RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 52, NUMBER 16 15 OCTOBER 1995-II

Tuning of the quantum-Hall-effect-state–insulator transition by tilting of magnetic field

S.I. Dorozhkin
Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, Moscow District, 142432, Russia

C.J. Emeleus and T.E. Whall
Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

G. Landwehr
Physikalisches Institut der Universität Würzburg, Am Hubland, 97074 Würzburg, Germany
(Received 26 January 1995; revised manuscript received 10 May 1995)

In a dilute two-dimensional hole gas located at a Si/SiGe heterojunction we have investigated the variation of magnetoresistance and Hall resistance with tilting of magnetic field. The only pronounced effect of the longitudinal component of field is a strong increase of the magnetoresistance in the insulating state located between the quantum-Hall-effect states with filling factors 1 and 3. The Hall resistance in the insulating state was found to be insensitive to the longitudinal field. A model is proposed that explains the appearance of an insulating state interrupted by the quantum-Hall-effect states. It describes a strong dependence of the insulating state width on the ratio of the Zeeman splitting and cyclotron energies. It is shown that the latter effect might be responsible for our observations.

The magnetic-field-induced metal-insulator transition is well known in bulk semiconductors (magnetic freeze-out) where it is caused by squeezing of the electron wave function at localization centers. Modern interest in this transition in high-quality two-dimensional electron systems is supported by an idea[1] that the magnetic field stimulates Wigner crystallization in these systems, with the observed insulating state being a Wigner crystal. At the moment this is a rather large area of research (see, for example, Ref. 2 and references therein) but in this paper we address the special case where an insulating state exists at magnetic level filling factors ν higher than unity, in between different quantum-Hall-effect states. Such a state was first observed in Si metal-oxide-semiconductor field-effect transistors (MOSFET's) of appropriate quality at low electron concentrations,[3–5] and the appearance of the insulating state was attributed to Wigner crystallization. The latter conclusion was based, in particular, on the following argument. Under quantum-Hall-effect conditions, the off-diagonal magnetoconductivity σ_{xy} is proportional to the number of bands of delocalized electron states under the Fermi level.[6] Divergence of the magnetoresistivity (i.e., magnetoresistance per square R_{xx}) in an insulating state implies vanishing σ_{xy} and, therefore, disappearance of the delocalized states under the Fermi level. On the other hand, for $\nu>1$ the conventional understanding is that at least one totally occupied magnetic level exists under the Fermi level, with a band of delocalized states located at the magnetic level center, which would give a nonzero σ_{xy}. To avoid this discrepancy an additional mechanism, different from the localization of noninteracting electrons (presumably Wigner crystallization), was supposed to be necessary in order to drive a system into the insulating state.

Recently, however, rather strong experimental arguments have been put forward,[7] which demonstrate that the transition from the insulating state to a metallic one in Si MOSFET's has a percolation nature, indicating electron localization to be the origin of the former state. A possible explanation of the effects observed, in terms of percolation phenomena, was proposed in a recent paper.[8] It was shown there that with the presence of a long-range potential modulation in a sample, oscillations of the Fermi level relative to the extended states of magnetic levels can lead to transitions between the quantum-Hall-effect states and the insulating state. As well as in electron channels of Si MOSFET's, such a reentrant insulating state at $\nu>1$ was recently reported for electron channels of $GaAs/Al_xGa_{1-x}As$ heterojunctions[9,10] and for p channels of $Si/Si_{1-x}Ge_x$ heterostructures.[11] In the present paper we report the strong promotion of this insulating phase in Si/SiGe p channels by magnetic field tilting and discuss a possible explanation of this result in terms of theory.[8]

The samples used for the investigations were grown by solid source molecular-beam epitaxy: detailed information on the growth method has been given elsewhere.[12] The two-dimensional holes are confined in an approximately triangular potential well, located at the surface of a $Si_{0.8}Ge_{0.2}$ layer and with a hole mobility at liquid helium temperatures of $\sim 2000\ \mathrm{cm^2/V\,s}$. Resistance measurements were made at 14 Hz with the sample current set to 50 nA, having ensured that the current-voltage relationship was linear in the range of temperatures investigated. Two Hall bars from the same wafer were studied in detail and the results of identical experiments on each show good agreement.

Typical experimental results are shown in Fig. 1 as a function of the normal component H_z of the magnetic field at different tilting angles θ. The Shubnikov–de Haas oscillations of magnetoresistance R_{xx} in the weak magnetic field are independent of θ, which proves that we are dealing with a two-dimensional system originating from heavy holes with angular momentum projection $m_J=\pm 3/2$.[13] Both size quantization and the strain present in the SiGe layer are respon-

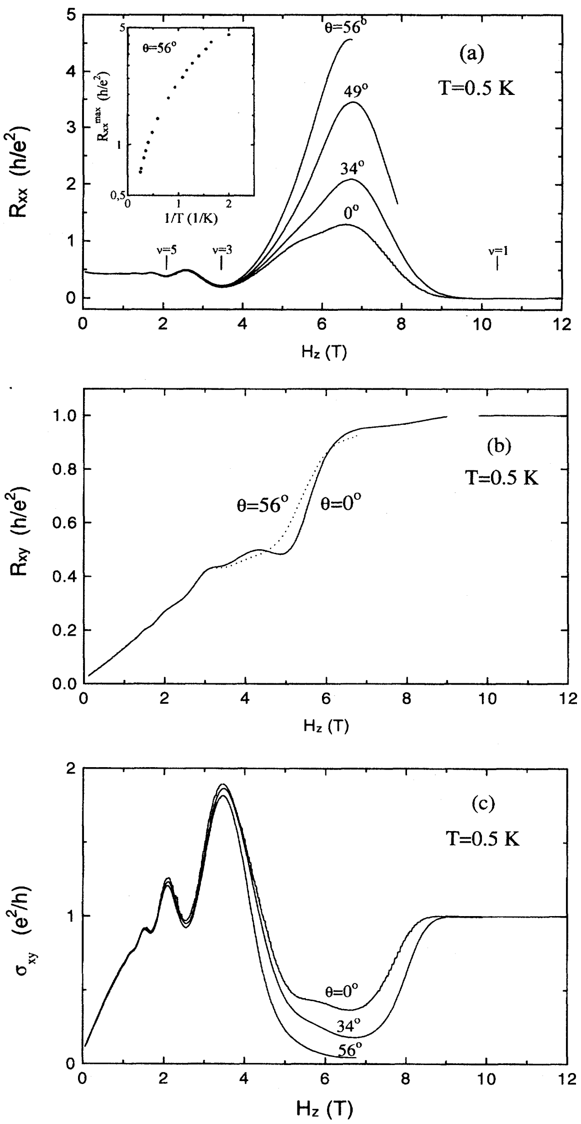

FIG. 1. (a) Magnetoresistance per square R_{xx} (in units of $h/e^2=25.813$ kΩ) vs normal magnetic field H_z at different angles θ between the magnetic field and a normal to the two-dimensional system. $T=0.5$ K. Inset: Temperature dependence of the magnetoresistance maximum $R_{xx}^{\max}$ at $\theta=56°$. (b) Hall resistance R_{xy} vs H_z at $\theta=0°$ (solid line) and $\theta=56°$ (dotted line). $T=0.5$ K. (c) Off-diagonal conductivity σ_{xy} vs H_z at different θ. The curves are calculated from the data of (a) and (b).

sible for splitting the light- and heavy-hole bands. The minima of the oscillations are periodic in the inverse magnetic field. Following the traditional procedure we can determine both the values of filling factors ν, shown at the minima, and the areal carrier concentration $n_s=2.5\times10^{11}$ cm^{-2}. The main effect of the magnetic field tilting is a large increase of the magnetoresistance maximum between filling factors 1 and 3. Its value at the largest θ $(=56°)$ of $R_{xx}^{\max}=117$ kΩ/□ considerably exceeds $h/e^2=25.813$ kΩ, characteristic of the transition to an insulating state. Note that the magnetoresistance maximum is strongly temperature dependent [see inset in Fig. 1(a)], demonstrating clearly a

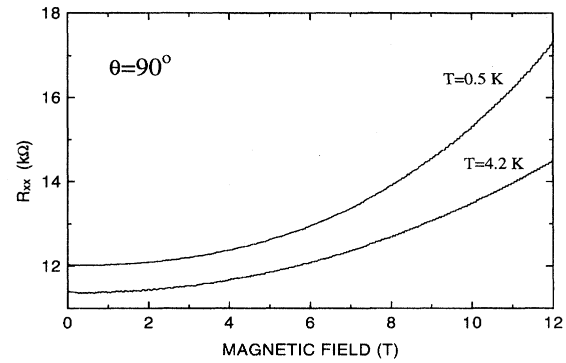

FIG. 2. Magnetoresistance per square vs magnetic field aligned parallel to the two-dimensional system. $T=4.2$ and 0.5 K.

tendency to diverge as the temperature goes to zero. This aspect of the R_{xx} behavior becomes much more pronounced in a tilted magnetic field. In particular, at $\theta=56°$ $R_{xx}^{\max}$ increases by more than a factor of 6 when the temperature is lowered from 4.2 K to 0.5 K. We believe that these results allow us to identify the state observed in tilted magnetic field between filling factors 1 and 3 as an insulating one.[14] It is extremely important that at higher fields the insulating state is replaced by the quantum-Hall-effect state corresponding to one occupied magnetic level. Note that the Hall resistance [Fig. 1(b)] is rather insensitive to the tilting angle, i.e., to the transition into and out of the insulating state. Such behavior of the magnetoresistance tensor components has been predicted[15,16] for the so-called Hall insulating state[16] and observed in GaAs/Al$_x$Ga$_{1-x}$As heterojunctions.[17–20] The large value of magnetoresistance in the insulating state indicates that the nondissipative edge currents are not of importance,[21] which allows us to assume local relations between the electric field and the current density through the magnetoconductivity tensor. The calculated off-diagonal component $\sigma_{xy}=R_{xy}/(R_{xx}^2+R_{xy}^2)$ versus H_z is shown in Fig. 1(c). In the insulating state, σ_{xy} tends to zero, implying an absence of delocalized electron states both on and under the Fermi level. In Fig. 2 the magnetoresistance is shown for the magnetic field aligned parallel to the two-dimensional layer $(\theta=90°)$. The increase of magnetoresistance is less than 50% over the whole range of longitudinal field. This shows for certain that the effects being considered are not caused by the longitudinal field alone: magnetic quantization is of crucial importance for driving the system into an insulating state.

A possible explanation for the reentrant transitions between the quantum-Hall-effect states and the insulating state was recently proposed[8] by one of the authors. It is based on a model considering a regular long-range potential modulation in a sample and is expected to be applicable to the case of long-range potential fluctuations.[8] In the following, we analyze the possibility of explaining the observed effect of magnetic field tilting in terms of this model.

Consider a regular potential modulation that looks like a chessboard with potential energy $V=0$ and $V=2V_0$ in the white and black squares, respectively. The potential energy $V(\mathbf{r})$ varies linearly between 0 and $2V_0$ within the transition regions, which are narrow in comparison with the square size

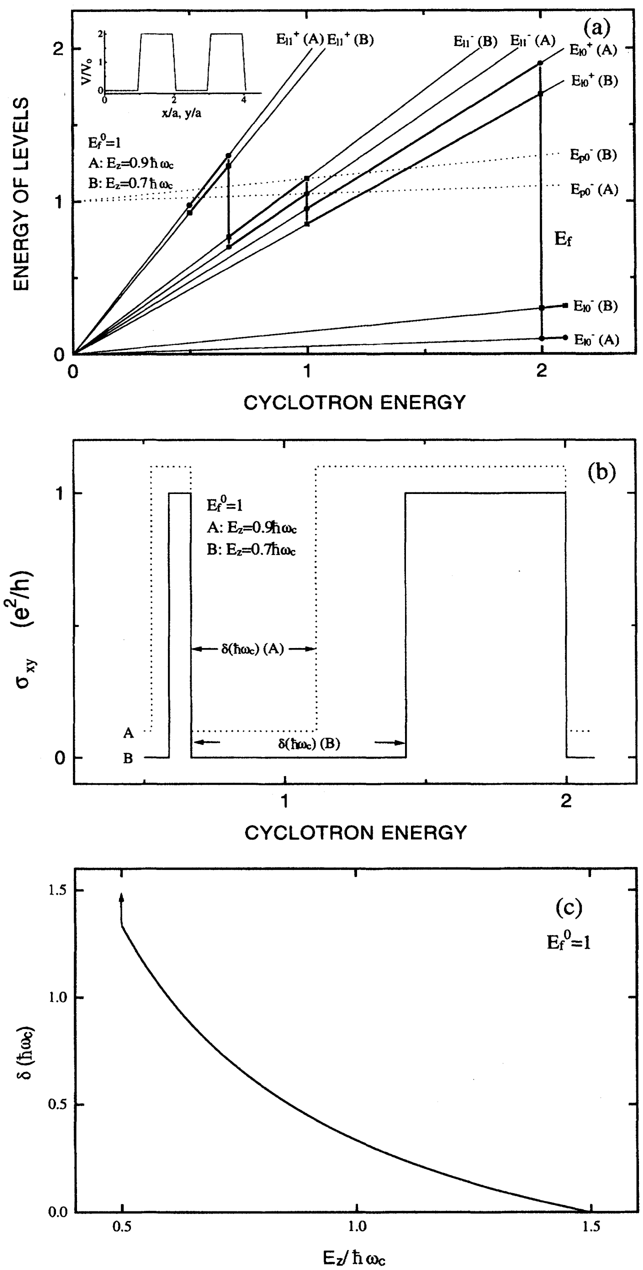

FIG. 3. (a) Fermi energy E_F (wide solid line) vs the cyclotron energy for two different values of the Zeeman splitting assumed to be proportional to the cyclotron energy: $E_z=0.9\hbar\omega_c$ (A) and $E_z=0.7\hbar\omega_c$ (B). The points of inflection are shown by dots and squares for cases A and B, respectively. The chosen carrier concentration corresponds to the zero-magnetic-field Fermi energy $E_F^0=1$, $T=0$ K. Lower magnetic sublevels E_{ln} are shown by narrow solid lines and marked in accordance with the notation used in the text. Letters A and B in the brackets indicate the choice of the Zeeman splitting. The extended states of the magnetic levels are shown by dotted lines with the corresponding notation. All the energies are given in the units of V_0. Inset: variation of the model potential with coordinates (x,y) in the plane of the two-dimensional electron system (a is the square size). (b) Off-diagonal conductivity σ_{xy}, calculated as described in the model, vs the cyclotron energy for the choice of parameters used in (a). In case A, the corresponding dotted line is shifted up by 0.1 for clarity. (c) Dependence of the insulating state width $\delta(\hbar\omega_c)$, defined in (b), on the ratio of the Zeeman splitting and cyclotron energies. $E_F^0=1$, $T=0$ K. The arrow at $E_z/\hbar\omega_c=0.5$ indicates the divergence of $\delta(\hbar\omega_c)$.

[see inset in Fig. 3(a)] but still much larger than the magnetic length. In such a potential, the magnetic levels $E_n^{\pm}(\mathbf{r})=(n+1/2)\hbar\omega_c\pm E_z/2+V(\mathbf{r})$ are inhomogeneously broadened with the extended states located at energies $E_{pn}^{\pm}=(n+1/2)\hbar\omega_c\pm E_z/2+V_0$ (see, for example, Ref. 22). Here n is an integer, $\omega_c=eH_z/m^*c$ is the cyclotron frequency (m^* is a carrier effective mass), and E_z is the Zeeman splitting. The narrow transition regions give a small contribution to the density of states, which can then be approximated for each magnetic level by two peaks at energies $E_{ln}^{\pm}=(n+1/2)\hbar\omega_c\pm E_z/2$ and $E_{un}^{\pm}=E_{ln}^{\pm}+2V_0$. These peaks with the degeneracy $eH_z/2hc$ are referred to below as magnetic sublevels. At a fixed carrier concentration the Fermi level E_F oscillates as a function of magnetic field [Fig. 3(a)], crossing the energies of extended states. Its zero-magnetic-field value E_F^0 characterizes the carrier concentration. As is easy to see from Fig. 3(a), the positions of some intersects depend strongly on the relationship between the Zeeman splitting and cyclotron energies. In accordance with the generally accepted point of view, we assume that the off-diagonal conductivity σ_{xy} is equal to e^2/h times the number of delocalized bands under the Fermi level. The corresponding dependence of conductivity σ_{xy} is shown in Fig. 3(b). This figure describes a reentrant transition between the quantum-Hall-effect state with $\sigma_{xy}=1$ and the insulating state with $\sigma_{xy}=0$. The insulating state width $\delta(\hbar\omega_c)$ depends on the ratio of the Zeeman splitting and cyclotron energies, as shown in Fig. 3(c). In accordance with the results of Ref. 7 the increase of the insulating state width should cause the increase of the magnetoresistance activation energy and the maximum magnetoresistance value, as observed in our experiment. At $E_z/\hbar\omega_c=0.5$, $\delta(\hbar\omega_c)$ goes to infinity due to the coalescence of the considered insulating state with those at $\hbar\omega_c>2$.

Our model naturally explains the appearance of an insulating state in between the quantum-Hall-effect states, with the effect being strongly dependent on the Zeeman splitting. Unfortunately, its direct quantitative comparison with our experimental data is unlikely to be possible. The main problem arises from the complicated energy spectrum of the two-dimensional holes. While we believe that the "naive picture" of a linear dependence of magnetic level energy on field is not a very bad approximation we do not definitely know the dependence of the Zeeman splitting on the longitudinal magnetic field. Indeed, the effect of a longitudinal field on the energy of magnetic levels of the ground subband in p channels is rather nontrivial. This subband originates from the heavy holes with the angular momentum projections $m_J=\pm 3/2$. To first order in perturbation theory a longitudinal field does not change the magnetic level energies, which manifests itself as an extreme anisotropy of the g factor.[13] An accurate consideration of the effect of this field is rather complicated and should include the mixing of heavy- and light-hole branches, which is dependent on both material parameters and a carrier concentration. Such investigations are possible but probably only by using computational methods.[23] Corresponding calculations for Si/SiGe heterostructures have not yet been performed. Note that there is some experimental evidence[24] that the effect of a longitudinal magnetic field on the energy spectrum of two-dimensional holes in Si MOSFET's is dependent on the orientation of this field relative to the crystal axes. The results,[24] when interpreted in terms of this "naive picture," mean that the ratio $E_z/\hbar\omega_c$ may either increase or decrease in the tilted field, depending on the direction of H_x in the plane of the system.

Experimental data for p channels of Si/SiGe heterostructures show that energy splittings corresponding to odd filling factors essentially exceed those corresponding to even filling factors. In terms of a linear energy-level dependence on field, this would signify that the Zeeman splitting is comparable to the cyclotron one.[11] Our experimental data in the tilted magnetic field would be consistent with the results of our model under the assumption that $E_z/\hbar\omega_c$ is not far from unity and decreases in tilting magnetic field.

To complete the discussion of our experimental results, we would like to point out that we do not believe that Wigner crystallization can occur in our samples with the rather high level of disorder existing in them. Indeed, the simple estimation of elastic scattering distance from the zero-magnetic-field conductivity shows that it is very close to the mean carrier-carrier spacing of 20 nm, which suggests that the charged carriers are unlikely to order in a crystalline manner in this potential environment. Instead, we believe that carrier localization and percolation effects due to long-range potential fluctuations, as illustrated by the model presented here, constitute the most plausible explanation for the reentrant behavior observed in σ_{xy}.

It would be of great interest to carry out similar investigations of the insulating state in two-dimensional electron systems, where the dependence of Zeeman splitting on longitudinal field is well known. It is also hoped that the phenomena reported here can be studied in more detail using gated samples, in order to vary the carrier density of the two-dimensional hole system.

We would like to thank R.A. Kubiak for growth of the sample used in this study. One of us (C.J.E.) is very grateful to the Royal Society for financial support of his visit to the Institute of Solid State Physics of the Russian Academy of Sciences, where the experiments were performed. This work was supported in part by the Deutsche Forschungsgemeinshaft with Grant No. La 179/54-1 and by the Russian Foundation for Fundamental Research with Grant No. 95-02-06107.

[1] Yu.E. Lozovik and V.I. Yudson, Pis'ma Zh. Éksp. Teor. Fiz. **22**, 26 (1975) [JETP Lett. **22**, 11 (1975)].

[2] H.W. Jiang *et al.*, Phys. Rev. B **44**, 8107 (1991).

[3] M D'Iorio, V.M. Pudalov, and S.G. Semenchinsky, Phys. Lett. A **150**, 422 (1990).

[4] S.V Kravchenko, J.A.A.J Perenboom, and V.M. Pudalov, Phys. Rev. B **44**, 13 513 (1991).

[5] M. D'Iorio, V.M. Pudalov, and S.G. Semenchinsky, Phys. Rev. B **46**, 15 992 (1992).

[6] B.I. Halperin, Phys. Rev. B **25**, 2185 (1982).

[7] A.A. Shashkin, V.T. Dolgopolov, and G.V. Kravchenko, Phys. Rev. B **49**, 14 486 (1994).

[8] S.I. Dorozhkin, Pis'ma Zh. Éksp. Teor. Fiz. **60**, 578 (1994) [JETP Lett. **60**, 595 (1994)].

[9] H.W. Jiang *et al.*, Phys. Rev. Lett. **71**, 1439 (1993).

[10] T. Wang *et al.*, Phys. Rev. Lett. **72**, 709 (1994).

[11] F.F. Fang *et al.* (unpublished).

[12] D.W. Smith *et al.*, Appl. Phys. Lett. **61**, 1453 (1992).

[13] S.I. Dorozhkin, Solid State Commun. **72**, 211 (1989).

[14] Subsequent investigations, using the present results, were carried out by V.T. Dolgopolov *et al.* (Pis'ma Zh. Éksp. Teor. Fiz. **62**, 152 (1995) [JETP Lett. **62**, 168 (1995)]) who measured nonlinear current-voltage characteristics and their temperature dependence in the insulating phase at a fixed, large tilting angle. The same samples, placed in a dilution refrigerator, exhibit an increase of the magnetoresistance maximum studied here by several orders of magnitude on lowering the temperature from 0.5 K to 30 mK (the magnetic field is about 14 T).

[15] O. Viehweger and K.B. Efetov, J. Phys. Condens. Matter **2**, 7049 (1990).

[16] S. Kivelson, D.-H. Lee, and S.-C. Zhang, Phys. Rev. B **46**, 2223 (1992).

[17] V.J. Goldman, M. Shayegan, and D.C. Tsui, Phys. Rev. Lett. **61**, 881 (1988).

[18] S.I. Dorozhkin *et al.*, Pis'ma Zh. Éksp. Teor. Fiz. **57**, 55 (1993) [JETP Lett. **57**, 58 (1993)].

[19] V.J. Goldman *et al.*, Phys. Rev. Lett. **70**, 647 (1993).

[20] T. Sajoto *et al.*, Phys. Rev. Lett. **70**, 2321 (1993).

[21] S.I. Dorozhkin *et al.*, Pis'ma Zh. Éksp. Teor. Fiz. **52**, 1233 (1990) [JETP Lett. **52**, 652 (1990)]. It has been shown that nondissipative edge currents introduce an upper limit on the magnetoresistance measured between series potential probes that is equal to the difference of the neighboring quantized Hall resistance values. In our case this limit is expected to be $(1-1/3)h/e^2=(2/3)h/e^2$.

[22] S. Luryi, in *High Magnetic Fields in Semiconductor Physics*, edited by G. Landwehr, Springer Series in Solid-State Sciences Vol. 71 (Springer-Verlag, Berlin, Heidelberg, 1987), p. 16.

[23] W. Heuring *et al.*, in *High Magnetic Fields in Semiconductor Physics II*, edited by G. Landwehr, Springer Series in Solid-State Sciences Vol. 87 (Springer-Verlag, Berlin, Heidelberg, 1989), p. 190.

[24] S.I. Dorozhkin, in *High Magnetic Fields in Semiconductor Physics III*, edited by G. Landwehr, Springer Series in Solid-State Sciences Vol. 101 (Springer-Verlag, Berlin, Heidelberg, 1992), p. 429.