path along the voltage probes, a parallel conductive channel will appear, which explains (iii). At low temperatures, a weakly temperature-dependent residual conductivity will override the activated conductivity of the bulk 2D plane.

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