PHYSICAL REVIEW B **73**, 121304(R) (2006)

Spin-dependent edge-channel transport in a Si/SiGe quantum Hall system

K. Hamaya,[1,*] S. Masubuchi,[1] K. Hirakawa,[1] S. Ishida,[2] Y. Arakawa,[2] K. Sawano,[3] Y. Shiraki,[3] and T. Machida[1,4,†]
[1]*Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*
[2]*Nanoelectronics Collaborative Research Center (NCRC), IIS and RCAST, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*
[3]*Research Center for Silicon Nano-Science, Advanced Research Laboratories, Musashi Institute of Technology, 8-15-1 Todoroki, Setagaya-ku, Tokyo 158-0082, Japan*
[4]*Nanostructure and Material Property, PRESTO, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi 332-0012, Japan*

(Received 10 January 2006; revised manuscript received 27 February 2006; published 23 March 2006)

We study the edge-channel transport of electrons in a high-mobility Si/SiGe two-dimensional electron system in the quantum Hall regime. By selectively populating the spin-resolved edge channels, we observe suppression of the scattering between two edge channels with spin-up and spin-down. In contrast, when the Zeeman splitting of the spin-resolved levels is enlarged with tilting magnetic field direction, the spin orientations of both the relevant edge channels are switched to spin-down, and the inter-edge-channel scattering is strongly promoted. The evident spin dependence of the adiabatic edge-channel transport is an individual feature in silicon-based two-dimensional electron systems, originating from a weak spin-orbit interaction.

DOI: 10.1103/PhysRevB.73.121304 PACS number(s): 73.43.−f

Characteristic features such as the valley degree of freedom,[1] a metal-insulator transition at zero field,[2] and a significant anisotropy of magnetotransport properties in the quantum Hall regime[3] have been discovered for silicon-based two-dimensional electron gas (2DEG) systems in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) and Si/SiGe heterostructures. For these systems, the quantum Hall (QH) effects and their related physics at the Landau-level crossing, which is so-called coincidence, have been explored in tilted magnetic fields so far.[3–7] Recently, the manipulation of the valley degree of freedom by changing the gate-bias voltage to tune the coincidence condition was further exploited in $SiO_2/Si/SiO_2$ quantum wells.[8]

In a single-particle picture, the Zeeman splitting (ΔE_z) depends on the total magnetic field (B_{total}), while the cyclotron energy, $\hbar\omega_c$, depends on the perpendicular component ($B_\perp$) of B_{total}. Thus, when we apply the parallel component ($B_\parallel$) in addition to the $B_\perp$ with tilting an external magnetic field direction θ between the direction of an applied magnetic field and the direction normal to the 2DEG plane, the ΔE_z of the spin-resolved levels can be enlarged, giving rise to a crossover of the Landau levels at a certain θ as schematically illustrated in Fig. 1(a). Using the tilted magnetic fields, we can determine the effective g-factor (g^*),[4–6] and one deduces that the value of g^* is concerned with carrier density for Si/SiGe heterostructures.[6] Also, it was indicated that an exchange interaction between different Landau levels is enhanced under the coincidence condition, showing an overshoot of the Hall resistance[4] at the filling factor of $\nu=3$ and transition peaks with unexpectedly huge resistance in the Shubnikov–de Haas (SdH) oscillations.[5–7]

Though the edge-channel picture is crucial to understand the electronic transport in QH systems,[9,10] few studies of the edge-channel transport have been reported for the silicon-based 2DEG systems. More than ten years ago, a preliminary work using Si-MOSFETs with mobility below 2.0 $m^2/V\,s$ was demonstrated,[11] but a collective view of the edge-channel transport has not been established because of the low mobility of Si-MOSFETs. Owing to development of high-quality Si/SiGe heterostructures,[12] however, the mobility value increases up to $\sim$50 $m^2/V\,s$,[12,4] in consequence, the fractional QH effect can be explored[13] and a possibility of spin-based quantum computing applications was indicated.[14] Using these high-quality Si/SiGe heterostructures, we can elucidate the edge-channel transport controlled by tuning the coincidence condition: At the filling factor of $\nu=4$, the edge channels with spin-down $0\downarrow$ and spin-up $0\uparrow$ are presented in $\hbar\omega_c > \Delta E_z$ while the edge channels with spin-down $0\downarrow$ and spin-down $1\downarrow$ are formed in $\hbar\omega_c < \Delta E_z$, as shown in Fig. 1(b).

In this Rapid Communication, we report on the observation of the spin-dependent edge-channel transport in a high-

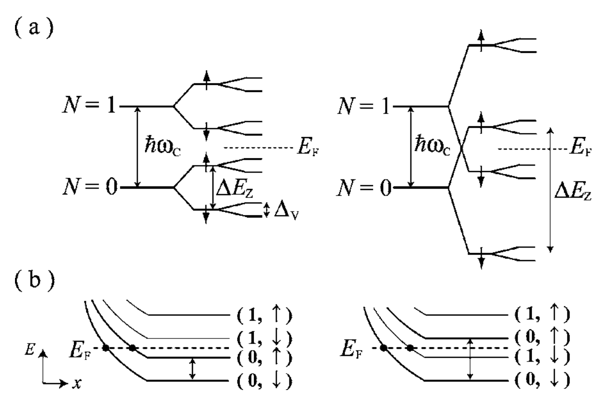

FIG. 1. (a) Energy diagrams of Landau levels between $N=0$ and $N=1$ for $\hbar\omega_c > \Delta E_z$ (left) and $\hbar\omega_c < \Delta E_z$ (right). The Fermi level E_F is located at the filling factor of $\nu=4$. The valley splittings (Δ_V) are also depicted. (b) Edge channel dispersions for $\hbar\omega_c > \Delta E_z$ (left) and $\hbar\omega_c < \Delta E_z$ (right) for $\nu=4$ (a two-channel case). The spin orientation of the relevant edge channels switches from ($0\downarrow$, $0\uparrow$) to ($0\downarrow$, $1\downarrow$) through the coincidence angle.

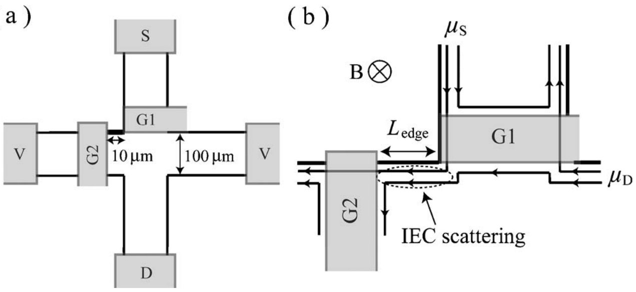

FIG. 2. (a) A schematic illustration of the Hall bar sample. (b) The enlarged figure of L_{edge} region for a two-channel case. The arrows indicate the direction of electron drift in the edge channels.

mobility Si/SiGe heterostructure in the QH regime. By selectively populating the spin-resolved edge channels, the Hall resistance deviates largely from the quantized value, indicating the first observation of the adiabatic edge-channel transport of electrons in the Si/SiGe heterostructure. The inter-edge-channel (IEC) scattering is strongly suppressed over macroscopic distance between (0↓, 0↑) edge channels while that is significantly promoted between (0↓, 1↓) edge channels. The spin dependence clearly observed is a characteristic property of silicon-based QH systems, being due to a small contribution of the spin-orbit interaction to the spin-flip IEC scattering.

A high-mobility $Si/Si_{0.75}Ge_{0.25}$ heterostructure studied was grown by molecular-beam epitaxy on the strained-relaxed $Si_{0.75}Ge_{0.25}$ buffer layer smoothed by chemical mechanical polishing.[15] The wafer has the electron mobility of 20 m^2/V s and the electron density of 1.35×10^{15} m^{-2} at 0.3 K. For transport measurements, the wafer was patterned into 100-μm-wide Hall bars with four alloyed AuSb ohmic contacts and two front gates (G1 and G2) crossing the channel as depicted in Fig. 2(a). The front gate structure is composed of a 100-nm-thick SiO_2 insulating layer grown by plasma enhanced chemical vapor deposition below 400 °C, followed by 2.5-nm-thick Ti/200-nm-thick Au layer deposited by electron-beam evaporation. The distance of the edge region in the Hall bar between the two gates is L_{edge} $=10$ μm. The filling factors of Landau levels in the bulk region and under the front gate, ν_B and ν_G, are controlled by adjusting the magnetic field B and the gate-bias voltage V_G. Transport measurements were basically performed using standard lock-in techniques (18 Hz) with an alternating current of 1.0 nA in a ^{3}He–^{4}He dilution refrigerator. The SdH oscillations were observed evidently and the longitudinal resistance (R_{xx}) showed the plateau corresponding to zero resistance at $\nu=1,2$, and 4.

To examine the edge-channel transport, we focus on the IEC scattering for a two-channel case as shown in Fig. 2(b).[16] We hereafter define the electrochemical potentials of the source and the drain reservoirs as μ_S and μ_D, respectively. When $\nu_B=4$ and $\nu_G=2$, the outer channel passes through the two front gates (G1 and G2) while the inner channel is reflected by the gates. Here, the value of V_G for $\nu_G=2$ was determined experimentally by the measurements of R_{xx} versus V_G.[10,17,19–21] As a consequence, the electrochemical potential of the outer channel (μ_S) is different from that of the inner channel (μ_D) at L_{edge} shown in Fig. 2(b). For 2DEG in AlGaAs/GaAs heterostructures, many experimental and theoretical studies of the edge-channel transport have been reported,[10,17–25] in which the IEC scattering is suppressed over macroscopic distance, resulting in a deviation of the Hall resistance (R_{xy}) from the quantized value at the QH regime. On the basis of the Landauer-Büttiker formalism,[26] the adiabatic transport in spin-resolved edge channels[18] at $\nu_B=4$ is likely to indicate $R_{xy}=h/2e^2$ while the nonadiabatic edge-channel transport shows the quantized value $h/4e^2$ in the case of 2DEG in Si/SiGe heterostructures.

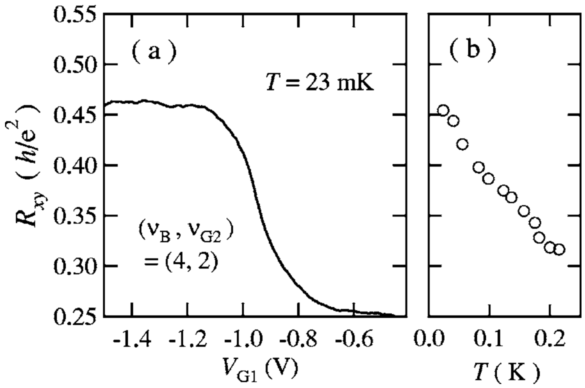

FIG. 3. R_{xy} as a function of V_{G1} at $(\nu_B,\nu_{G2})=(4,2)$ at 23 mK. (b) Temperature dependence of R_{xy} at $(\nu_B,\nu_{G1},\nu_{G2})=(4,2,2)$.

Figure 3(a) displays R_{xy} as a function of V_{G1} for $\nu_B=4$ ($B=2.01$ T) and $\nu_{G2}=2$ ($V_{G2}=-1.10$ V) at 23 mK. When V_{G1} is reduced down to about -0.70 V, a deviation of R_{xy} from 0.25 h/e^2 (ΔR_{xy}) can be seen, and then R_{xy} reaches 0.46 h/e^2 at $V_{G1}=-1.10$ V. Taking the relationship of ΔR_{xy} $=\exp(-L_{edge}/L_{eq})(h/4e^2)$,[10] where L_{eq} is the equilibration length corresponding to the distance over which electrons are traveling adiabatically, we roughly find $L_{eq}\approx57$ μm at 23 mK, being even larger than that of the high-mobility 2DEG in AlGaAs/GaAs heterostructures.[20] We also observe the evident temperature dependence of R_{xy} as shown in Fig. 3(b), in which ΔR_{xy} decreases with increasing temperature. This means that the IEC scattering is accelerated and L_{eq} shrinks due to the increase in temperature. The results presented are the first experimental data associated with the edge-channel transport of high-mobility Si/SiGe heterostructures.

In Fig. 4(a), we show the plots of R_{xy} versus $B_\perp$ (R_{xy} $-B_\perp$ curve) at around $\nu_B=4$ for various θ in detail, where $B_\perp=B_{total}\cos\theta$. In $66.5°\lesssim\theta\lesssim67.5°$, the plateau in the QH regime of $\nu_B=4$ becomes unclear, which is general behavior of R_{xy} under around coincidence condition.[7] Consequently, we can approximately regard the coincidence angle of the first Landau-level crossing of our sample as $\theta=66.5°$. We also confirmed the coincidence in the vicinity of $\theta=66.5°$ in $R_{xx}-B_\perp$ curves. Assuming the effective mass $m^*=0.19$ m_0, where m_0 is the free electron mass, we can deduce $g^*=4.2$, being consistent with previous studies.[4–6,27] At the coincidence angle ($\theta=66.5°$), the spin orientations of the relevant edge channels are transferred from (0↓, 0↑) to (0↓, 1↓): the edge-channel transport in $\theta\lesssim66.0°$ or in $\theta\gtrsim68.0°$ arises from (0↓, 0↑) or (0↓, 1↓) edge channels, respectively.

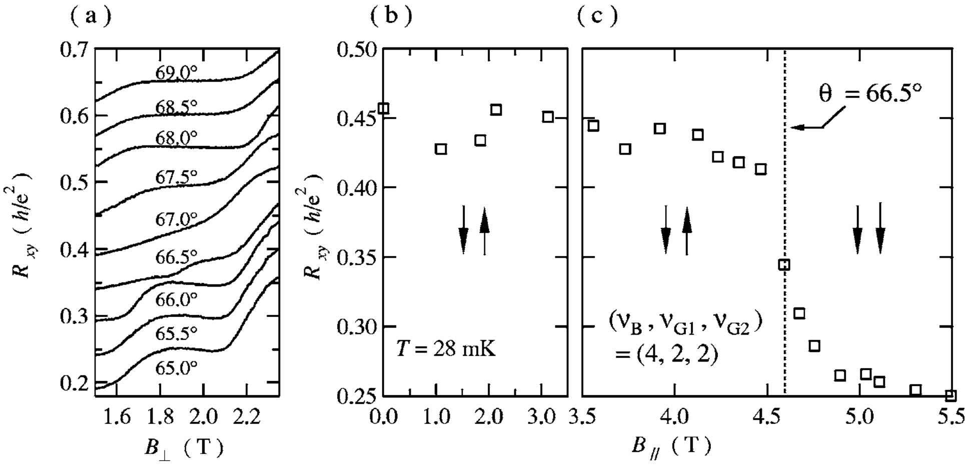

FIG. 4. (a) Plots of R_{xy} vs $B_\perp$ for various θ at around ν_B=4 at 28 mK. $R_{xy}-B_\perp$ curves include an offset by 0.05 h/e^2 for each curve. (b) and (c) R_{xy} as a function of $B_\parallel$ at 28 mK for $(\nu_B,\nu_{G1},\nu_{G2})=(4,2,2)$. The arrows illustrated represent the spin orientation of the relevant edge channels in each $B_\parallel$ range.

To get insight into the spin dependence of the edge-channel transport in the Si/SiGe heterostructure, we examine R_{xy} as a function of θ systematically at $(\nu_B,\nu_{G1},\nu_{G2})=(4,2,2)$, and summarize the dependence of R_{xy} on $B_\parallel$, where $B_\parallel=B_{total}\sin\theta$, at 28 mK in Figs. 4(b) and 4(c). A deviation of R_{xy} from 0.25 h/e^2 expresses suppression of the IEC scattering. We find that the value of R_{xy} is nearly constant, i.e., 0.42 $h/e^2 \lesssim R_{xy} \lesssim 0.46$ h/e^2, in $\theta \lesssim 66.0°$ ($B_\parallel \lesssim 4.47$ T), whereas R_{xy} is markedly reduced at around the coincidence angle θ=66.5° ($B_\parallel \simeq 4.59$ T), and then the value of R_{xy} is settled down to $R_{xy}\sim 0.25$ h/e^2 in $\theta \gtrsim 71.5°$ ($B_\parallel \gtrsim 5.5$ T). Komiyama *et al.*[10] have reported that a spatial separation (ΔX) between edge channels affects the IEC scattering for 2DEG in AlGaAs/GaAs heterostructures with $m^*=0.067$ m_0 and $g^*=-0.44$. In general, if ΔE_z is enhanced by increasing θ, ΔX between spin-resolved edge channels increases and the IEC scattering is suppressed due to the reduction in the overlap of electron wave functions.[10] However, the above interpretation cannot be applied to the data in Figs. 4(b) and 4(c).

In order to explain the above feature, we attempt to approximately calculate ΔX.[10,20,21] Here, we use a parabolic-type confining potential with the confinement frequency of 1.7×10^{12} s^{-1}, $m^*=0.19$ m_0, and $g^*=4.2$. For θ=0°, ΔE_z (=$g^*\mu_B B$, where μ_B is Bohr's magneton) of 0.4 meV indicates $\Delta X\sim 47.5$ Å at 2.01 T for the sample used. With increasing θ, ΔE_z is enlarged but the related ΔX is always smaller than 145 Å, which is the maximum value of ΔX derived from the Landau gap ($\hbar\omega_c$) of 1.22 meV.[10,20,21] Since the magnetic length $l_c=\sqrt{\hbar/(eB)}$ is $\sim$180 Å, a strong mixing of the wave functions of electrons between edge channels can be deduced irrespective of θ. Hence we conclude that the wave functions of electrons between edge channels usually overlap for the high-mobility Si/SiGe heterostructure used. This feature basically originates from the fact that m^* of Si/SiGe heterostructures is large relative to that of AlGaAs/GaAs heterostructures by a factor of 3. We also note that the edge-channel transport is ascribed to the spin orientation of the relevant edge channels either $(0\downarrow, 0\uparrow)$ or $(0\downarrow, 1\downarrow)$: we can see the long L_{eq} in $(0\downarrow, 0\uparrow)$ while a considerably shorter L_{eq} is found in $(0\downarrow, 1\downarrow)$.

For 2DEG in AlGaAs/GaAs heterostructures, Müller *et al.*[20] explained that L_{eq} of electrons in spin-resolved edge channels is inversely proportional to the spinor overlap, $|\chi_\downarrow^\dagger(k_i)\chi_\uparrow(k_f)|^2$, where i and f denote the initial and final states in the scattering process of electrons. The spinor overlap can be written as $\chi_\downarrow^\dagger(k_i)\chi_\uparrow(k_f)\propto(g^*\mu_B B)\gamma\hbar\,\delta k/\{(g^*\mu_B B)^2+\gamma^2(2\hbar k)^2\}$, where $\delta k=k_f-k_i$ and γ is the spin-orbit coupling constant.[20,24,25] They suggested that large values of $L_{eq}\sim 100$ μm in spin-resolved edge channels can be interpreted by the small spinor overlap.[20,24] We also obtain the long $L_{eq}\sim 57$ μm between $(0\downarrow, 0\uparrow)$ edge channels, implying the small spinor overlap, although the wave functions of electrons between edge channels are strongly mixed for the 2DEG in Si/SiGe heterostructure used, as mentioned in the previous paragraph. In this regard, we infer that a small contribution of the spin-orbit interaction, derived from the inversion symmetry of a unit cell of Si crystal, causes the small spinor overlap of the above equation, and leads to suppression of the IEC scattering with spin-flips. On the other hand, we judge that the IEC scattering between $(0\downarrow, 1\downarrow)$ edge channels without spin-flips is accelerated due to the overlap of the

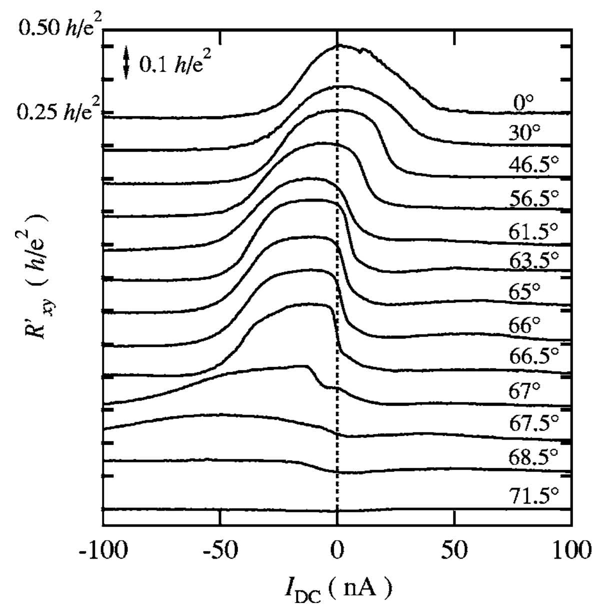

FIG. 5. R'_{xy} vs I_{dc} for different θ at 28 mK for $(\nu_B,\nu_{G1},\nu_{G2})=(4,2,2)$. The data traces of R'_{xy} include an offset by 0.1 h/e^2 for each curve, and the major ticks are presented at every 0.1 h/e^2.

wave functions of electrons. Although the effect of the hyperfine interaction between electron and nuclear spins is also predicted, we can rule out it because 95.33% of nuclear isotopes (^{28}Si and ^{30}Si) in Si has no nuclear moment.

We finally refer to the IEC scattering controlled by I_{dc}. At $(\nu_B, \nu_{G1}, \nu_{G2})=(4,2,2)$, when the positive direct current, $I_{dc}>0$ ($\mu_S>\mu_D$), is applied between inner (μ_D) and outer (μ_S) edge channels, the IEC scattering from outer to inner occurs markedly, while the IEC scattering from inner to outer becomes significant in $I_{dc}<0$ ($\mu_S<\mu_D$). Thus, the differential Hall resistance, $R'_{xy}=\partial V_{xy}/\partial I$, as a function of I_{dc} ($R'_{xy}-I_{dc}$ curve) shows characteristic nonlinearity.[10,18,28,29] Figure 5 shows $R'_{xy}-I_{dc}$ curve for various applied magnetic field directions θ. For $\theta=0°$, a marked nonlinear feature is seen in $I_{dc}\lesssim\pm 40$ nA and the symmetry of the $R'_{xy}-I_{dc}$ curve is comparatively maintained in that regime. In contrast, the IEC scattering is promoted and R'_{xy} becomes 0.25 h/e^2 in $I_{dc}\gtrsim\pm 50$ nA. With θ increased, the symmetric shape of the $R'_{xy}-I_{dc}$ curve is broken and the shift of the nonlinear region toward $I_{dc}<0$ is observed. For 2DEG in AlGaAs/GaAs heterostructures, nonlinear features shown in $R'_{xy}-I_{dc}$ curves are explained by the rearrangement of edge channels due to unequal edge-channel population.[10,18,28,29] On the other hand, for 2DEG in the Si/SiGe heterostructure we use, the above I_{dc} dependence of R'_{xy} cannot be interpreted by this explanation. The cause of this asymmetric feature is still unclear but the $R'_{xy}-I_{dc}$ curves vary systematically with increasing θ under around the coincidence condition, strongly supporting that these I_{dc} dependences of R'_{xy} are associated with the spin dependence of the edge-channel transport described. Therefore, this should be considered to be a peculiar property of the 2DEG in Si/SiGe heterostructures.

In summary, we have studied the edge-channel transport in the high-mobility 2DEG in a Si/SiGe heterostructure in the QH regime. We observed the spin-dependent edge-channel transport at around the Landau-level crossing in tilted magnetic fields. The evident spin dependence is due to a small contribution of the spin-orbit interaction in Si to the spin-flip IEC scattering.

Two of the authors (K.H. and T.M.) acknowledge S. Komiyama, M. Jung, and A. Umeno of University of Tokyo for many useful discussions and experimental support. This work is partially supported by the Inamori foundation and the Support Center for Advanced Telecommunications Technology Research.

*Email address: hamaya@iis.u-tokyo.ac.jp
†Email address: tmachida@iis.u-tokyo.ac.jp

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