Coexistence of weak localization and a metallic phase in Si/SiGe quantum wells

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Magnetoresistivity measurements on *p*-type Si/SiGe quantum wells reveal the coexistence of a metallic behavior and weak localization. Deep in the metallic regime, pronounced weak localization reduces the metallic behavior around zero magnetic field without destroying it. In the insulating phase, a positive magnetoresistivity emerges close to $B=0$, possibly related to spin-orbit interactions.

The recently discovered metal-insulator transition (MIT) in Si MOSFET's (Ref. 1) has been observed in a variety of material systems, such as *p*-type[2–5] and *n*-type[6,7] GaAs heterostructures, Si/SiGe,[8,9] and AlAs (Ref. 10) quantum wells. These experiments challenge the scaling theory of localization for noninteracting electrons in two dimensions (2D) in the weakly disordered ($k_f l \gg 1$) regime.[11] Since then, an increasing number of experiments[12–18] have investigated more details of this MIT. In spite of considerable theoretical research[19–28] the origin of the metallic phase is still controversially discussed.

In high density 2D carrier systems, which can be treated as noninteracting, the scaling theory of localization fits the experimental data well, yielding insulating behavior as one approaches the zero temperature limit. But in all systems showing a MIT (with the possible exception of Refs. 7 and 16), the ratio r_s between carrier-carrier interaction energy and kinetic energy is of the order of 10, suggesting that interactions are driving the formation of the metallic phase and cannot be neglected when calculating corrections to the conductivity. This path is followed in the majority of the theoretical models,[19–26] although several ideas not relying on strong interactions have been developed as well.[27,28] Weak localization (WL) can only describe one part of the total conductivity correction and additional contributions such as particle-particle interactions, spin-orbit interactions or multi-subband transport, must be included. Experimentally, only the superposition of all contributions at $B=0$ can be detected. In total, a complex conductivity behavior $\sigma(T,B)$ is expected.

Recent studies on the low-field magnetoresistance in the metallic phase have been done in Si-MOSFET's (Ref. 12) and *p*-type Si/SiGe quantum wells.[9] In this paper, we investigate WL effects as a function of magnetic field and temperature in the regime where the system shows metallic behavior. The samples used in this study are *p*-type Si/SiGe quantum wells exhibiting the MIT as a function of hole density. We find that (i) the shape of the low-field magnetoresistance in the metallic phase can be well described by standard WL theory, (ii) there is no indication of a novel dephasing mechanism in the metallic regime, (iii) the magnitude and even the sign of the temperature dependence of the resistivity can depend on the applied magnetic field, and

(iv) a broad negative magnetoresistance develops in the insulating phase, with a small positive magnetoresistance superimposed around zero magnetic field. These observations indicate that the resistivity in the metallic phase is determined by different, similarly important contributions.

The samples investigated in this study were grown by molecular beam epitaxy, and consist of a 200 Å $\text{Si}_{0.85}\text{Ge}_{0.15}$ layer surrounded by undoped Si layers, a 150 Å *B*-doped Si layer with a setback of 180 Å from the well, and a 200 Å undoped Si cap. The SiGe layer forms a triangular potential well for the two-dimensional hole gas. Due to the lattice mismatch between Si and SiGe, the heavy hole ($m_J = \pm 3/2$) energy level is split from the light hole ($m_J = \pm 1/2$) energy level, which ensures that the lowest occupied bound state has heavy hole character. The transport effective mass of this state is $m^* \approx 0.25 m_0$, as extracted from the temperature dependence of Shubnikov–de Haas oscillations. Conventional Hall bar structures were fabricated with a source-drain length of 0.6 mm and a width of 0.2 mm. The distance between the voltage probes was 0.3 mm. The hole density p could be tuned between 1.1×10^{11} cm$^{-2} \leqslant p \leqslant 2.6 \times 10^{11}$ cm^{-2} using a Ti/Al Schottky gate. Transport measurements using standard four terminal lock-in techniques were performed in a pumped liquid He cryostat, as well as in the mixing chamber of a ^{3}He/^{4}He dilution refrigerator. The mobility in these structures was found to increase strongly with carrier concentration, from 1000 cm^2/Vs (for $p = 1.1 \times 10^{11}$ cm^{-2}) to 7800 cm^2/Vs ($p = 2.6 \times 10^{11}$ cm^{-2}). Figure 1 shows a series of magnetoresistance measurements for several carrier densities and temperatures. From top to bottom, the carrier density decreases and the sample undergoes a transition from metallic to insulating behavior at $B=0$ as well as for small magnetic fields. For large hole densities [Figs. 1(a),1(b)], the resistivity at $B=0$ clearly decreases with decreasing temperature, indicating metallic behavior. Similar results have been obtained in the metallic regime in Si MOSFET's,[18] and in SiGe quantum wells with fixed carrier density,[9] where the authors also discuss the broad background in terms of interactions. In the present paper, we focus on the evolution of $\rho(B)$ as a function of p. As the hole density is decreased by suitable gate voltages, the metallic behavior becomes weaker [Fig. 1(b)]. The sample behaves insulating as the carrier density is further reduced [Figs. 1(d),
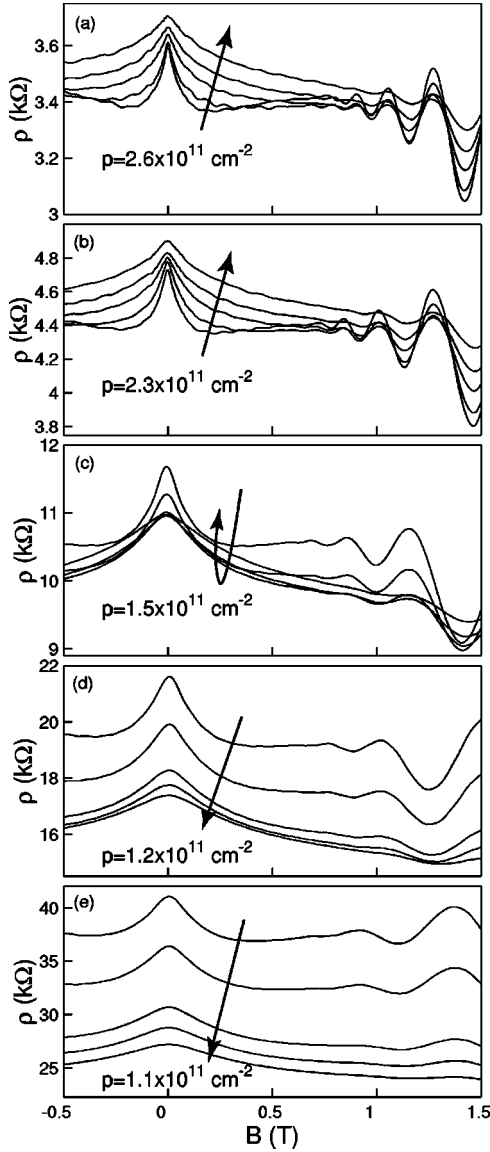
FIG. 1. A series of magnetoresistivity measurements $\rho(B)$ for several carrier densities and temperatures. From top to bottom, the carrier density decreases and the sample goes from metallic to insulating behavior around zero magnetic field. The temperatures for the individual traces are 0.19, 0.36, 0.57, 0.74, and 0.95 K. The arrows denote the direction of increasing temperature. In the metallic phase, the WL reduces the increase of the resistivity with increasing T (a),(b). Close to the transition point, the behavior changes from insulating to metallic as T is increased [(c), see also the inset in Fig. 3], while the peak around $B=0$ enhances the temperature dependence of ρ in the insulating phase (d),(e).

1(e)]. At intermediate hole densities [Fig. 1(c)], we find $d\rho/dT<0$ at low temperatures, but $d\rho/dT>0$ at higher temperatures.

Magnetoresistivity measurements allow to distinguish different contributions to the total resistivity. While the WL effect leads to negative magnetoresistivity $\rho(B)$, spin-orbit coupling results in a positive magnetoresistivity.[29] Interactions produce a complex magnetoresistivity, which depends on the sample parameters.[30,31] Within experimental accuracy, the measured Hall density is identical to that obtained from Shubnikov–de Haas measurements (Fig. 1). Hence, we have
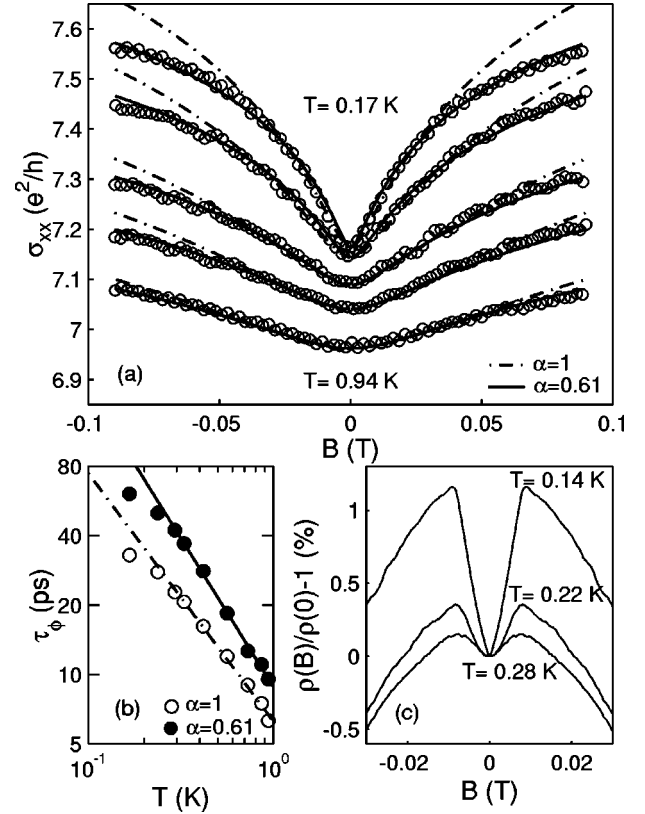

FIG. 2. (a) $\sigma_{xx}(B)$ around $B=0$, as obtained for $p=2.6 \times 10^{11}$ cm^{-2} for different temperatures (open circles); the lines represent curves according to the standard theory of WL, with $\tau_\phi(T)$ and α as parameter (see text). We obtain the best fits for $\alpha=0.61$ (solid line; curves are fitted for -90 m T$\leqslant B \leqslant 90$ mT). Fits for -30 mT$\leqslant B \leqslant 30$ mT with only τ_ϕ as parameter (i.e., $\alpha=1$) are shown (dash-dotted lines). (b) Temperature dependence of τ_ϕ as obtained from (a), i.e., in the metallic regime. We find $\tau_\phi \propto T^{-\gamma}$, with $\gamma=1.09\pm0.2$ for $\alpha=1$ (open circles), and $\gamma=1.29\pm0.2$ for $\alpha=0.61$ (full circles). For the fits, the value for τ_ϕ at the two lowest temperatures was left out. (c) Relative change of $\rho(B)$ with respect to $\rho(0)$ for $p=1.1\times10^{11}$ cm^{-2}, close to $B=0$. For very low temperatures $T\leqslant200$ mK, a resistance minimum occurs at $B=0$.

no indication that a parallel conductive layer is present in our samples. The slope of the Hall resistivity is slightly temperature dependent. This effect originates in interactions[31] and is not discussed here.[32] From the magnetic field dependence of the resistivity one can clearly discern a negative magnetoresistance in the metallic phase [Figs. 1(a),1(b)]. Figure 2(a) shows the longitudinal magnetoconductivity $\sigma(B)$ for $p=2.6\times10^{15}$ m^{-2} around $B=0$ in the metallic phase. In addition, theoretical curves for the WL correction of $\sigma(B)$,[29] i.e.,

$$\delta\sigma(B,T)=\alpha\frac{e^2}{2\pi^2\hbar}\left[\Psi\left(\frac{1}{2}+\frac{\tau_B}{2\tau_\phi}\right)-\Psi\left(\frac{1}{2}+\frac{\tau_B}{2\tau_e}\right)\right], \quad (1)$$

are fitted to the data with the temperature dependent phase coherence time $\tau_\phi(T)$ and α as parameters. Here, τ_B denotes the magnetic time, τ_e the elastic scattering time, and Ψ is the digamma function. The constant α is a phenomenological parameter that describes additional mechanisms, for example, scattering by the Maki-Thompson process,[33] or aniso-

tropic scattering.[31] If no such additional scattering mechanism exist, α is expected to be 1.[34] In n-type Si MOSFET's, intervalley scattering is supposed to determine α.[18] Our data are fitted best for $\alpha = 0.61$, similar to the results of Ref. 9. The mechanism that leads to this reduction of α remains an open question. It can not, however, be explained by spin-orbit scattering between the light hole and the heavy hole band, since their energy separation is more than 24 meV in our system[35] and therefore much larger than the Fermi energy. For the temperature dependence of τ_ϕ, we find $\tau_\phi \propto T^{-\gamma}$, with $\gamma = 1.09 \pm 0.2$ for $\alpha = 1$, and $\gamma = 1.29 \pm 0.2$ for $\alpha = 0.61$. For dephasing by quasielastic electron-electron collisions (i.e., Nyquist noise), $\gamma = 1$ is expected.[36] Similar agreement between experiment and theory has also been found in insulating 2D systems.[37,38] Hence, from the temperature dependence of τ_ϕ, there is no indication of a novel dephasing mechanism due to the presence of the metallic phase. Furthermore, neither α nor γ depend significantly on p in the metallic phase.

Assuming that Nyquist noise causes the dephasing, we find that τ_ϕ is smaller than expected from theory, which states according to Ref. 38,

$$\frac{1}{\tau_\phi T} = \frac{k_B e^2}{2\pi\hbar^2}\rho \, \ln\frac{\pi\hbar}{e^2\rho}. \tag{2}$$

From our fits, we find $(\tau_\phi T)^{-1} = 1.0 \times 10^{11} s^{-1} K^{-1}$ (using $\alpha = 0.61$), which is a factor of ≈ 4 above the value expected from theory. Similar discrepancies between experiment and theory are found for insulating 2D carrier systems.[38]

These results indicate that even in the metallic regime, a significant amount of carriers still contributes to WL. We do not find clear evidence for a different dephasing mechanism than in other 2D systems. Furthermore, we conclude from the existence of the WL peak that in our system, a spontaneous flux state at $B = 0$, which would break the time reversal symmetry,[39] is of minor importance. At $B = 0$ in the metallic phase, the resistance drops faster with decreasing temperature than the WL peak increases. In order to distinguish the temperature dependence of WL from the background resistance, we compare the resistivity at $B = 0$ with the one at $B = 0.3$ T. This field is larger than the characteristic field $B_\tau = \hbar/(4eD\tau) = 0.11$ T, and therefore the WL is quenched (Fig. 3). Especially at low temperatures the metallic behavior becomes more pronounced as one moves out of the WL peak. This suggests that two different contributions to the conductivity (or two conducting systems) may exist, one with a metallic temperature behavior and another one with a standard, insulating WL behavior. A possible theoretical description could be the two-phase model proposed recently in Ref. 21. However, from our data, we cannot extrapolate what will happen to the metallic phase at $T = 0$, as has recently been done by Simmons *et al.*[32] As one enters the
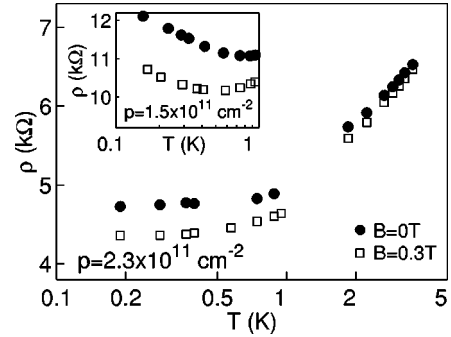

FIG. 3. ρ as a function of T for the density $p = 2.3 \times 10^{11}$ cm^{-2} at $B = 0$ and at $B = 0.3$ T, where the WL contribution is quenched. Inset: $\rho(T)$ at the transition point from metallic to insulating behavior [Fig. 1(c)].

insulating regime at $B = 0$ [Fig. 1(d)], a very broad negative magnetoresistivity develops that determines the overall temperature dependence. In this situation, (i.e., for $k_F l \lesssim 1$, where l is the elastic mean free path) τ_ϕ cannot be extracted from fitting Eq. (1) to the data. In this regime, the sample looks rather like a conventional two-dimensional carrier gas with low mobility.

We would like to report another finding occurring in the insulating phase. For very low temperatures $T \lesssim 300$ mK and small carrier densities, an additional minimum occurs in the magnetoresistance around $B = 0$. Similar features have been observed on n-type Ga[Al]As heterostructures [40] and explained by spin-orbit coupling. Also, recent data on p-type GaAs heterostructures[4] show a dip in the magnetoresistance around $B = 0$ which, however, is superimposed on a rather flat background. Spin-orbit coupling effects are expected to be important in p-type SiGe heterostructures and could be the reason for this low-temperature feature. Note, however, that in contrast to Ref. 4, we observe this feature only deep in the *insulating* phase.

In summary, we have investigated the influence of perpendicular magnetic fields on the resistance in the metallic regime of a two-dimensional hole gas in Si/SiGe quantum wells. A dip in the magnetoresistivity at $B = 0$, possibly due to spin-orbit coupling, is found deep in the insulating phase. We have observed the coexistence of WL and metallic behavior. Time inversion symmetry seems not to be spontaneously broken at $B = 0$ in our samples. The temperature dependence of the dephasing time τ_ϕ suggests that Nyquist noise determines the dephasing even when the sample is in the metallic phase. We find no significant indication that τ_ϕ behaves differently than in insulating 2D systems. Our data are consistent with a model based on (at least) two different conductivity contributions for the metallic phase.

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