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Two-dimensional metal-insulator transition and in-plane magnetoresistance in a high-mobility strained Si quantum well

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The apparent metal-insulator transition is observed in a high-quality two-dimensional electron system (2DES) in the strained Si quantum well of a $\mathrm{Si/Si_{1-x}Ge_x}$ heterostructure with mobility $\mu=1.9\times10^5\ \mathrm{cm^2/V\,s}$ at density $n=1.45\times10^{11}\ \mathrm{cm^{-2}}$. The critical density, at which the thermal coefficient of low T resistivity changes sign, is $\sim0.32\times10^{11}\ \mathrm{cm^{-2}}$, a very low value obtained in Si-based 2D systems. The in-plane magnetoresistivity $\rho(B_{ip})$ was measured in the density range, $0.35\times10^{11}<n<1.45\times10^{11}\ \mathrm{cm^{-2}}$, where the 2DES shows the metalliclike behavior. It first increases and then saturates to a finite value $\rho(B_c)$ for $B_{ip}>B_c$, with B_c the full spin-polarization field. Surprisingly, $\rho(B_c)/\rho(0)\sim1.8$ for all the densities, even down to $n=0.35\times10^{11}\ \mathrm{cm^{-2}}$, only 10% higher than n_c. This is different from that in clean Si metal-oxide-semiconductor field-effect transistors, where the enhancement is strongly density dependent and $\rho(B_c)/\rho(0)$ appears to diverge as $n\rightarrow n_c$. Finally, we show that in the fully spin-polarized regime, dependent on the 2DES density, the temperature dependence of $\rho(B_{ip})$ can be either metalliclike or insulating.

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The two-dimensional (2D) metal-to-insulator transition (MIT) has been of great interest.[1–3] According to the well-established scaling theory,[4] any amount of disorder in a noninteracting 2D electron system (2DES) will localize the carriers at zero temperature (T) and zero magnetic (B) field, and the ground state of the 2DES is an insulator, whose conductivity goes to zero logarithmically as $T\rightarrow0$. Recent experimental studies in high-quality dilute 2D systems where the electron-electron ($e-e$) interaction is large, however, have shown the existence of a metalliclike state and an apparent metal-insulator transition. There, the magnitude of the 2DES resistivity (ρ) undergoes a change from decreasing with decreasing T, ($d\rho/dT>0$), a metalliclike behavior, to increasing with decreasing T, ($d\rho/dT<0$), an insulating behavior, at a critical density n_c, where $d\rho/dT\sim0$.

For the metalliclike state, its response to a pure in-plane magnetic field (B_{ip}) is intriguing and has generated many studies.[5–15] In conventional clean Si metal-oxide-semiconductor field-effect transistors (MOSFETs) it is observed that the in-plane magnetoresistance (MR) of the 2DES, $\rho(B_{ip})$, first increases as B_{ip}^2 at low B_{ip}. After a critical B field B_c, which has been identified as the full spin-polarization B field for the 2DES,[7–9] the in-plane MR saturates to a constant value $\rho(B_c)$.[16] The enhancement of $\rho(B_{ip})$ under high B_{ip} in this 2DES is attributed to the reduction of screening of charged impurities in a Fermi liquid, caused by the loss of spin degeneracy.[17–19] A ratio of $\rho(B_c)/\rho(0)=4$ is expected in Si MOSFETs where the background impurity scattering dominates, and it does not depend on carrier density. Experimentally, however, this ratio was observed to be strongly density dependent and close to the critical density n_c, $\rho(B_c)/\rho(0)$ can be as large as several orders of magnitude.[5,19] Though its origin remains unclear, it is speculated[19] that this extremely large enhancement probably is related to strong surface roughness scattering in Si MOSFETs.

In recent years, the 2DES in the high-quality strained Si quantum well (QW) in $\mathrm{Si/Si_{1-x}Ge_x}$ heterostructures has emerged as a promising Si system to study strong electron-electron interaction physics, e.g., the fractional quantum Hall effect.[20] In this system, electron mobility at least two to three times better than that in the cleanest Si MOSFETs can be routinely achieved. Compared to Si MOSFETs where the 2D carriers experience short-range scattering, in strained Si QW's the main scattering mechanism is of long range, due to the remote impurities in the modulation doping layer. Indeed, in our high-quality $\mathrm{Si/Si_{1-x}Ge_x}$ sample, the ratio of the transport time and quantum time is ~10, confirming that the carrier scattering is of a small angle nature. Furthermore, the interface of $\mathrm{Si/Si_{1-x}Ge_x}$ is much smoother than that of $\mathrm{Si/SiO_2}$. Taking these facts together, the strained Si QW is an ideal, alternative Si system to study the MIT. In fact, a few experiments have been carried out. However, due to the difficulty of density modulation in $\mathrm{Si/Si_{1-x}Ge_x}$, to date, experiments have been limited to relatively high densities.

In this paper, we report experimental results on the apparent metal-insulator transition in a high-quality 2DES in the strained Si quantum well of a $\mathrm{Si/Si_{1-x}Ge_x}$ heterostructure. The 2DES density is tuned from $1.45\times10^{11}\ \mathrm{cm^{-2}}$ to a record low $n=0.27\times10^{11}\ \mathrm{cm^{-2}}$. The critical density is found to be $\sim0.32\times10^{11}\ \mathrm{cm^{-2}}$, much smaller than that observed in clean Si MOSFETs, where $n_c\sim0.8\times10^{11}\ \mathrm{cm^{-2}}$. The in-plane magnetoresistivity $[\rho(B_{ip})]$ measurements were carried out in the density regime where the 2DES shows the metalliclike behavior at $B=0$. It is observed that $\rho(B_{ip})$ first increases as $\sim B_{ip}^2$ and then saturates to a finite value $\rho(B_c)$ for $B>B_c$. When plotted vs B_{ip}/B_c, $\rho(B_{ip})/\rho(0)$ collapses onto a single curve. Surprisingly, $\rho(B_c)/\rho(0)\sim1.8$ for all the densities ranging from 0.35×10^{11} to $1.45\times10^{11}\ \mathrm{cm^{-2}}$. This is differ-

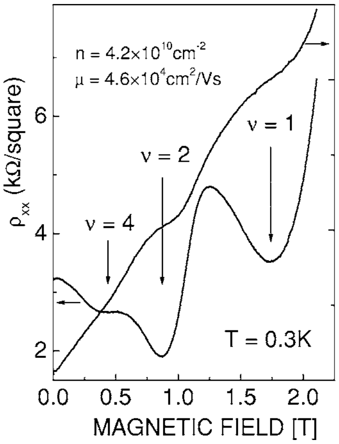

FIG. 1. The magnetoresistivity and the Hall resistance at the density of $n=0.42\times10^{11}$ cm^{-2}. The sample temperature is 0.3 K. The vertical arrows mark the positions of the IQHE states.

ent from that in clean Si MOSFETs, where $\rho(B_c)/\rho(0)$ is strongly density dependent and appears to diverge as $n\to n_c$. We believe that this quantitative difference is probably related to a smooth interface and thus less roughness scattering in our high-quality specimen.

The starting wafer is a molecular beam epitaxy-grown $\mathrm{Si/S}_{1-x}\mathrm{Ge}_x$ heterostructure, with a 15-nm-wide strained Si quantum well. Details of the heterostructure are given in Ref. 21. A field-effect transistor-type device was then fabricated.[22] At $T\sim300$ mK and zero gate voltage, the 2DES has a density $n=1.45\times10^{11}$ cm^{-2} and mobility $\mu=190\,000$ cm^2/V s. Standard low-frequency ($\sim$7 Hz) lock-in techniques were used to measure the 2D transport coefficients.

We show in Fig. 1 the magnetoresistivity ρ_{xx} and Hall resistance ρ_{xy} at $n=0.42\times10^{11}$ cm^{-2}. The appearance of strong integer quantum Hall effect (IQHE) states at Landau level fillings $\nu=1$, 2, as well as at $\nu=4$ demonstrates the high quality of the 2DES.

In Fig. 2, the temperature dependence of ρ, the zero B resistivity, is displayed at the selected densities. For $n\geqslant0.63\times10^{11}$ cm^{-2}, ρ monotonically decreases with decreasing temperature. Below 0.3×10^{11} cm^{-2}, ρ increases rapidly with decreasing T and the 2DES is in the insulating regime. The critical density n_c, at which the thermal coefficient of low T resistivity changes sign, is 0.32×10^{11} cm^{-2}. At this density, the variation in resistivity is $\sim\pm2.5\%$ and $d\rho/dT\sim0$ below $T=1$ K. We emphasize that it is by far the lowest n_c obtained in the Si-based 2D systems. In the so-called transition regime between $0.33\times10^{11}\leqslant n\leqslant0.515\times10^{11}$ cm^{-2}, ρ first increases with decreasing T, reaches a maximum, and then decreases with continuously decreasing temperature.

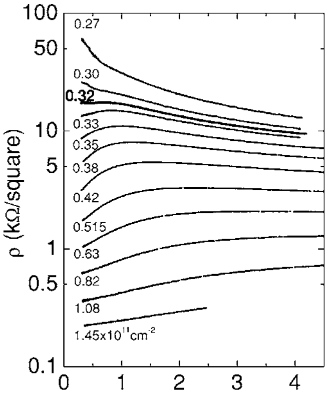

FIG. 2. 2D resistivity ρ as a function of temperature at various densities.

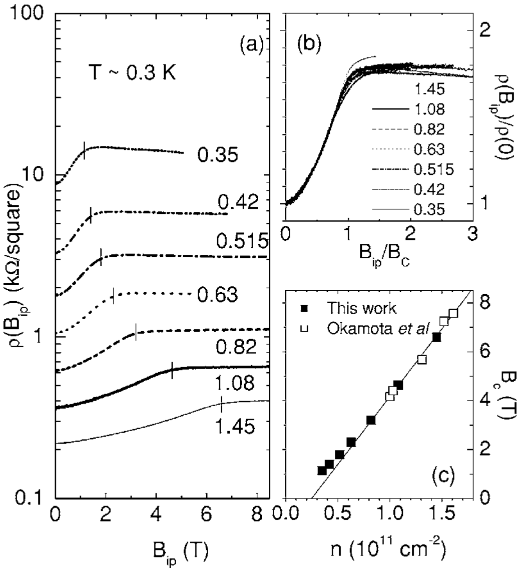

FIG. 3. (a) In-plane magnetoresistivity at a few selected 2DES densities. n is in units of 10^{11} cm^{-2}. The positions of full polarization of the B field are marked by the short lines. (b) The normalized in-plane magnetoresistivity $\rho(B_{ip})/\rho(0)$ vs B_{ip}/B_c. (c) B_c as a function of electron density. Results from Ref. 24 are included. The straight line is a linear fit for densities $n>0.8\times10^{11}$ cm^{-2}.

The in-plane magnetoresistivity $\rho(B_{ip})$ is measured at the densities $n>n_c$ where the 2DES shows the metalliclike behavior.[5–15] In Fig. 3(a), $\rho(B_{ip})$ is plotted for several densities. As in Si MOSFETs, $\rho(B_{ip})$ first increases as $\sim B_{ip}^2$. After a critical B field B_c,[23] it saturates to a roughly constant value, $\rho(B_c)$. In Fig. 3(b), $\rho(B_{ip})/\rho(0)$ is plotted vs B_{ip}/B_c. It is clear that in a large density range, from 0.35×10^{11} to 1.45×10^{11} cm^{-2}, $\rho(B_{ip})/\rho(0)$ collapses onto a single curve, and $\rho(B_c)/\rho(0)\sim1.8$ for all the densities.

B_c in Fig. 3(a) represents the B field beyond which electrons become fully spin polarized.[7–9] In Fig. 3(c), we plot B_c as a function of n. The data points obtained by Okamoto *et al.*[24] and measured at densities $n>1\times10^{11}$ cm^{-2} are also included. Results from the two experiments are in good agreement with each other. At high n's, B_c decreases roughly linearly with n. In fact, for $n>0.8\times10^{11}$ cm^{-2}, $B_c=-1.38+5.55\times n[10^{11}$ cm$^{-2}]$. The decreasing rate slows down at lower electron densities and deviates from that of the linear dependence. B_c appears to approach a finite value as $n\to0$. We caution here that B_c in this experiment was determined at $T\sim0.3$ K, and is expected to be larger than its zero T value. Consequently, the zero T behavior of B_c vs n may be different.

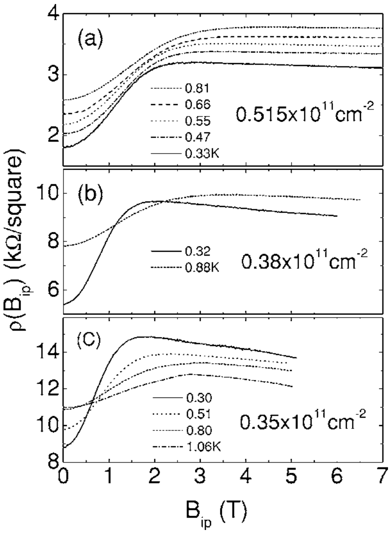

FIG. 4. Temperature dependence of in-plane magnetoresistivity $\rho(B_{ip})$ at three 2DES densities: (a) $n=0.515\times10^{11}$ cm^{-2}, (b) $n=0.38\times10^{11}$ cm^{-2}, and (c) $n=0.35\times10^{11}$ cm^{-2}.

It has been shown that in Si MOSFETs the metalliclike state is suppressed under a B_{ip}, and completely destroyed for $n<1.5n_c$. A recent study has demonstrated that the disappearance of the positive $d\rho/dT$ in large B_{ip} is due to a competition between weak localization and other mechanisms, such as screening.[15] In Fig. 4, we show in this high-quality strained Si QW the temperature dependence of the in-plane MR at three different densities. At the low density of $n=0.35\times10^{11}$ cm$^{-2}\sim1.1n_c$, the in-plane field simply destroys the zero B metalliclike phase, and the 2DES becomes insulating at $B_{ip}>\sim1$ T, consistent with previous results. At the intermediate density of $n=0.38\times10^{11}$ cm^{-2}, however, the temperature dependence becomes complicated. The 2DES shows metalliclike behavior at small B_{ip}, becomes insulating at $B_{ip}\sim1.5$ T, and then reenters into the metalliclike phase at higher B_{ip}. At an even higher density of $n=0.515\times10^{11}$ cm^{-2}, the 2DES remains metalliclike in the whole in-plane B field range, even at $B_{ip}=7$ T, much higher than the critical B field of $B_c\sim2$ T.

The observed critical density $n_c=0.32\times10^{11}$ cm^{-2} is about one order of magnitude smaller than the n_c observed in lower quality SiGe systems (for example, $n_c=2.35\times10^{11}$ cm^{-2} in Ref. 22 with the highest 2DES mobility of $\mu=7.5\times10^4$ cm^2/V s, and $n_c=4.05\times10^{11}$ cm^{-2} in Ref. 25 with the highest mobility $\mu=6.0\times10^4$ cm^2/V s). Thus, our result demonstrates that n_c in the strained Si systems also decreases as the sample quality increases, consistent with previous observations in the GaAs systems.[26]

At the critical density of $n_c=0.32\times10^{11}$ cm^{-2}, the dimensionless *e-e* interaction parameter $r_s=(\pi/n)^{1/2}(e/h)^2(m^*/\epsilon\epsilon_0)$ is 10, where $m^*=0.2m_e$ is the electron band mass and $\epsilon=11.7$ is the dielectric constant for strained Si, and other parameters have their usual meanings. This is the largest critical r_s so far obtained in the Si-based 2DES's, and about twice of that reported in clean Si MOSFETs ($r_s=6.2$ at $n_c=0.8\times10^{11}$ cm^{-2}). We note here that in calculating r_s in Si MOSFETs, according to Dharmawardana and Perrot,[27] the dielectric constant of $\epsilon=11.5$ is used. As pointed in Ref. 27, this choice of $\epsilon=11.5$ is based on the exact atomic structure of the Si/SiO$_2$ interface, and is consistent with other calculations.[28,29] It is also consistent with an earlier conclusion reached by Okamoto *et al.*,[24] that in previous calculations in clean Si MOSFETs the critical r_s value was overestimated, due to the usage of the average relative dielectric constant of silicon and SiO$_2$, $\epsilon_{av}=7.7$.

The observed enhancement of the $\rho(B_{ip})$ under high in-plane B field can be explained by the reduction of screening of charged impurities in a Fermi liquid, caused by the loss of spin degeneracy.[17–19] It has been shown that, when the background impurity scattering dominates, a ratio of $\rho(B_c)/\rho(0)=4$ is expected.[17] On the other hand, when the remote ionized impurity scattering prevails, this ratio is reduced to ~1.2 at high densities.[19] The ratio of $\rho(B_c)/\rho(0)\sim1.8$ in our measurements sits between these two limits and is closer to 1.2, indicating that the dominating scattering mechanism at low temperatures is from remote ionized impurities. This is consistent with our sample structure, where the doping layer is 150 Å away from the 2D electron channel. The slightly higher ratio than 1.2 is probably related to the strain field, which can act as background scattering centers. We note that a similar enhancement of the $\rho(B_{ip})$ under high in-plane B field was also observed in previous experiments in other high-quality strained Si QW samples, at high 2DES densities.[24,30] What is surprising in our results is that in a wide density range the enhancement of $\rho(B_c)/\rho(0)$ is nearly the same, even at the density of $n=0.35\times10^{11}$ cm^{-2}, which is only 10% higher than the critical density of $n_c=0.32\times10^{11}$ cm^{-2}. On the contrary, in high-quality Si MOSFETs, while $\rho(B_c)/\rho(0)\sim2.2$ at very high densities,[31] the enhancement is much higher when n is close to n_c, e.g., $\rho(B_c)/\rho(0)\sim10$ at 0.89×10^{11} cm^{-2},[8] which also is about 10% higher than the n_c of $\sim0.8\times10^{11}$ cm^{-2}. We speculate that this quantitative difference in $\rho(B_c)/\rho(0)$ as $n\rightarrow n_c$ in the two systems is probably related to a smoother interface between Si and SiGe and thus less surface roughness scattering in our high-quality strained Si quantum well.

In summary, in a high electron mobility 2DES realized in the strained Si quantum well, we observe that, with increasing sample quality, the critical density in the 2D metal-insulator transition decreases to a smaller value. Moreover, the measured full spin-polarization magnetic field, B_c, decreases monotonically with n but appears to saturate to a finite value as n approaches zero. The saturation value of the in-plane magnetoresistivity, $\rho(B_c)$, over the zero field resistivity is constant, ~1.8, for all the densities ranging from 0.35×10^{11} to 1.45×10^{11} cm^{-2} and, when plotted vs B_{ip}/B_c, $\rho(B_{ip})/\rho(0)$ collapses onto a single curve.

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[1] S. V. Kravchenko and M. P. Sarachik, Rep. Prog. Phys. **67**, 1 (2004).

[2] V. M. Pudalov, cond-mat/0405315 (unpublished).

[3] S. Das Sarma and E. H. Hwang, Phys. Rev. B **69**, 195305 (2004).

[4] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979).

[5] D. Simonian, S. V. Kravchenko, M. P. Sarachik, and V. M. Pudalov, Phys. Rev. Lett. **79**, 2304 (1997).

[6] J. Yoon, C. C. Li, D. Shahar, D. C. Tsui, and M. Shayegan, Phys. Rev. Lett. **84**, 4421 (1999).

[7] T. Okamoto, K. Hosoya, S. Kawaji, and A. Yagi, Phys. Rev. Lett. **82**, 3875 (1999).

[8] S. A. Vitkalov, H. Zheng, K. M. Mertes, M. P. Sarachik, and T. M. Klapwijk, Phys. Rev. Lett. **85**, 2164 (2000).

[9] E. Tutuc, E. P. De Poortere, S. J. Papadakis, and M. Shayegan, Phys. Rev. Lett. **86**, 2858 (2001).

[10] A. A. Shashkin, S. V. Kravchenko, and T. M. Klapwijk, Phys. Rev. Lett. **87**, 266402 (2001).

[11] V. M. Pudalov, G. Brunthaler, A. Prinz, and G. Bauer, Phys. Rev. Lett. **88**, 076401 (2002).

[12] J. Zhu, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **90**, 056805 (2003).

[13] I. V. Gornyi and A. D. Mirlin, Phys. Rev. B **69**, 045313 (2004).

[14] G. Zala, B. N. Narozhny, I. L. Aleiner, and V. I. Fal'ko, Phys. Rev. B **69**, 075306 (2004).

[15] A. Lewalle, M. Pepper, C. J. B. Ford, D. J. Paul, and G. Redmond, Phys. Rev. B **69**, 075316 (2004).

[16] In GaAs-based systems where the finite width of 2DES is not small, $\rho(B_{ip})$ first increases as $\exp(B_{ip}^2)$ at low B_{ip} and then continues to increase as $\exp(B_{ip})$ for $B_{ip} > B_c$.

[17] V. T. Dolgopolov and A. Gold, JETP Lett. **71**, 27 (2000).

[18] I. F. Herbut, Phys. Rev. B **63**, 113102 (2001).

[19] A. Gold, Physica E (Amsterdam) **17**, 305 (2003); JETP Lett. **72**, 274 (2000).

[20] K. Lai, W. Pan, D. C. Tsui, S. Lyon, M. Mühlberger, and F. Schäffler, Phys. Rev. Lett. **93**, 156805 (2004).

[21] K. Lai, W. Pan, D. C. Tsui, S. A. Lyon, M. Mühlberger, and F. Schäffler, Int. J. Mod. Phys. B **18**, 3533 (2004).

[22] K. Lai, W. Pan, D. C. Tsui, and Y. H. Xie, Appl. Phys. Lett. **84**, 302 (2004).

[23] B_c is determined by the B field value where the low-B parabolic extrapolation meets the high-B linear extrapolation.

[24] T. Okamoto, M. Ooya, K. Hosoya, and S. Kawaji, Phys. Rev. B **69**, 041202(R) (2004).

[25] E. B. Olshanetsky, V. Renard, Z. D. Kvon, J. C. Portal, N. J. Woods, J. Zhang, and J. J. Harris, Phys. Rev. B **68**, 085304 (2003).

[26] J. Yoon, C. C. Li, D. Shahar, D. C. Tsui, and M. Shayegan, Phys. Rev. Lett. **82**, 1744 (1999).

[27] M. W. C. Dharma-wardana and F. Perrot, Phys. Rev. B **70**, 035308 (2004).

[28] P. Carrier, L. J. Lewis, and M. W. C. Dharma-wardana, Phys. Rev. B **65**, 165339 (2002).

[29] A. Pasquarelleo, M. S. Hybertsen, and R. Car, Appl. Phys. Lett. **68**, 625 (1996).

[30] V. T. Dolgopolov, E. V. Deviatov, A. A. Shashkin, U. Weiser, U. Kunze, G. Abstreiter, and K. Brunner, Superlattices Microstruct. **33**, 271 (2003).

[31] J. M. Broto, M. Goiran, H. Rakoto, A. Gold, and V. T. Dolgopolov, Phys. Rev. B **67**, 161304(R) (2003).