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In-plane field magnetoresistivity of Si two-dimensional electron gas in Si/SiGe quantum wells at 20 mK

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We report measurements of in-plane field magnetoresistivity of the two-dimensional electrons in two Si/SiGe quantum wells with different disorder strength at 20 mK. For both samples, the ratio of the saturation resistivity in the high magnetic field to the zero-field resistivity was approximately constant in the high-density limit. In the metallic to insulating transition (MIT) regime, it is strongly enhanced and appears diverging as the electron density approaches a sample-dependent characteristic density n^*. n^* is below n_c, the critical density of MIT at which the temperature dependence of resistivity changes sign. Disorder is believed to play an important role in this phenomenon. Furthermore, the field at which the magnetoresistivity saturates appears to extrapolate to zero, suggesting that ferromagnetic instability does not occur in Si/SiGe, at least down to $n \sim 0.3 \times 10^{11}/\mathrm{cm}^2$.

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Almost 15 years ago, a metallic to insulating transition (MIT) in conductivity was observed in high-mobility two-dimensional electron systems (2DESs) realized in Si metal-oxide-semiconductor field-effect transistors (Si MOSFETs).[1] Extensive studies have since been carried out to understand the nature of this transition. To date, there is still no unequivocal explanation for the observation and many issues remain unresolved. One example is the large response of the 2DES metallic conductivity to an in-plane magnetic field (B_{ip}). It was observed that the in-plane magnetoresistivity $\rho(B_{\mathrm{ip}})$ first increases as B_{ip}^2 at low B_{ip}. After a characteristic magnetic field B_s, which has been identified as the full spin-polarization magnetic field for the 2DES,[2] the in-plane magnetoresistivity saturates to a constant value. In general, the enhancement of $\rho(B_{\mathrm{ip}})$ is due to the reduction in screening of charged impurities in a Fermi liquid caused by the loss of spin degeneracy. Depending on the nature of the disorder, i.e., the background impurity scattering vs the remote ionized impurity scattering, an enhancement ratio $R_{\mathrm{ip}} \equiv \rho(B_{\mathrm{ip}} > B_s)/\rho(B_{\mathrm{ip}}=0)$ of 4 or ~ 1.2 is expected, respectively.[3–5] However, in most measurements in Si MOSFETs, this enhancement ratio is much larger up to several orders of magnitude when the electron density (n) is close to the critical density n_c, at which the temperature dependence of resistivity changes sign. It remains unclear whether this colossal enhancement is simply a disorder effect or is related to the strong electron-electron interaction. Besides the enhancement ratio, B_s is also controversial. In Ref. 6, Shashkin *et al.* showed that B_s was linear with n and, by extrapolation, vanished at n_c. This vanishing B_s was then taken as evidence of a ferromagnetic instability in 2DES at n_c. Later, however, this interpretation was criticized.[7]

Recently in the 2DES realized in Si/SiGe quantum wells, which experiences much weaker disorder and has higher mobility than in Si MOSFETs, very different results were obtained.[8] It was found that the resistivity enhancement ratio R_{ip} in in-plane magnetic field remains roughly constant at 1.8 even down to $n=0.35\times 10^{11}/\mathrm{cm}^2$ (only 10% above $n_c = 0.32\times 10^{11}/\mathrm{cm}^2$). Furthermore, in the density dependence plot, B_s deviates from linear dependence at low densities and appears to saturate to a finite value or extrapolate to zero at $n=0$. These observations present serious challenges to previous claims made in Si MOSFETs. However, there is a caveat. Compared to the previous experiment in Si MOSFETs, which were carried out at $T\sim 30$ mK, the measurements in Si/SiGe were all carried out at $T\sim 300$ mK. Thus, it is unclear whether these apparent discrepancies are temperature effects.

In this Brief Report, we report our measurements of the in-plane field magnetoresistivity of high-quality low-density 2DES in two Si/SiGe quantum wells of different disorder strength at 20 mK, a much lower temperature than in the previous experiments. Different from the previous result at $T=300$ mK,[8] a rapidly increasing in-plane field magnetoresistivity ratio R_{ip} near n_c was observed at $T=20$ mK. The B_s as a function of n, on the other hand, agreed with the previous study and again appears to saturate to a finite value or extrapolate to zero at $n=0$. Our results highlight the importance of disorder in the diverging in-plane magnetoresistivity ratio and suggest that ferromagnetic instability is unlikely at least in the 2DES in Si/SiGe quantum wells.

Both samples studied in this Brief Report were molecular-beam-epitaxially grown strained Si quantum wells sand-

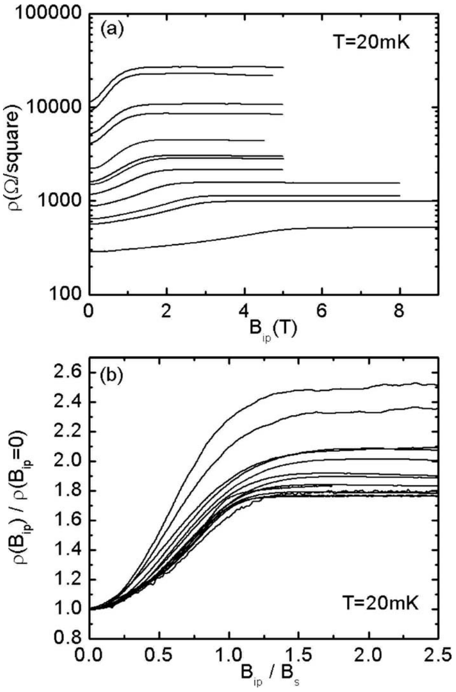

FIG. 1. (a) Magnetoresistivity of sample A at $T=20$ mK. From top to bottom, the curves correspond to densities of 0.320, 0.325, 0.355, 0.346, 0.377, 0.437, 0.455, 0.500, 0.566, 0.619, 0.717, 0.769, and $1.15\times10^{11}/\text{cm}^2$. (b) Scaled magnetoresistivity $\rho(B_{\text{ip}})/\rho(B_{\text{ip}}=0)$ as a function of B_{ip}/B_s.

wiched by relaxed SiGe layers. Sample A (wafer no. 1317) is cut from the same wafer as the one in Refs. 8 and 9 and has similar density and mobility after device fabrication. Sample B (wafer no. LJ131) is also a quantum well with well width of 5 nm and setback distance of 20 nm. Contacts to the 2DES were made by alloying $\text{Au}_{0.99}\text{Sb}_{0.01}$ into the heterostructures. A gate stack of $\text{Au}/\text{Cr}/\text{Al}_2\text{O}_3$ was employed to tune n. The samples were mounted on a rotator probe and cooled down to 20 mK. Quasi-dc transport measurement was done using standard lock-in techniques at 0.3–10 Hz. An excitation current of 0.1–10 nA was used to minimize electron heating. Shubnikov–de Haas oscillations were measured to determine the gate voltage dependence of n. At $n=1.3\times10^{11}/\text{cm}^2$, the mobility of samples A and B were 1.9×10^5 cm^2/Vs and 2.8×10^4 cm^2/Vs at 20 mK, respectively.

The in-plane magnetoresistivity of sample A at 20 mK at different densities is shown in Fig. 1(a). Consistent with previous reports,[8,10,11] the magnetoresistivity first increases approximately as B_{ip}^2 and then saturates at high B_{ip}. The saturation field B_s was determined by the intersection of the low-field parabolic fit and the high-field saturation magnetoresistivity. In Fig. 1(b), the scaled magnetoresistivity $\rho(B_{\text{ip}})/\rho(B_{\text{ip}}=0)$ is plotted as a function of the scaled magnetic field B_{ip}/B_s. It can be seen that at high density ($n>0.5\times10^{11}/\text{cm}^2$), the magnetoresistivity collapses onto one curve reasonably well. This scaling behavior is consistent with the spin-polarization-dependent screening theory,[3,5] in which the scaled magnetoresistivity depends only on the degree of spin polarization. The ratio of 1.8/1.9 is slightly higher than what is calculated (~1.2).[5] This discrepancy with the theory may be resolved if additional disorder, such as the width variation in the quantum well and ionized impurites in the channel, is included in the model. Similar to what was observed in Si MOSFETs, at low density ($n<0.5\times10^{11}/\text{cm}^2$), the magnetoresistivity starts to deviate from the universal function and the ratio R_{ip} increases as n is decreased.

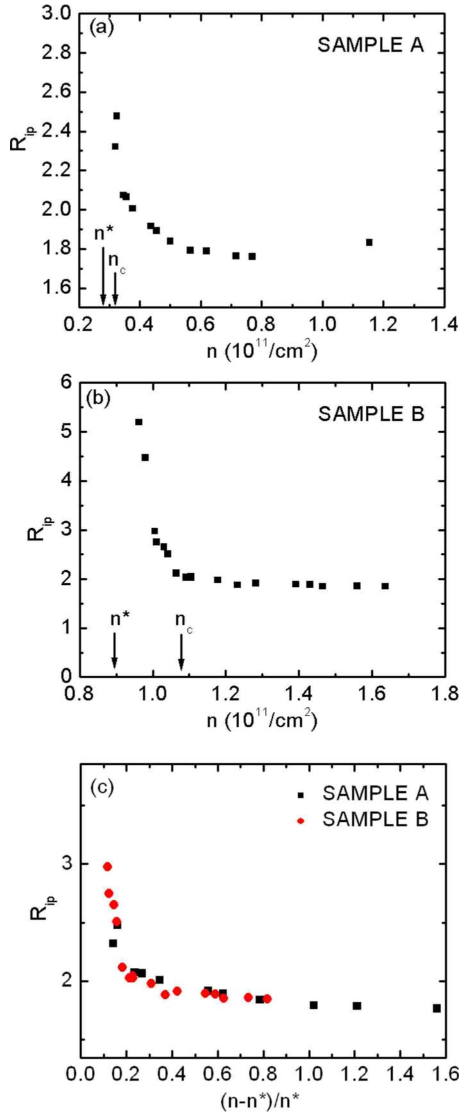

FIG. 2. (Color online) The ratio $R_{\text{ip}}\equiv\rho(B_{\text{ip}}>B_s)/\rho(B_{\text{ip}}=0)$ as a function of n for (a) sample A and (b) sample B. The n_c and n^* are labeled by the arrows in each figure. (c) R_{ip} plotted as a function of the scaled density $(n-n^*)/n^*$.

We show in Figs. 2(a) and 2(b) the ratio R_{ip} as a function of n for samples A and B, respectively. The n_c's determined from the temperature dependence of the resistivity from 0.3 to 1 K (not shown) are labeled by the arrows. The n_c for sample A was taken as the same as in Ref. 8, since the two samples show very similar sample characteristics. For the clean sample (sample A), R_{ip} starts to increase at $n\sim1.7n_c$ and increases sharply as n approaches n_c. This is not the case for sample B, where R_{ip} remains nearly constant at high n. Even at n_c, R_{ip} only increases slightly compared to the high-density limit. Only when $n<n_c$ does R_{ip} show a similar in-

crease and seem to be divergent near $n=0.9\times10^{11}/\text{cm}^2$. In Fig. 2(c), we make an attempt to collapse the data onto a single curve by plotting R_{ip} as a function of $(n-n^*)/n^*$, with n^* as the fitting parameter. Although the range is limited and there are a few scattered points, the data collapse reasonably well onto one curve. The n^* is $0.28\times10^{11}/\text{cm}^2$ for sample A and $0.9\times10^{11}/\text{cm}^2$ for sample B. We note here that in a previous study by Lai *et al.*[9] $0.28\times10^{11}/\text{cm}^2$ was identified as the percolation threshold density in a sample very similar to sample A.

When the exchange and correlation effects and multiple-scattering effects are taken into account, the spin-polarization-dependent screening theory formulated by Gold[4] for Si MOSFETs is able to produce the feature of rapidly increasing ratio R_{ip} near n_c. According to the theory, electrons are localized by impurities due to multiple-scattering effects and the ratio diverges at the MIT density. The more impurities there are in the structure, the higher the MIT density at which the ratio diverges. The density dependence of the ratio observed in SiGe in general agrees well with Gold's model. The divergence of R_{ip} was not observed in the previous experiment,[8] presumably due to the higher temperature. Indeed, a strong temperature dependence of R_{ip} was apparent in previously reported Si MOSFETs data at relatively high temperatures from ~0.25 to 3.1 K.[12] One discrepancy, however, does exist. The divergence occurs at n^* rather than n_c in our Si/SiGe quantum wells. n^* being the same as the percolation threshold density n_p in the percolation fitting in Ref. 9 suggests that the divergence is probably also related to the inhomogeneity of the 2DES. Furthermore, the apparent scaling of the data in Fig. 2(c) for the two samples with very different strength of disorder and electron-electron interaction highlights that disorder plays an important role in the strongly enhanced in-plane field magnetoresistivity ratio R_{ip}. Finally, we want to point out that the enhancement ratio in Si MOSFETs is usually larger than that in Si quantum wells. This might be due to the different nature of the disorder that the 2DES experiences in the two types of samples. It is known that in Si MOSFETs the dominant disorder is short-range interface roughness; while in Si/SiGe quantum wells, presumably remote ionized donors and ionized impurities in the 2D channel are the dominant sources of disorder.

In Fig. 3 we plot B_s vs n of both samples together with the data obtained by Lai *et al.*[8] and Okamoto *et al.*[13] It can be seen that all data fall onto one curve and there is no noticeable temperature dependence for B_s between 20 and 300 mK. At high n $(n>0.7\times10^{11}/\text{cm}^2)$, B_s decreases linearly with decreasing n. The slope of the linear portion is $5.8\ \text{T}/10^{11}\ \text{cm}^{-2}$ consistent with the reported value of $5.7\ \text{T}/10^{11}\ \text{cm}^{-2}$ for Si MOSFETs.[14] The linear fit to the high-density region extrapolates to a finite density at $B_s=0$. The same behavior was observed in Si MOSFETs. At lower n $(n<0.7\times10^{11}/\text{cm}^2)$, however, B_s deviates from the high-density linear fit and appears to extrapolate to $B_s=0$ or finite value at $n=0$. When taking all the data points in Fig. 3 into fitting, we have found that a power-law dependence, $B_s\sim n^{1.3}$ (gray line in Fig. 3), fits the whole density range the best. In the power-law fit, again, B_s is zero at $n=0$. This observation together with the deviation at low density from the high-density linear fit clearly shows that ferromagnetic instability at low n is an unlikely scenario in our samples.

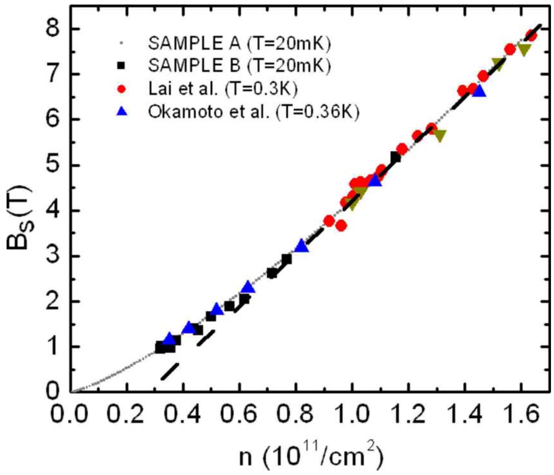

FIG. 3. (Color online) B_s vs n. Data of samples A and B and data from Refs. 8 and 13 are shown on the same plot. The high-density linear fit is the dashed line. The power-law fit with an exponent of 1.3 is the gray dotted line.

To conclude, we have measured the in-plane field magnetoresistivity of dilute 2DES in Si/SiGe quantum wells at 20 mK. The magnetoresistivity ratio $R_{\text{ip}}\equiv\rho(B_{\text{ip}}>B_s)/\rho(B_{\text{ip}}=0)$ is strongly enhanced in the metallic to insulating transition regime and appears diverging as n approaches a sample dependent n^*. The n^*'s do not coincide with n_c's, at which the temperature dependence of resistivity changes sign. The dependence of B_s on n at low n deviates from the high-density linear fit and extrapolates to $B_s=0$ at $n=0$, indicating that ferromagnetic instability does not occur and spin susceptibility remains finite at least down to $n\sim0.3\times10^{11}/\text{cm}^2$ in Si/SiGe quantum wells.

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[1] S. V. Kravchenko, G. V. Kravchenko, J. E. Furneaux, V. M. Pudalov, and M. D'Iorio, Phys. Rev. B **50**, 8039 (1994).

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

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

[4] A. Gold, JETP Lett. **72**, 274 (2000).

[5] A. Gold, Physica E (Amsterdam) **17**, 305 (2003).

[6] A. A. Shashkin, S. V. Kravchenko, V. T. Dolgopolov, and T. M. Klapwijk, Phys. Rev. Lett. **87**, 086801 (2001).

[7] V. M. Pudalov, M. E. Gershenson, H. Kojima, N. Butch, E. M. Dizhur, G. Brunthaler, A. Prinz, and G. Bauer, Phys. Rev. Lett. **88**, 196404 (2002).

[8] K. Lai, W. Pan, D. C. Tsui, S. A. Lyon, M. Mühlberger, and F. Schäffler, Phys. Rev. B **72**, 081313(R) (2005).

[9] K. Lai, W. Pan, D. C. Tsui, S. Lyon, M. Mühlberger, and F. Schäffler, Phys. Rev. B **75**, 033314 (2007).

[10] V. M. Pudalov, G. Brunthaler, A. Prinz, and G. Bauer, JETP Lett. **65**, 932 (1997).

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

[12] Y. Tsui, S. A. Vitkalov, M. P. Sarachik, and T. M. Klapwijk, Phys. Rev. B **71**, 033312 (2005).

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

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