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LETTER TO THE EDITOR

Selective population of edge states in Si-MOSFETs in the quantum Hall regime

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Abstract. We have performed electron transport studies in the quantum Hall regime on high-mobility Si-MOSFETs with an adjustable discontinuity in the density of the two-dimensional electron gas. To achieve this we etch a gap with submicron width in the gate electrode and bias the two parts independently. For equal and integer filling factors on both sides of the gap there is negligible reflection of electrons in edge states meaning that the barrier is low compared with the Landau-level separation. For unequal but integer filling factors the longitudinal resistance across the gap is quantized, indicating that in this case the transmission coefficient of the edge states is either zero or one, depending on the gate voltages.

Since the discovery of the quantum Hall (QH) effect [1] the transport properties of a two-dimensional electron gas (2DEG) in a high magnetic field have been studied extensively. The longitudinal resistance is zero and the Hall conductance is accurately quantized in units of e^2/h if an integer number of Landau levels is completely filled. Deviations from this behaviour have been observed in samples with an inhomogeneous electron density [2–6]. Syphers and Stiles [2] used Si-MOSFETs with a step in the gate-oxide thickness to create the inhomogeneous electron density [2]. The disadvantage of this structure is that the electron density on both sides can not be adjusted independently. More recently GaAs/AlGaAs heterojunctions have been studied with a cross-gate partially depleting the electron gas below the gate [3–6]. The results have been analysed in terms of reflection and transmission of electrons in edge states following Büttiker [7].

In this letter we introduce another way to obtain a discontinuous electron density in the QH regime and to study selective population of edge states in Si, namely by using a split gate on a high-mobility Si-MOSFET. The advantage of our samples is that we can adjust the electron densities on both sides of the gap independently by changing the gate voltages V_{g1} and V_{g2}. This structure has been used before by Kopley *et al* [8] to study resonant tunnelling. In their samples a potential barrier separated the 2DEG into two parts and resonant tunnelling occurred through electronic states in the barrier. In our samples the barrier is much lower and does not exceed the Fermi level. In a high magnetic field the barrier height turns out to be even smaller than the Landau-level separation and it may be neglected if the Fermi level lies in between two Landau levels. Instead of tunnelling through the barrier the electrons pass over it with almost unit probability or are completely reflected due to discontinuity in the electron density.

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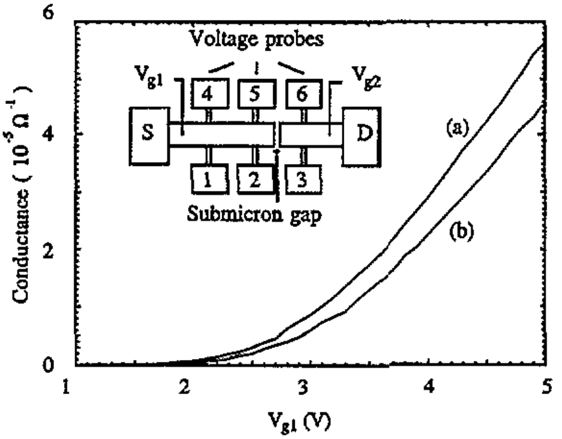

Figure 1. Conductance versus V_{g1} in zero magnetic field and at a temperature of $T = 4.2$ K. G_{s2} (curve (*a*)) is the conductance between contact source and contact 2. G_{sd} (curve (*b*)) is the conductance between contact source and contact drain (i.e. across the gap for $V_{g1} = V_{g2}$). Curve (*a*) has been scaled to compensate for the difference in geometry. The inset shows a top view of the device which has a length of 600 μm, a width of 20 μm, and a distance between the voltage probes of 160 μm.

The MOSFETs are produced on 100 Ωcm p-Si ⟨100⟩ wafers. The surface roughness is reduced by repeated oxide growth and etching. Contacts are established by a phosphorus implantation dose of 5×10^{19} $\mathrm{m^{-2}}$. The 100 nm thick gate oxide is thermally grown at 1000 °C in dry oxygen. With an aluminum gate, mobilities up to 2.7 $\mathrm{m^2\,V^{-1}\,s^{-1}}$ at 4.2 K have been reached [9]. Here we report our first results with an 80 nm thick tungsten gate. The submicron gap (with a width of about 120 nm) is defined by electron beam lithography (EBL) and by reactive ion etching (RIE). The peak mobility of the samples is 1.4 $\mathrm{m^2\,V^{-1}\,s^{-1}}$ at 4.2 K and at a carrier concentration of 1.29×10^{16} $\mathrm{m^{-2}}$. After the gap processing and an anneal step it maintains this value.

To characterize the influence of the gap we have performed two-terminal conductance measurements (see figure 1) in zero magnetic field and at a temperature of $T = 4.2$ K. G_{s2} is the conductance between contact source and contact 2, avoiding the gap (the device lay-out is shown in the inset of figure 1). G_{sd} (from source to drain) is the conductance across the gap for $V_{g1} = V_{g2}$. Although the gap reduces the conductance of the 2DEG the results do not show either the resonant tunnelling behaviour or the increased threshold voltage due to the potential barrier observed by Kopley *et al* [8]. This is due to the thicker gate oxide and the narrower gap in our samples. These features cause a larger influence of fringing fields in the gap region and therefore a lower barrier in the 2DEG.

The measurements in the QH regime were carried out in a constant magnetic field of $B = 12$ T, which was oriented perpendicularly to the 2DEG and at a temperature of $T = 1.1$ K. A small AC current ($I = 10$ nA at 83 Hz) was sent from contact i to contact j and the voltage difference between contact k and contact l was measured with a lock-in amplifier. The resulting resistance is denoted by $R_{ij,kl}$.

First we show in figure 2(*a*) the longitudinal resistance $R_{s5,12}$ as a function of V_{g1}. The fully developed Shubnikov–de Haas minima at $V_{g1} = 6.5$ V, 9.2 V and 11.8 V correspond to complete filling of the first ($\nu = 4$), of the lowest spin band of the second ($\nu = 6$), and of the second ($\nu = 8$) Landau levels, respectively. The structure due to valley splitting

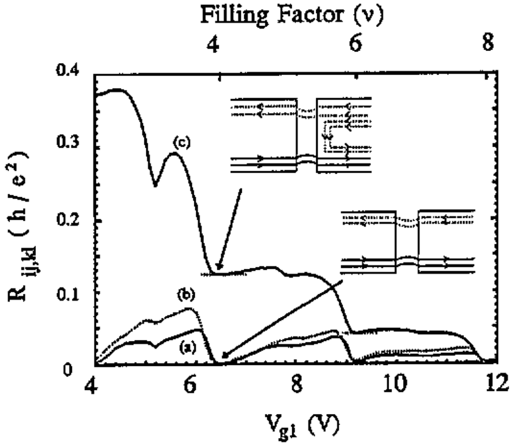

Figure 2. Four terminal resistances as a function of V_{g1} for different V_{g2} at $T = 1.1$ K and $B =$ 12 T. Curve (*a*) is $R_{s5,12}$ for $V_{g2} = 0$ V. Curves (*b*) and (*c*) are $R_{sd,23}$ for $V_{g2} = V_{g1}$ and $V_{g2} =$ 11.8 V, respectively. For filling factors $\nu = 4$ and 6 in curve (*c*), the resistance across the gap is equal to the Hall resistance difference (indicated by the horizontal broken lines) of the two regions. The insets show a representation of the edge channels in which each line corresponds to a spin band. The upper left inset is for the case of $\nu_1 = 4$ and $\nu_2 = 8$. The lower right one is for the case of $\nu_1 = \nu_2 = 4$.

Table 1. Transmission coefficient T_u of the upper spin band and resistance minimum R_{min} for different integer filling factors ν. T_u follows from $(1 - T_u) = [(\nu/2)R_{min}]/[(h/\nu e^2) + R_{min}]$.

ν	R_{min} (Ω)	T_u (%)
4	36	98.9
6	117	92.1
8	48	94.1

(odd filling factor) does not develop completely at the available magnetic field and temperature.

In figure 2(*b*), for which $V_{g1} = V_{g2}$, the longitudinal resistance across the gap $R_{sd,23}$ shows almost the same minima as $R_{s5,12}$ for integer filling factors $\nu = 4$, 6 and 8. This indicates that when the Landau levels are completely filled the barrier height produced by the submicron gap is low compared with the Landau-level separation. We assume that reflection only occurs for electrons in the upper spin band and calculate, following Büttiker [7], the transmission coefficient T_u of these electrons from the measured longitudinal resistance of the minima R_{min} (table 1). There is negligible reflection of electrons in the edge states for equal and integer filling factors. When the Landau levels are not completely filled there is still some reflection due to the barrier. The longitudinal resistance across the gap is larger than that of an equivalent part of the 2DEG without a gap (curves (*b*) and (*a*) in figure 2).

For $V_{g1} \neq V_{g2}$ the measured longitudinal resistance across the gap (shown by figure 2(*c*)) is equal to the Hall resistance difference ΔR_H of the two regions for integer filling factor $\nu_1 = 4$ and 6 ($\nu_2 = 8$ is constant, where $\nu_{1,2}$ are the filling factors on the two sides of the gap). The deviation of the measured longitudinal resistance $R_{sd,23}$ from the theoretical value $\Delta R_H = (1/\nu_1 - 1/\nu_2)\, h/e^2$ is less than 10 Ω. It reveals that electrons in ν_1 edge channels are completely transmitted and in $(\nu_2 - \nu_1)$ edge channels are completely reflected where ν_1 and ν_2 can be adjusted independently. Similar behaviour has been found at the boundary of the gated and ungated regions in a GaAs/AlGaAs heterojunction with a cross-gate [4, 5].

One of the features of the present structure is that the edge states are populated selectively up to different levels. Edge channels that have been reflected at the discontinuity in the electron density have a different occupation number from channels that are transmitted from the other side. This means that a non-equilibrium distribution of electrons among the edge states is created at a single edge. If additional submicron gaps are fabricated in the voltage leads it is also possible to detect these different occupations of the edge states by allowing additional edge states to enter the voltage contact one by one. This has been demonstrated before in a GaAs/AlGaAs heterojunction with quantum point contacts in the presence of a magnetic field [10]. An extension of this techique to Si offers the possibility of comparing the relevant relaxation mechanisms in these materials.

In summary, the experiments show that a split-gate Si-MOSFET can offer a discontinuous filling factor in the QH regime. The transport properties can be explained by using the Büttiker picture of reflection and transmission of electrons in edge states. Furthermore the technique can be applied to study the relaxation of a non-equilibrium distribution of electrons in edge states in Si.

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References

[1] von Klitzing K, Dorda G and Pepper M 1980 *Phys. Rev. Lett.* **45** 494
[2] Syphers D A and Stiles P J 1985 *Phys. Rev.* B **32** 6620
[3] Hirai H, Komiyama S, Hiyamizu S and Sasa S 1989 *Proc. 19th Int. Conf. on the Physics of Semiconductors (1988)* ed W Zawadski (Singapore: World Scientific) p 55
[4] Haug R J, MacDonald A H, Streda P and von Klitzing K 1988 *Phys. Rev. Lett.* **61** 2797
[5] Washburn S, Fowler A B, Schmid H and Kern D 1988 *Phys. Rev. Lett.* **61** 2801
[6] Komiyama S, Hirai H, Sasa S and Hiyamizu S 1989 *Phys. Rev.* B **40** 12 566
[7] Büttiker M 1988 *Phys. Rev.* B **38** 9375
[8] Kopley T E, McEuen P L and Wheeler R G 1988 *Phys. Rev. Lett.* **61** 1654
[9] Kruithof G H, Klapwijk T M and Bakker S 1991 *Phys. Rev.* B **43** 6642
[10] van Wees B J, Willems E M M, Kouwenhoven L P, Harmans C J P M, Williamson J G, Foxon C T and Harris J J 1989 *Phys. Rev.* B **39** 8066