High Temperature Quantum Kinetic Effects in Silicon Nanosandwiches

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Abstract—The negative-$U$ impurity stripes confining the edge channels of semiconductor quantum wells are shown to allow the effective cooling inside in the process of the spin-dependent transport, with the reduction of the electron-electron interaction. The aforesaid promotes also the creation of composite bosons and fermions by the capture of single magnetic flux quanta on the edge channels under the conditions of low sheet density of carriers, thus opening new opportunities for the registration of the high temperature de Haas-van Alphen, 300 K, quantum Hall, 77 K, effects as well as quantum conductance staircase in the silicon sandwich structure.

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1. INTRODUCTION

The Shubnikov–de Haas (ShdH) and de Haas–van Alphen (dHvA) effects as well as the quantum Hall effect (QHE) are quantum phenomena that manifest themselves at the macroscopic level and have attracted a lot of attention, because they reveal a deeper insight into the processes due to charge and spin correlations in low-dimensional systems [1, 2]. Until recently the observation of these quantum effects in the device structures required ultra-low temperatures and ultrahigh magnetic fields [3]. Otherwise there were the difficulties to provide small effective mass, $m^*$, and long momentum relaxation time, $\tau_m$, of charge carriers, which result from the so-called strong field assumption, $\mu B \gg 1$, where $\mu = e\tau_m/m^*$ is the mobility of the charge carriers. This severe criterion along with the condition $\hbar \omega_0 \gg kT$ hindered the application of the ShdH-dHvA-QHE techniques to control the characteristics of the device structures in the interval between the liquid-nitrogen and room temperatures, where $\hbar \omega_0$ is the energy gap between adjacent Landau levels, $\omega_0 = eB/m^*$ is the cyclotron frequency. Nevertheless, the ShdH oscillations were observed at room temperature in graphene, a single layer of carbon atoms tightly packed in a honeycomb crystal lattice, owing to the small effective mass of charge carriers, $\sim 10^{-3}m_0$, although the magnetic field as high as 29T was necessary to be used because of relatively short momentum relaxation time [4]. Thus, the problem of the fulfillment of the strong field assumption at low magnetic fields has remained virtually unresolved. Perhaps, its certain decision is to use the pairs of edge channels in topological two-dimensional insulators and superconductors, in which the carriers with anti-parallel spins move in opposite directions [5]. Especially as recently the ideas are suggested that the mobility and spin-lattice relaxation time of the carriers in topological channels can be increased, if to hide them in the cover consisting of the $d$- and $f$-like impurity centers [6]. Here we use as similar clothes the striations of the negative-$U$ dipole boron centers that allow except noted advantages to achieve the effective cooling inside the edge channels of semiconductor quantum wells in the process of the spin-dependent transport. The aforesaid promotes also the creation of composite bosons and fermions by the capture of single magnetic flux quanta on the edge channels under the conditions of low sheet density of carriers, thus opening new opportunities for the registration of the quantum kinetic phenomena in weak magnetic fields at high temperatures up to the room temperature. As a certain version noted above we present the first findings of the high temperature de Haas-van Alphen, 300 K, and quantum Hall, 77 K, effects as well as the quantum conductance staircase in the silicon sandwich structure that represents the ultra-narrow, 2 nm, $p$-type quantum well (Si-QW) confined by the delta barriers heavily doped with boron on the $n$-type Si (100) surface. These data appear to result from the efficiency reduction of the electron-electron interaction.

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2. EXPERIMENT

The device was prepared using silicon planar technology. After precise oxidation of the $n$-type Si (100) wafer, making a mask and performing photolithography, we have applied short-time low temperature diffusion of boron from a gas phase [7]. Finally, the ultra-shallow $p^-–n$ junction has been identified, with the $p^+$ diffusion profile depth of 8 nm and the extremely high concentration of boron, $5 \times 10^{21}$ cm$^{-3}$, according to the SIMS data [7]. Next step was to apply the cyclotron resonance, the electron spin resonance, the tunneling spectroscopy, infrared Fourier spectroscopy methods as well as the measurements of the quantum conductance staircase for the studies of the quantum properties of the silicon nanosandwich structures [7–9].

Firstly, the cyclotron resonance angular dependences have shown that the $p^+$ diffusion profile contains the ultra-narrow $p$-type silicon quantum well, Si-QW, confined by the wide-gap delta-barriers heavily doped with boron [8]. Secondly, the one-electron band scheme for the delta barriers and the energy positions of two-dimensional subbands of holes in the Si-QW have been revealed using the tunneling and the infrared Fourier spectroscopy techniques [7, 8]. Then, the studies of the spin interference by measuring the Aharonov–Casher oscillations allowed the identification of the extremely low value of the effective mass of holes [7]. These data have been also confirmed by measuring the temperature dependence of the ShdH and dHvA oscillations [8].

The planar silicon sandwich structures prepared were very surprised to demonstrate the high mobility of holes in the Si-QW in spite of the extremely high concentration of boron inside the delta barriers. Specifically, the cyclotron resonance spectra exhibit the long moment relaxation time for both heavy and light holes, $\gg 5 \times 10^{-10}$ s, and electrons, $\gg 2 \times 10^{-10}$ s [8]. These results appeared to be caused by the formation of the trigonal dipole boron centers, $B^+ – B^-$, due to the negative-$U$ reaction: $2B_0^+ \rightarrow B^+ + B^-$. The excited triplet states of the negative-$U$ centers were observed firstly by measuring the electron spin resonance angular dependences. It is important that the ESR spectra of the negative-$U$ centers are revealed only after cooling in magnetic fields, $>5 \times 10^{-10}$ s and electrons, $>2 \times 10^{-10}$ s [8].

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Thus, the magnetic susceptibility response to the capture of magnetic flux quanta on the edge channel is caused by the magnetic ordering of the stripes through single holes. This exchange interaction seems to lead to partial localization of single holes and as a result to the reduction of electron-electron interaction. Moreover, by increasing the magnetic field the static magnetic susceptibility begins to reveal the dHvA oscillations due to the creation of the Landau levels, $E_L = \hbar \omega_L (\nu + 1/2)$, $\nu$ is the number of the Landau level. In particular, a prerequisite to cover the edge channel by single magnetic flux quanta appears to be accomplished when the external magnetic field is equal to $B_0 = 1240 \mathrm{G}$, see the relationship presented above, $\Phi_0 = \Delta B \cdot S = B_0 \cdot S_0$, that is consistent with the first Landau level feeling, $v_1 = 1, v_1 = \rho_{2D} \cdot \hbar/eB_0$.

We studied carefully the dHvA oscillations created at both parallel and perpendicular orientation of the magnetic field to the Si-QW plane and registered except the dips related to the Landau levels, $\nu = 1, 2, 3, 4, 5, 6$, the fractional peaks, $\nu = 4/3$ and $\nu = 5/3$. These findings demonstrate that in certain ratio between the number of magnetic flux quanta and single holes, $1/\nu$, both composite bosons and fermions seem to be proceeded by step-by-step change of a magnetic field. Besides, using specific diagram of magnetic field—edge channel feeling, the variations of
integer and fractional values of \( \nu \) illustrate conveniently their relationship by varying the external magnetic field. It should be noted also that the strong diamagnetism of the negative \( U \) impurity stripes surrounding the Si-QW edge channels allowed the observation of the room temperature hysteresis of the dHvA oscillations dependent on the proximity of the Landau and Fermi levels. In turn, the creation of the composite bosons even in weak magnetic fields inside stripes containing single holes can lead to the emergence of the Faraday effect under the conditions of the source–drain current in the edge channel, \( I_{ds} = dE/d\Phi \). This model has been suggested by Laughlin to account for the quantum staircase of the Hall resistance [11]. Here we present the results of the measurements of not only integer but also fractional quantum Hall effect in the same magnetic field as well as the dHvA oscillations, \( I_{ds} = I_{ex} = eU_{ex}/(1/\nu)\Phi_{0} = > G_{xy} = ve^{2}/h \), where \( v \) can accept both integer and fractional values.

3. QUANTUM HALL EFFECT

Firstly, the SdH oscillations and the quantum Hall staircase are demonstrated, with the identification of both the integral and fractional quantum Hall effects (Figs. 1a and 1b). Secondly, the range of a magnetic field corresponding to the Hall plateaus and the longitudinal “zero” resistance is in a good agreement with the interval of the dHvA oscillations thereby verifying the principal role of the Faraday effect in these processes. Here, the confinement of single holes inside the stripes consisting of the negative-\( U \) dipole boron centers seems to lead not only to the efficiency reduction of the electron–electron interaction, but also promotes quantization of the interelectronic spacing [12–14]. Thus, the stabilization of a ratio between the number of magnetic flux quanta and single holes in edge channels, \( 1/\nu \), is reached at certain values of an external magnetic field, thereby promoting the registration of both integer, and fractional quantum Hall effect [15, 16].

In addition to the aforesaid, the DX- and oxygen—related centers as well as the antisite donor–acceptor pairs reveal the negative-\( U \) properties to confine effectively the edge channels in III–V compound low-dimensional structures [17–19]. However the preparation of dipolar configurations in this case appears to be accompanied by preliminary selective illumination at low temperatures.

Nevertheless, the question arises—how is possible to measure these quantum effects at high temperatures in weak magnetic fields? One of the reasons that are noted above is small effective mass, \( 10^{-4}m_{0} \), which is considered within the concept of the squeezed silicon arising owing to the negative-\( U \) impurity stripes in edge channels [7]. Other reason is caused by very effective self-cooling inside negative-\( U \) dipole boron strata under the conditions of the drain-source current [19].

4. QUANTUM CONDUCTANCE STAIRCASE IN EDGE CHANNELS OF SILICON NANOSANDWICHES

At present, the methods of a semiconductor nano-technology such as the split-gate [20–22] and cleaved edge overgrowth [23] allow the fabrication of the quasi-one-dimensional (1D) constrictions with low density high mobility carriers, which exhibit the characteristics of ballistic transport. The conductance of such quantum wires with the length shorter than the mean free path is quantized in units of \( G_{0} = g_{e}e^{2}/h \) depending on the number of the occupied 1D channels, \( N \). This quantum conductance staircase, \( G = G_{0} \cdot N \), has been revealed by varying the split-gate voltage applied to the electron and hole GaAs— [20–22] and Si-based [7] quantum wires. It is significant that spin factor, \( g_{s} \), that describes the spin degeneration of carriers in a 1D channel appears to be equal to 2 for non-interacting fermions if the external magnetic field is absent and becomes unity as a result of the Zeeman splitting of a quantum conductance staircase in strong magnetic field.

However, the first step of the quantum conductance staircase has been found to split off near the value of \( 0.7(2e^{2}/h) \) in a zero magnetic field. Two experimental observations indicate the importance of the spin component for the behavior of this \( 0.7(2e^{2}/h) \) feature. Firstly, the electron \( g \) factor was measured to increase from 0.4 to 1.3 as the number of occupied 1D subbands decreases [24]. Secondly, the height of the \( 0.7(2e^{2}/h) \) feature attains a value of \( 0.5(2e^{2}/h) \) with increasing external magnetic field [24]. These results have defined the spontaneous spin polarization of a 1D gas in a zero magnetic field as one of possible mechanisms for the \( 0.7(2e^{2}/h) \) feature in spite of the theoretical prediction of a ferromagnetic state instability in ideal 1D system in the absence of magnetic field [25].

However, the quantum conductance staircase caused by the carriers in the edge channels is still uninvestigated in a zero magnetic field. Here we demonstrate the quantum conductance staircase of holes that is revealed by varying the voltage applied to the Hall contacts prepared at edges of the ultra-narrow \( p \)-type silicon quantum well, Si-QW.

The fractional features that emerge in this conductance staircase appear to be evidence of the high spin polarization of holes in the helical edge channels. The \( R_{x} \) dependence on the bias voltage applied to the Hall contacts, \( V_{xy} \), exhibits the quantum conductance staircase to a maximum of \( 4e^{2}/(h \text{ Fig. 2a}) \). This conductance feature appeared to be independent of the sample geometric parameters that should point out on the
formation of the edge channels in Si-QW. Therefore we assume that the maximum number of these channels is equal to 2, one for up-spin and other for down-spin. It should be noted that the important condition to register this quantum conductance staircase is to stabilize the drain-source current at the value of lower than 1 nA.

In addition to the standard plateau, $2e^2/h$, the quantum conductance staircase appears to reveal the distinguishing features as the plateaus and steps that bring into correlation respectively with the odd and even fractions. Since similar quantum conductance staircase was observed by varying the top gate voltage which controls the sheet density of carriers and thus can be favorable to the spontaneous spin polarization, the variations of the $V_{xy}$ value seem also to result in the same effect on the longitudinal resistance, $R_{xx}$.

The $R_{xx}$ fractional values revealed by tuning the $V_{xy}$ voltage appear to evidence that the only closely adjacent helical channels to the edge of Si-QW make dominating contribution in the quantum conductance staircase as distinguished from the internal channels. Besides, if the silicon nanosandwich is taken into account to be prepared along the [011] axis, the trigonal dipole boron centers ordered similarly appear to give rise to the formation of the helical edge channels in Si-QW. The exchange interaction between holes localized and propagating through the QPC inside a quantum wire has been shown to give rise to the fractional quantization of the conductance unlike that in electronic systems [26]. Both the offset between the bands of the heavy and light holes, $\Delta$, and the sign of the exchange interaction constant appeared to affect on the observed value of the conductance at the addi-

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**Fig. 1.** The Hall resistance $R_{xy} = V_{xy}/I_{ds}$ and the magnetoresistance $R_{xx} = V_{xx}/I_{ds}$. $I_{ds} = 10$ nA, of a two-dimensional hole system, $p_{2D} = 3 \times 10^{13}$ m$^{-2}$, in silicon nanosandwich at the temperature of 77K vs magnetic field. (b) Manifestation of the fractional quantum Hall effect near $\nu = 1/2$, $p_{2D} = 3 \times 10^{13}$ m$^{-2}$.
tional plateaus. Within the framework of this approach for the Si-based quantum wire, the conductance plateaus have to be close to the values of $e^2/4h$, $e^2/h$ and $9e^2/4h$ from the predominant antiferromagnetic interaction [26].

Nevertheless, within frameworks of the model suggested by Laughlin the quantum conductance in the edge channels appears to result from the magnetic moment of the stripes, which is induced by the stabilized drain-source current, $I_{ds}$. Here, the value of the longitudinal conductance is defined by the number of induced fluxes, $n_{ind}$, that are captured at stripes containing the single holes which can be analyzed within frameworks of the model of quantum harmonic oscillator:

$$G_{xx} \sim \frac{e}{\partial \Phi_{ind}} = \frac{e}{n_{ind} \Phi_0} = \frac{1}{n_{ind} \hbar} e^2. \quad (1)$$

Therefore the fractional values of the longitudinal conductance appear to be caused by the combinations of composite fermions and bosons that are possible to be created in both small and large values of the stabilized drain-source current (see Figs. 3a, 3b).

Besides, by varying the voltage applied to the Hall contacts, the phase coherence of spin-dependent transport in the edge channels seems to be controlled.

5. SUMMARY

Negative-$U$ impurity stripes containing single holes appear to reduce the electron-electron interaction in the edge channels of the silicon nanosandwiches that allow the observations of quantum kinetic effects at high temperatures up to the room temperature.

The edge channels of semiconductor quantum wells confined by the subsequence of negative-$U$ impurity stripes containing single holes give rise to the creation of the composite bosons and fermions in weak magnetic fields by the step-by-step capture of magnetic flux quanta.

The strong diamagnetism of the impurity stripes that consist of the negative $U$ dipole boron centers surrounding the Si-QW edge channels allowed the high temperature observation of the de Haas–van Alphen oscillations as well as integer and the fractional quantum Hall effect.

We have also found the fractional form of the longitudinal quantum conductance staircase of holes, $G_{xx}$, that was measured as a function of the $V_{xy}$ bias voltage applied to the silicon nanosandwich prepared in the framework of the Hall geometry. This quantum conductance staircase measured to a maximum of $4e^2/h$, with the plateaus and steps that bring into correlation respectively with the odd and even fractional values, seems to reveal the formation of the helical edge channels in the $p$-type silicon quantum well.

![Fig. 2. Conductance measured at the temperature of 77 K by biasing the voltage applied to the Hall contacts, $V_{xy}$, when the drain-source current was stabilized at the value of 0.5 nA. (a) Conductance increases as a function of $V_{xy}$ to a maximum of $4e^2/h$ demonstrating the standard plateaus, $2e^2/h$ and $3e^2/h$. The inset shows the conductance feature at the value of $15/4(e^2/h)$. (b) Fractional quantum conductance staircase close to the standard plateau at the value of $2e^2/h$. Insert shows the conductance plateaus and steps corresponding to the odd and even fractions. (c) Conductance measured as a function of $V_{xy}$ in the range of the values corresponding to the $0.7(2e^2/h)$ feature.]

Finally, it should be noted that the step-by-step capture of magnetic flux quanta on all negative $U$ impurity stripes in the edge channels is determined by...
the balance between the numbers of composite bosons and fermions which is also revealed by measuring the quantum conductance value, with controlled phase coherence by varying the stabilized drain-source current value even in the absence of the external magnetic field that seems to be very interesting for models of quantum computing.

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