Magnetoconductance of metallic Si:B near the metal-insulator transition

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The magnetoconductance of p-type Si:B samples with dopant concentrations just above the metal-insulator transition is negative (positive magnetoresistance) at all measured temperatures between 0.1 and 4.2 K and for magnetic fields up to 9 T. We attribute this to the effects of strong spin-orbit scattering associated with the valence bands in p-type materials. The magnetoconductivity varies as H^2 in small magnetic fields and approximately as $H^{1/2}$ at high fields, with deviations from this simple form which become increasingly significant as the metal-insulator transition is approached. Based on the assumption that the high-field magnetoconductance is attributable mainly to electron-electron interactions, a separation of the low-field magnetoconductance into components associated with interactions and localization yields a hole inelastic scattering rate $\hbar/\tau_{in}$ which varies approximately linearly with temperature.

INTRODUCTION

Localization and electron-electron interactions both play important roles in determining the behavior of electronic transport in disordered metals[1] where the electrons suffer frequent elastic collisions due to the random nature of the impurity potentials. In the absence of dephasing mechanisms such as inelastic scattering, magnetic fields, or spin-flip scattering, quantum interference enhances the probability of back scattering, leading to weak localization. Moreover, the electronic motion is diffusive so that screening is less effective and the electrons interact strongly with each other. An external magnetic field affects localization and electron correlations in different ways, and has often been used to investigate the relative importance of the two contributions and to identify and study the phase-breaking mechanism associated with the localization process.

The contribution to the magnetoconductance due to electron-electron interactions is negative (positive magnetoresistence) and arises predominantly from Zeeman splitting of the spin-up and spin-down bands. In contrast, the sign of the magnetoconductance associated with localization can be negative or positive depending on whether or not spin-orbit effects are important. The constructive interference between time-reversed backscattered loops which gives rise to the localization in the usual case is instead destructive in the presence of strong spin-orbit scattering, yielding "antilocalization." By breaking time-reversal symmetry, a magnetic field gives a positive magnetoconductance when spin-orbit effects are weak[2] and a negative magnetoconductance[3] when spin-orbit scattering is strong. The expected change in sign has been demonstrated experimentally by Bergmann[4] in studies of thin films of Mg containing Au.

Numerous studies of the magnetoresistance near the metal-insulator transition now exist for amorphous materials and doped semiconductors. In most of the materials investigated, spin-orbit effects are unimportant, and the contributions to the magnetoresistance due to interactions and localization are of opposite sign. Experiments on n-type doped semiconductors include the measurements of Rosenbaum *et al.*[5] and of Paalanen and Bhatt[6] on Si:P; of Roth *et al.*[7] on Ge:As; Koon[8] on Si:As; and by Ootuka, Matsuoka, and Kobayashi,[9] Polyanskaya, Saidashev, and Shmartsev,[10] and Rosenbaum *et al.*[11] for Ge:Sb.

In the materials which have been studied to date, spin-orbit scattering is generally associated with the presence of impurities which have large mass. In p-type material such as Si:B, however, there are strong spin-orbit effects which are instead associated with the nature of the valence bands of the host material itself. Silicon has degenerate light- and heavy-hole $J=\frac{3}{2}$ valence-band maxima at $k=0$ and a spin-orbit split $J=\frac{1}{2}$ band at an energy 0.044 eV below these. The scattering by impurities causes transitions among states of different m_J values at a rate comparable to ordinary potential scattering.[12,13] Experimental support for the importance of spin-orbit effects in Si:B is provided by the fact that the hole g value[14,15] of 1.2 is substantially different from the free-electron value of 2. In early experiments, Roth *et al.*[7] found a low-field positive magnetoresistance (negative magnetoconductance) for Ge:Ga samples and for a very heavily doped Si:B sample with dopant concentration about 20 times the critical concentration for the metal-insulator transition. A positive magnetoresistance was also found by Sugiyama[16] in p-type Ge in 1964.

In this paper we report a systematic study of the magnetoresistance of metallic p-type Si:B samples with boron concentrations near the metal-insulator transition. The same samples were used earlier in our investigations of the critical conductivity exponent.[17,18] Our major finding is that the magnetoresistance is positive (negative magnetoconductance) for all samples at all fields and temperatures of our measurements. This is in contrast with results obtained by Paalanen and Bhatt[6] in Si:P, who observed a small negative component of the magnetoresistance in small magnetic fields at temperatures on the order of 1 K. We attribute this difference to the presence of strong spin-orbit scattering in Si:B. Since the contributions arising from localization and from interactions are of the same sign in Si:B, a reliable separation of the total magnetoconductance into separate components is more difficult to obtain than in the case of n-type doped semiconductors. This is further complicated by a fairly strong shift in the critical concentration with magnetic field. Following a brief summary of available theory, we show that the data for Si:B agrees approximately with theoretical expectations, with deviations which become more significant as the metal-insulator transition is approached. Based on the assumption that the magnetoconductance at high magnetic fields is due mainly to interactions, we proceed in the last section of the paper to determine the low-field component of the magnetoconductance due to localization, from which we estimate the hole inelastic-scattering time and its temperature dependence.

THEORETICAL BACKGROUND

To leading-order, the magnetoconductances due to (anti)localization and electron correlations are additive:

$$\Delta\sigma(H,T)=\sigma(H,T)-\sigma(0,0)=\Delta\sigma_I(H,T)+\Delta\sigma_L(H,T) . \quad (1)$$

In the absence of a magnetic field, the interaction term is given by[19]

$$\Delta\sigma_I(0,T)=\sigma_I(0,T)-\sigma_I(0,0) =\alpha[\tfrac{4}{3}-\gamma(3F_\sigma/2)]T^{1/2} , \quad (2)$$

$$\alpha=(e^2/\hbar)(1.3/4\pi^2)(k_B/2\hbar D)^{1/2} , \quad (2a)$$

where D is the diffusion constant and F_σ is an interaction parameter related to the Fermi liquid parameter F, the Fermi surface average of the screened electron-electron interactions. The value of γ depends on the valley degeneracy, mass anisotropy, and intervalley scattering,[20] and it is not known for Si:B. When a magnetic field is applied, the splitting of the spin-up and spin-down bands gives rise to two terms:[1,21]

$$\Delta\sigma_I(H,T)=\sigma_I(H,T)-\sigma_I(0,0)=\Delta\sigma_I'(T)+\Delta\sigma_I''(H,T) . \quad (3)$$

The first term on the right-hand side of Eq. (3) is the field-independent exchange and singlet Hartree contribution,

$$\Delta\sigma_I'(T)=\alpha[\tfrac{4}{3}-\gamma F_\sigma/2]T^{1/2} , \quad (3a)$$

and the second term is the triplet contribution, given by

$$\Delta\sigma_I''(H,T)=-0.77\alpha\gamma F_\sigma T^{1/2}g_3(h)-\alpha\gamma F_\sigma T^{1/2} , \quad (3b)$$

with $h=g\mu_B H/k_B T$, and

$$g_3(h)=\int_0^\infty d\Omega[\Omega N(\Omega)]\{(\Omega+h)^{1/2}+(|\Omega-h|)^{1/2}-2\Omega^{1/2}\} ,$$

where $N(\Omega)=1/(e^\Omega-1)$. The high-field and low-field limits are given by

$$g_3=h^{1/2}-1.3, \quad h\gg1$$

$$g_3=0.053h^2, \quad h\ll1 .$$

Combining these expressions, one finds the limiting forms for the magnetoconductance due to interactions at very small and very large magnetic fields:

$$\Delta\sigma_I(H,T)=\alpha(\tfrac{4}{3}-\tfrac{3}{2}\gamma F_\sigma)T^{1/2} -0.041\alpha(g\mu_B/k_B)^2\gamma F_\sigma T^{-3/2}H^2 , \quad g\mu_B H\ll k_B T \quad (4a)$$

$$\Delta\sigma_I(H,T)=\alpha(\tfrac{4}{3}-\tfrac{1}{2}\gamma F_\sigma)T^{1/2} -0.77\alpha(g\mu_B/k_B)^{1/2}\gamma F_\sigma H^{1/2} , \quad g\mu_B H\gg k_B T . \quad (4b)$$

The quantity which is deduced experimentally is the difference at finite temperature T between the conductivity in a magnetic field and in zero field:

$$\Delta\Sigma_I(H,T)=\sigma_I(H,T)-\sigma_I(0,T) =-0.77\alpha\gamma F_\sigma T^{1/2}g_3(h) , \quad (5a)$$

for which the low-field and high-field limits are

$$\Delta\Sigma_I(H,T)=-0.041\alpha(g\mu_B/k_B)^2\gamma F_\sigma T^{-3/2}H^2 , \quad g\mu_B H\ll k_B T \quad (5b)$$

$$\Delta\Sigma_I(H,T)=\alpha\gamma F_\sigma T^{1/2}-0.77\alpha(g\mu_B/k_B)^{1/2}\gamma F_\sigma H^{1/2} , \quad g\mu_B H\gg k_B T . \quad (5c)$$

Note that the magnetoconductance due to interactions is expected to behave as H^2 and $H^{1/2}$ at very low and very high fields, respectively.

In the presence of strong spin-orbit effects, backscattering gives rise to antilocalization rather than localization. Although some theoretical work has been done for the magnetoconductance in this case, no convenient or reliable mathematical expression currently exists with which to compare experimental results in p-type cubic semiconductors. According to Altshuler *et al.*,[22] the magnetoconductivity is given by

$$\Delta\Sigma_L=\sigma_L(H,T)-\sigma_L(0,T)=-\tfrac{1}{4}\Sigma_0+\tfrac{3}{4}\Sigma_1-\tfrac{5}{4}\Sigma_2+\tfrac{7}{4}\Sigma_3 , \quad (6)$$

where the four terms correspond to the total moment of two holes with values 0, 1, 2, and 3. Σ_0 is the same as without spin-orbit scattering,[2] that is,

$$\Sigma_0=(e^2/2\pi^2\hbar)(eH/\hbar)^{1/2}f_3(H/H_i) , \quad (7)$$

and the other terms have not been calculated. At large magnetic field, Kawabata[2] showed that $\Sigma_0 H^{1/2}$. For strong spin-orbit scattering, the first term is the major contribution for small magnetic fields. The magnetoconductivity due to weak antilocalization for small magnetic fields can be written as

$$\Delta\Sigma_L(H,T) \approx -\tfrac{1}{4}\Sigma_0 \approx -(1/48\pi^2)(e/\hbar)^2 G_0 l_{\rm in}^3 H^2 , \quad H \ll H_i \qquad (8)$$

where $G_0 = e^2/\hbar$, $l_{\rm in} = (D\tau_{\rm in})^{1/2}$ is the inelastic scattering length, $H_i = (\hbar/4De)\tau_{\rm in}^{-1}$, and $\tau_{\rm in}^{-1} \ll \tau_{\rm s.o.}^{-1}$. Here, $\tau_{\rm in}$ and $\tau_{\rm s.o.}$ are the inelastic- and spin-orbit-scattering times, respectively.

We note that localization and interactions give the same limiting behavior for the magnetoconductance, namely, H^2 at small fields and $H^{1/2}$ in the limit of very large magnetic fields. In most cases, the two terms are of opposite sign. When spin-orbit scattering is strong, however, the corrections to the magnetoconductance due to (anti)localization and correlations are both negative, and it is thus particularly difficult to obtain a reliable separation.

EXPERIMENTAL PROCEDURE

The eight nominally uncompensated Czochralski-grown boron doped silicon samples used in these studies were obtained from Pensilco Crystals. The dopant concentrations were deduced using the Thurber[23] scale and ranged from 4.20×10^{18} to 5.22×10^{18} cm^{-3}. These samples have been used in earlier studies,[17] where the critical concentration in zero field was found to be $n_c = 4.06\times10^{18}$ cm^{-3}. All specimens were etched in a CP-4 solution to remove any damaged surface layers. Ion implantation of boron was made to four thin striplike areas on each sample. Gold wires were then attached to the ion-implanted areas by a special arc discharge technique.[24] Data at temperatures below 1.5 K were taken in an Oxford Model No. 75 dilution refrigerator in a 9-T superconducting magnet. It was found that thermal anchoring by the usual method of attaching samples to a holder with Apiezon grease or GE varnish causes stresses in the Si:B samples which produce substantial and uncontrolled changes in their properties. In order to mount samples free from stress and to achieve good thermal contact, samples were immersed directly in the ^{3}He-^{4}He mixture during the measurement. Standard ac low-frequency (15 Hz) four-terminal methods were used for the resistivity measurements with a Ry-Elektronikka oy model AVS-46 resistance bridge. Data at temperatures above 1.5 K were taken in a ^{4}He Dewar with a 4-T superconducting magnet. Samples were again immersed directly in liquid helium, except at temperatures above 4.2 K, where thermal contact to the sample holder was established by applying Apiezon grease at only one end of a sample to avoid stresses. Different excitation currents were used to ensure Ohmic behavior.

EXPERIMENTAL RESULTS AND DISCUSSION

A magnetic field has a considerably larger effect in Si:B than in Si:P.[6] This is illustrated in Fig. 1, where the magnetoconductivities of two samples with similar values of n/n_c are shown at the same fixed temperature of 0.1 K. While the magnetoconductance of Si:P (Refs. 5 and 6) has a positive component due to weak localization, as shown in the inset, we find that the magnetoconductance of Si:B

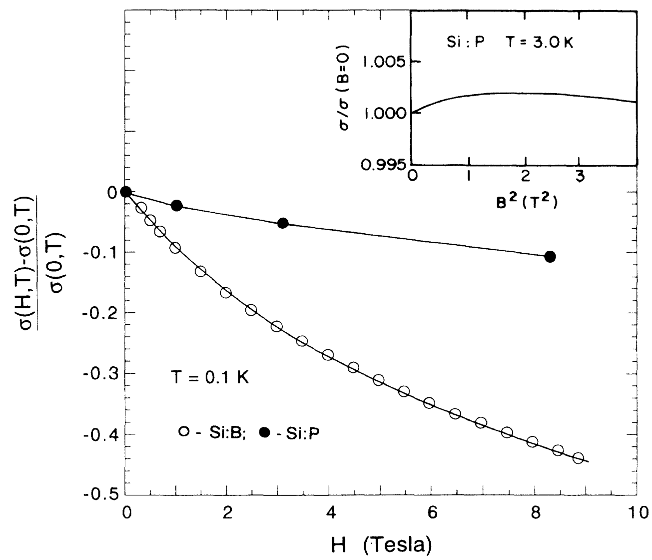

FIG. 1. The magnetoconductivity $[\sigma(H,T)-\sigma(0,T)]/\sigma(0,T)$ for a Si:B sample with dopant concentration $n = 1.23n_c$ and of a Si:P sample with dopant concentration $n = 1.25n_c$ at a fixed temperature of 0.1 K. The data for Si:P is taken from Ref. 6. The lines are drawn to guide the eye. As shown in the inset, the magnetoconductance of Si:P has a positive component.

is negative at all fields and temperatures of our measurements. We attribute this difference to the strong spin-orbit coupling associated with the valence bands in p-type Si, as discussed earlier. The dramatic difference in the overall size of the magnetoconductances of Si:P and Si:B derives at least partly from the fact that the contributions of localization and interactions are of opposite sign in Si:P, while in Si:B the contributions are additive.

Eight Si:B samples with boron concentrations 4.20, 4.30, 4.38, 4.57, 4.86, 4.95, 5.01, and 5.22×10^{18} cm^{-3} were studied in magnetic fields up to 9 T at temperatures between 0.1 and 4.2 K. The critical concentration varies with magnetic field, and was found in earlier experiments[17,18] to be 4.06×10^{18} cm^{-3} in magnetic fields up to 1 T, and 4.22 at 7.5 T; its detailed dependence on magnetic field has not been established.

The magnetoconductivities, $\Delta\Sigma = \sigma(H,T) - \sigma(0,T)$, of four samples at a fixed temperature of 0.10 K are plotted in Fig. 2 as a function of magnetic field, and the magnetoconductivities at three different temperatures are shown for two of the samples in Figs. 3 and 4.

The conductivity is expected to go approximately as $H^{1/2}$ at sufficiently high magnetic fields. Figure 5 shows $\Delta\Sigma$ plotted as a function of $H^{1/2}$ at a fixed temperature of 0.10 K for four samples with different dopant concentrations. There are clear deviations from $H^{1/2}$ behavior at high fields which become increasingly serious as the dopant concentration is decreased toward the critical concentration. One should bear in mind that the theory is less reliable near the transition, and the critical concentration is itself a function of magnetic field.

We note that the slopes at high fields of the curves of Fig. 5, given by the prefactor of the $H^{1/2}$ term of Eq. (5c),

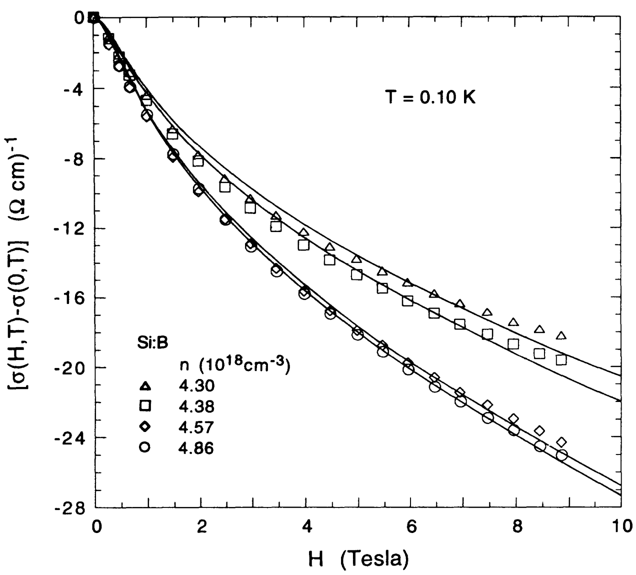

FIG. 2. The change in the conductivity, $\sigma(H,T)-\sigma(0,T)$, plotted as a function of magnetic field for four samples at a fixed temperature of 0.10 K. The lines represent fits to interaction theory over the entire range of magnetic field.

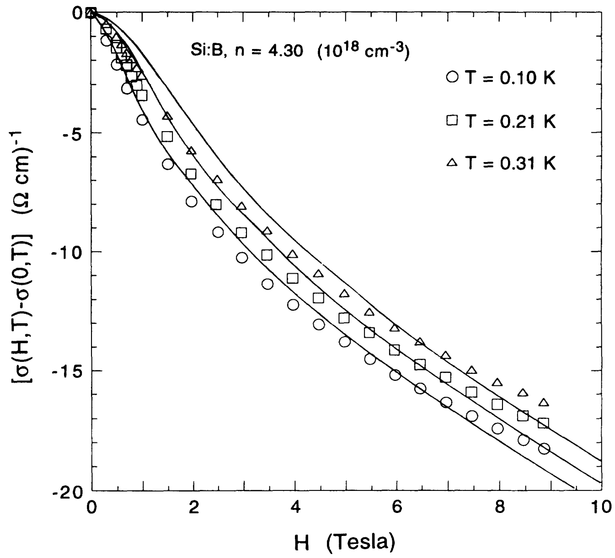

FIG. 4. The change in the conductivity, $\sigma(H,T)-\sigma(0,T)$, as a function of magnetic field at three different temperatures, as shown, for a Si:B sample with dopant concentration 4.30×10^{18} cm^{-3}. The lines represent fits to interaction theory over the entire range of magnetic field.

are related to the interaction constant F_σ and to α. Estimates of γF_σ and α were obtained in earlier studies of the temperature dependence of the conductivity of the same samples,[25] by combining the temperature dependence in zero magnetic field, given by Eq. (2), with the temperature dependence measured in a field of 7.5 T, given by Eq. (4b). The values of γF_σ deduced from these earlier experiments are denoted by crosses in Fig. 6. A second determination of these parameters can be deduced from our measurements of the field dependence of the magnetoresistance. Using the slopes at high magnetic fields of the curves shown in Fig. 5 and Eq. (5c), and the α's obtained from our earlier estimates, values are obtained for γF_σ which are plotted as open circles as a

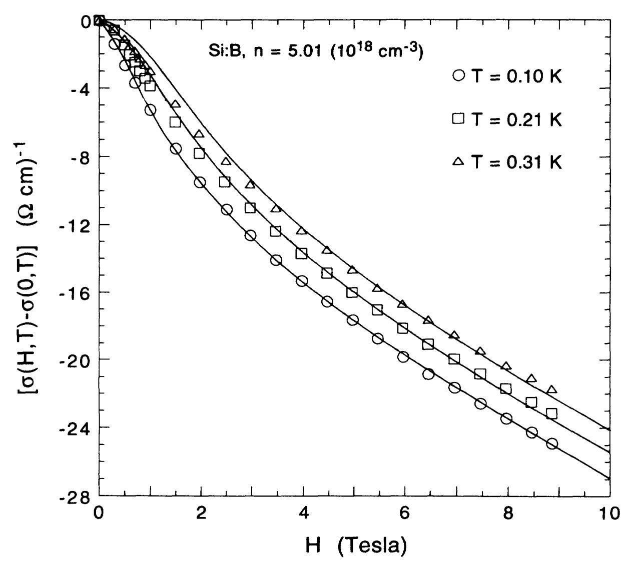

FIG. 3. The change in the conductivity, $\sigma(H,T)-\sigma(0,T)$, as a function of magnetic field at three different temperatures, as shown, for a Si:B sample with dopant concentration 5.01×10^{18} cm^{-3}. The lines represent fits to interaction theory over the entire range of magnetic field.

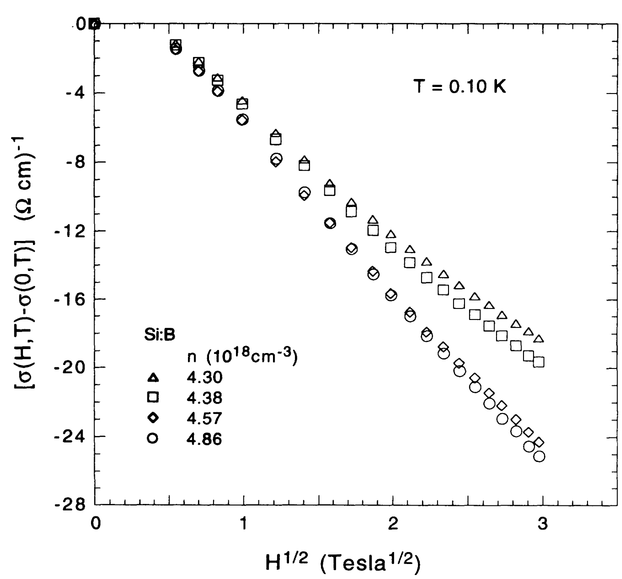

FIG. 5. The change in the conductivity, $\sigma(H,T)-\sigma(0,T)$, as a function of $H^{1/2}$ for four Si:B samples at a fixed temperature of 0.10 K. The dopant concentrations are as labeled.

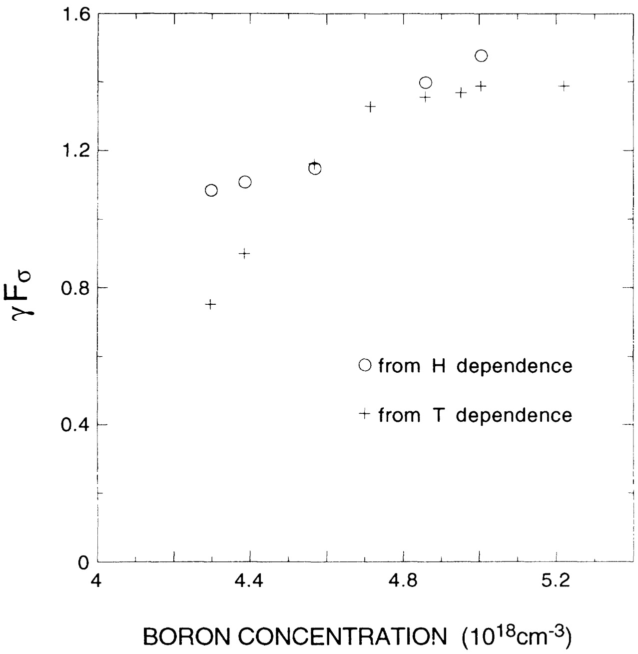

FIG. 6. γF_σ plotted as a function of boron concentration. The crosses are deduced from the temperature dependence and the open circles from the field dependence, as discussed in the text.

function of boron impurity concentration in Fig. 6. A similar analysis has been done for Si:P by Lohneysen and Welsch.[26] The γF_σ's obtained from the two methods agree with each other fairly well except for samples very close to the transition. This is not surprising, since the theory is not expected to be valid very near the transition. The localization contribution to the magnetoconductivity, which has not been taken into account, may also add to the discrepancy. One should note, however, that comparable parameters are obtained both from the temperature dependence and the field dependence at large magnetic fields using interaction theory alone. This indicates that the magnetoresistance at large magnetic fields may be accounted for largely by interaction effects and that the contribution due to localization may be relatively less important in strong fields. Similar conclusions can be drawn in n-type material, where the negative magnetoresistance due to localization is evident only at low fields, while the positive contribution due to correlations dominates the high-field behavior.[5,6]

More recent calculations by Raimondi, Castellani, and Di Castro[27] have shown that F_σ of the second term of the right-hand side of Eq. (5c) should be replaced by a different multiplicative factor A which is related to F_σ by

$$A = 4x[1+2x^2\ln(x)/(1-x^2)] , \quad (9)$$

where $x = 1 - F_\sigma/2$. The values of γF_σ depend on the value of γ, which is not known, and generally lie below those shown in Fig. 6. However, the concentration dependence of γF_σ deduced using the theory of Raimondi, Castellani, and Di Castro[27] is not very different from that shown in Fig. 6.

Motivated by the fact that the temperature and field dependences of the high-field magnetoconductance yield comparable values for the parameter γF_σ of Fig. 6 and in the absence of a better method for separating the two components which contribute to the magnetoresistance, we make the assumption that the magnetoconductivity at high fields is due primarily to Zeeman splitting and that contributions due to localization are negligible by comparison at large magnetic fields. The solid curves shown in Figs. 2, 3, and 4 are theoretical fits, assuming interaction effects over the entire range of magnetic field. These curves were obtained by calculating $\Delta\Sigma_I$ from Eq. (5a) using a g-factor of 1.2 appropriate to Si:B and choosing the prefactor $\alpha\gamma F_\sigma$ for each sample to match the experimentally observed $\Delta\Sigma$ at high fields. Although the quality of the fits deteriorates noticeably for samples close to the transition, the temperature and field dependences at large magnetic field are reproduced reasonably well for samples relatively far from n_c. We point out that these are one-parameter fits, and the good agreement with theory at high magnetic fields for samples with $n/n_c > 1.15$ is indeed significant. In all cases, however, there are substantial discrepancies at low fields, and these discrepancies become more serious for samples closer to the transition. The effects of localization have not been considered in these calculations, and although they may be relatively unimportant at high fields, they must clearly be included to account for the behavior at small magnetic fields.

THE HOLE INELASTIC-SCATTERING TIME

The magnetoresistance due to weak localization involves an interplay of the magnetic-field, inelastic-scattering, spin-scattering and spin-orbit processes, and thus provides a useful tool for studying the relative importance of these effects. The inelastic-scattering rate is expected to exhibit a power-law dependence on temperature, $\tau_{in}^{-1} = T^p$, with $p=3$ for inelastic electron-phonon scattering. In the case of inelastic electron-electron scattering, $p=2$ for a clean metal and $p=\frac{3}{2}$ for a disordered metal.[28] Recent work by Belitz and Wysokinski predicts a value $p=1$ very near the transition.[29]

Experiments have yielded mixed results. Polyanskaya and Saidashev[30] showed that $p \approx \frac{3}{2}$ for n-Ge:Sb near the metal-insulator transition in a temperature range between 1.8 and 4.2 K. Ootuki, Matsuoka, and Kobayashi[9] found $p=\frac{3}{2}$ for n-Ge:Sb samples at temperatures above liquid helium and $p<1$ at lower temperatures. Morita *et al.*[31] obtained $p=1$ in n-GaAS samples from measurements down to 50 mK. Dynes *et al.*[32] reported $p=3$ for n-InSb samples at low temperatures, which they attributed to inelastic electron-phonon scattering. More recently, Paalanen and Bhatt[6] studied n-Si:P samples near the transition and obtained $p<1$. There have also been many studies on amorphous materials and 2D films.[4,33] Very recently, the carrier dephasing rate in the normal state of high-T_c material has been studied through magnetotransport measurements.[34] In contrast with the large number of studies on n-type doped semiconductors, there have been few such studies on p-type materials. Bil'gil'deeva, Karyaev, and Polyanskaya[35] interpreted results for p-$GaAS_{0.94}Sb_{0.06}$ between 1.9 and 4.2 K as deriving from a superposition of $p=\frac{3}{2}$ due to electron-electron scattering and $p=1$ which they attributed to phonons.

The dephasing scattering rate is deduced from the contribution to the magnetoconductivity due to localization, and therefore requires a reliable separation into components arising from interactions and localization. This is particularly difficult to do for materials where spin-orbit scattering is strong so that the contributions are of the same rather than opposite sign, and have similar limiting functional forms at small and large magnetic fields. We will nevertheless attempt to separate the two contributions by assuming that the magnetoconductance at high magnetic fields is predominantly due to interactions. We will restrict our analysis to samples that are relatively far from the transition, where this assumption is more likely to be valid.

Following the work of Rosenbaum *et al.*[5] and Paalanen and Bhatt,[6] we assume that the contributions associated with interactions and with localization are additive:

$$\Delta\Sigma(H,T)=\sigma(H,T)-\sigma(0,T)=\Delta\Sigma_I(H,T)+\Delta\Sigma_L(H,T)\ . \tag{10a}$$

The first and second terms on the right-hand side are given by Eqs. (5b) and (8), respectively, at small magnetic field. Thus, in small fields,

$$\Delta\Sigma(H,T)=-0.041(g\mu_B/k_B)^2\alpha\gamma F_\sigma T^{-3/2}H^2 -(1/48\pi^2)(e/\hbar)^2G_0 l_{\rm in}^3 H^2\ . \tag{10b}$$

Note that the contributions are both negative in our case and quadratic in H. The interaction term involves the prefactor $\alpha\gamma F_\sigma$, while the antilocalization term includes $l_{\rm in}$, neither of which are known. In order to obtain an estimate for $l_{\rm in}$, from which the dephasing time can be obtained, we will assume that the high-field magnetoconductance is due mainly to interactions and will use values of $\alpha\gamma F_\sigma$ obtained from the high-field magnetoresistance data in the previous section.

The magnetoconductivity

$$\Delta\Sigma(H,T)=\sigma(H,T)-\sigma(0,T)$$

is plotted as a function of the square of the magnetic field for four samples at the same temperature of 0.86 K in Fig. 7 and for a single sample at various different temperatures in Fig. 8. The magnetoconductivity is negative (i.e., the magnetoresistance is positive) for all samples at all fields and temperatures measured, and is proportional to H^2 at small fields. We note again that the data fit theory considerably better for samples far from the transition, as indicated in Fig. 7. Figure 8 demonstrates that the magnetic-field range over which $\Delta\Sigma$ follows H^2 dependence gets narrower as the temperature decreases. According to theory,[1,21] the quadratic dependence of $\Delta\Sigma_I$ on H should be observed up to a field $H_{IC}=k_BT/g\mu_B$; using $g=1.2$ for Si:B, this gives $(H_{IC})/T=1.2$ T/K. Our data show deviations from quadratic dependence at about $H/T=0.5$, a smaller value than that predicted by interaction theory. This may be due to the admixture of a contribution due to localization, which is expected to deviate from quadratic dependence at a lower field.

The contribution due to weak localization was ob-

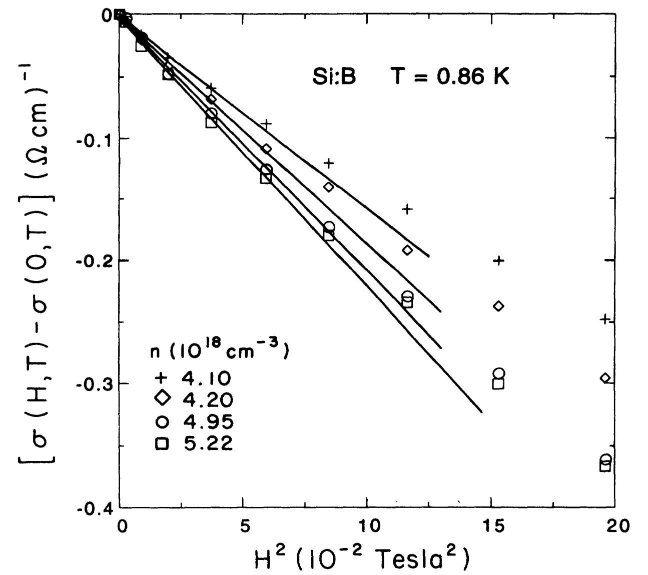

FIG. 7. The change in the conductivity, $\sigma(H,T)-\sigma(0,T)$, plotted as a function of H^2 at 0.86 K for four samples with different boron concentrations, as labeled. The straight lines are drawn to guide the eye.

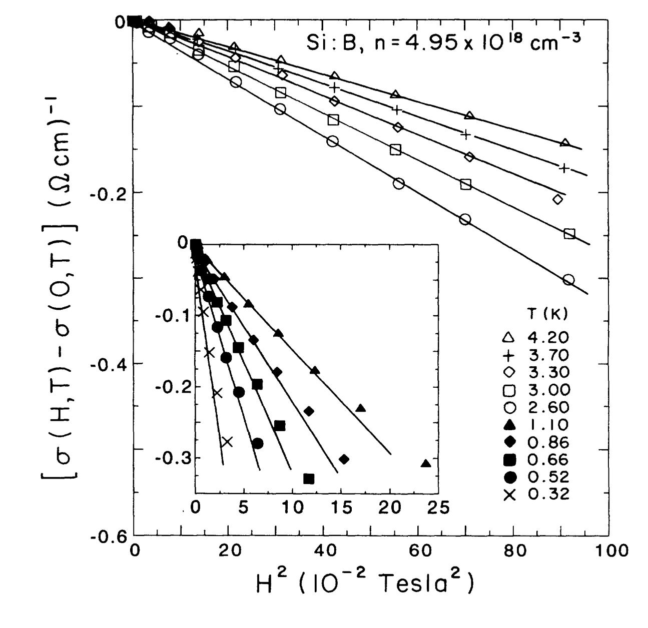

FIG. 8. The change in the conductivity, $\sigma(H,T)-\sigma(0,T)$, vs H^2 for a Si:B sample with dopant concentration 4.95×10^{18} cm^{-3}. The figure shows data for various temperatures above 1.5 K, as labeled, and the inset shows data at temperatures below 1.5 K. The lines are drawn to guide the eye.

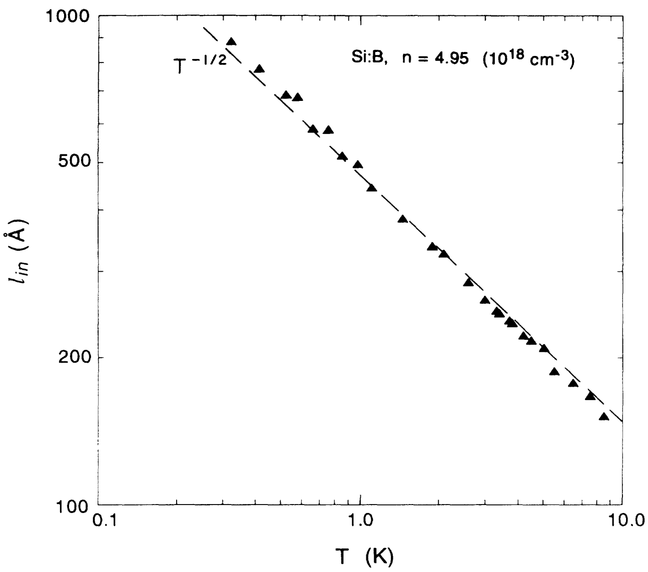

FIG. 9. The inelastic-scattering length l_{in} as a function of temperature plotted on a double logarithmic scale for a Si:B sample with dopant concentration 4.95×10^{18} cm^{-3}. The line denotes slope -0.5, or $l_{\text{in}} \propto T^{-1/2}$.

tained by subtracting the component due to interactions given by Eq. (5b) using the value of $\alpha\gamma F_\sigma$ estimated from the high-field data. The inelastic-scattering length l_{in} at each temperature was then calculated.

The values of l_{in} are shown as a function of temperature on a double logarithmic plot in Fig. 9. Our results show that the inelastic-scattering length is roughly inversely proportional to the square root of the temperature. Since $\tau_{\text{in}}=l_{\text{in}}^2/D$, this implies that the inelastic-scattering time $\tau_{\text{in}} \propto T^{-1}$, in agreement with the theoretical prediction of Belitz and Wysokinski[29] for material very close to the metal-insulator transition. Although this sample is quite metallic compared with the others used in our studies, its concentration $n=1.22n_c$ nevertheless places it reasonably close to the transition. Our results differ, however, with those of Paalanen and Bhatt[6] who obtained $p<1$ for Si:P samples near the transition.

The exponent p also appears in the theoretical expression for the correction to the conductivity due to localization, i.e., $\Delta\sigma_L(T) \propto T^{p/2}$. We note that the temperature dependence of the conductivity yields $p=\frac{3}{2}$, a value which is distinctly different from that obtained from our study of the magnetoconductivity above. This is a clear indication that current theory does not offer a consistent or complete description of the behavior of Si:B.

SUMMARY

We have made a systematic study of the magnetoconductance of eight metallic p-type Si:B samples in magnetic fields up to 9 T at temperatures between 0.1 and 4.2 K. The magnetoconductance is found to be negative for all samples at all measured fields and temperatures. We attribute this to strong spin-orbit scattering associated with the degenerate valence bands in p-type silicon.

The contributions to the magnetoconductivity due to interactions and due to (anti)localization are both negative and of the same sign, so that it is difficult to separate the two components. The magnetoconductance exhibits a quadratic dependence on magnetic field at small fields and follows approximately $H^{1/2}$ behavior at large fields. Analysis of the temperature and field dependences at large magnetic fields indicates that the data for samples not too close to the metal-insulator transition are consistent with the assumption that the high-field magnetoconductance is attributable mainly to interactions. Within this approximation, we have separated the low-field magnetoresistance into contributions due to localization and due to interactions. Analysis of the component due to localization yields a hole inelastic-scattering rate which is roughly proportional to temperature, consistent with a recent theoretical prediction[29] of Belitz and Wysokinski.

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