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Hopping conduction in doped silicon: The apparent absence of quantum interference

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A negative magnetoconductance is found for insulating, uncompensated *n*-type Si:P and Si:As, uncompensated *p*-type Si:B, and compensated Si:P,B at temperatures between 1.6 and 4.2 K. The positive component expected for quantum interference in the hopping regime is absent or undetectably small in all these Si-based semiconductors even in magnetic fields as small as 200 G.

The conductivity of materials in the hopping regime is influenced by magnetic fields in several interesting ways.[1] A magnetic field reduces the conductivity by changing the asymptotic form of the wave functions at moderate fields and by reducing wave-function overlap at high fields. Quantum-mechanical interference gives rise to a magnetoconductance of the opposite sign. Thus, when suitably summed over a sample of macroscopic dimensions, interference between different paths connecting initial and final states of individual hopping events is expected to give a positive contribution.[2-4] A positive magnetoconductance of this type has been observed and studied in some detail in various materials, including InO,[5] *n*-type GaAs,[6] δ-doped GaAs,[7] *n*-type Ge,[8] and *n*-type CdSe.[9,10] There has been an interesting debate[11-15] on whether spin-orbit scattering causes the contribution due to interference to reverse sign, that is, to be negative rather than positive. In addition, recent evidence[16,17] suggests that the conductivity is partly determined by correlations between electrons due to exchange in ways that have yet to be studied in detail, both theoretically and experimentally.

The relative importance of these factors is not well understood, and appears to vary for different materials in different ranges of temperature and magnetic field. The aim of our study was to explore the role of spin-orbit effects, which are known to be important in *p*-type materials such as Si:B, and the possible role of compensation, which generally increases the density of states near the Fermi energy. Our results indicate that, regardless of the sign of the dopant impurity, and of the presence or absence of compensation, all the Si-based semiconductors we measured have negative magnetoconductances of comparable size between 1.6 and 4.2 K.

The materials used in our investigations, all grown by the Czochralski method, include uncompensated *n*-type Si:P obtained from Crysteco, uncompensated *n*-type Si:As provided by Thomas, uncompensated *p*-type Si:B from Puresil, and compensated *n*-type Si:P,B grown by Mulab and provided by Holcomb and Thomanschefsky. The dopant concentrations of the uncompensated materials were determined by measuring the resistance ratios $R_{4.2}/R_{300}$. Based on a systematic study by Thomanschefsky and Holcomb[18] of the Hall coefficients and neutron activation analysis of a series of Si:P,B samples, we used room-temperature resistivity and Hall-coefficient measurements to estimate that the net donor concentration of the compensated sample used in this experiment is very approximately 3.1×10^{18} cm^{-3}, the compensation $K\approx0.65$ and $n/n_c\approx0.55$. Samples were cut into thin bars and etched in a CP-4 solution to remove any damaged surface layers. Contacts were made to the Si:B samples by depositing four thin strip-shaped Al films on each sample and then attaching Au wires by an arc discharge technique. For the Si:P, Si:As, and Si:P,B samples, Au wires were attached directly to the samples with the same arc technique. Standard ac low-frequency (15 Hz) four-terminal methods were used for the resistivity measurements. The excitation currents were varied to insure Ohmic behavior. Measurements were made at temperatures between 1.6 and 4.2 K in a ^{4}He dewar in magnetic fields up to 2 T.

The logarithm of the ratio of the conductivity in a

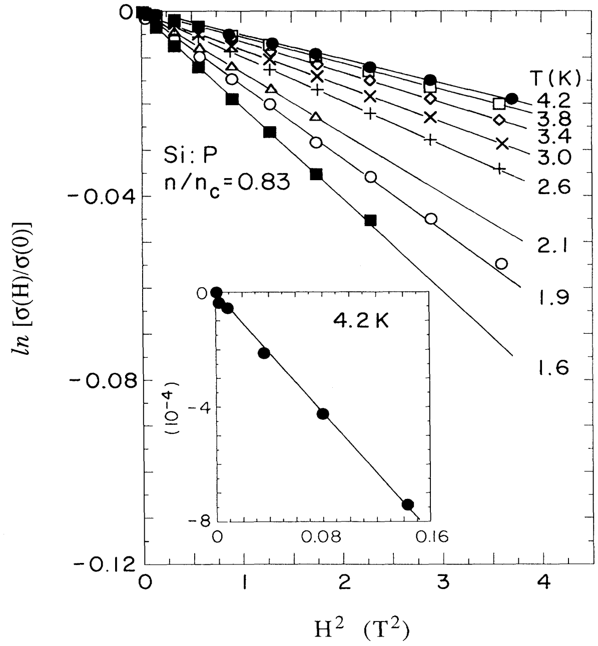

FIG. 1. The logarithm of the ratio of the conductivities, $\ln[\sigma(H)/\sigma(0)]$, vs H^2 at several different temperatures for nominally uncompensated *n*-type Si:P. The inset shows data at small magnetic fields.

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magnetic field H to that in zero field, $\ln[\sigma(H)/\sigma(0)]$, is shown as a function of H^2 at several different temperatures for nominally uncompensated n-type Si:P in Fig. 1, for nominally uncompensated p-type Si:B in Fig. 2, and for compensated n-type Si:P,B in Fig. 3. Although about 50% larger, the magnetoconductance is essentially the same for uncompensated n-type Si:As as for Si:P. The magnetoconductance is surprisingly similar for all these silicon-based doped semiconductors. It is negative for all the systems under investigation at temperatures between 1.6 and 4.2 K down to the lowest magnetic fields measured (200 G for Si:B and about 50 G for Si:P). Neither the sign of the dopant nor the presence of compensation appear to play significant roles. Negative magnetoconductances have been observed earlier by Ionov *et al.*[19] in Si:P at moderate fields, and in Si:As by Shafarman *et al.*[20] at substantially higher magnetic fields.

A positive magnetoconductance is expected by Nguyen, Spivak, and Shklovskii[2] for quantum interference in the hopping regime at all dopant concentrations. Sivan and co-workers[3] predict a positive magnetoconductance for material deep in the insulating range, and negative near the metal-insulator transition. It has also been suggested[9,11] that the backscattering, which leads to localization as the metal-insulator transition is approached from the metallic side, also contributes a positive magnetoconductance in barely insulating samples. Thus, although the sign near the transition has been a matter of debate, all theoretical[2-4] work to date predicts that the magnetoconductance associated with quantum-mechanical interference should be positive in the deeply insulating phase. As illustrated in the inset to Fig. 2 for Si:B, the magnetoconductance of our samples becomes instead increasingly negative as the dopant concentration is reduced, and shows no sign of saturating or turning back. Thus, the positive magnetoconductance predicted for quantum interference and observed in many other systems is apparently negligible or absent in silicon-based doped semiconductors, irrespective of the sign of the dopant, or the degree of compensation. This should be contrasted with n-type Ge, where a positive component of the order of 2% or 3% is clearly evident at comparable temperatures in magnetic fields of 0.3 T and higher.[8]

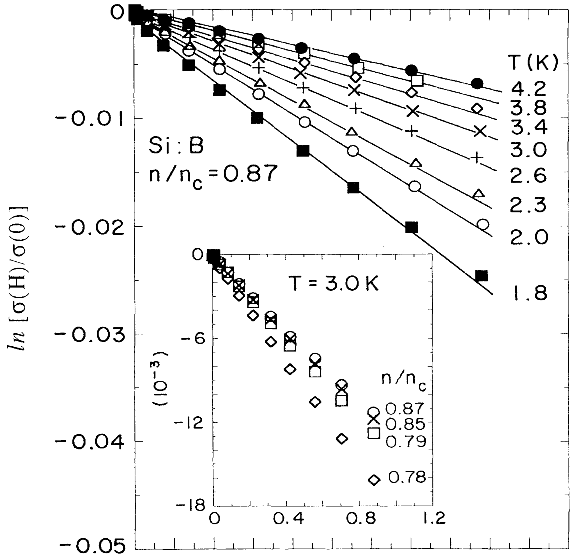

FIG. 2. The logarithm of the ratio of the conductivities, $\ln[\sigma(H)/\sigma(0)]$, vs H^2 at several different temperatures for nominally uncompensated p-type Si:B. The inset shows data for different boron dopant concentrations, as labeled.

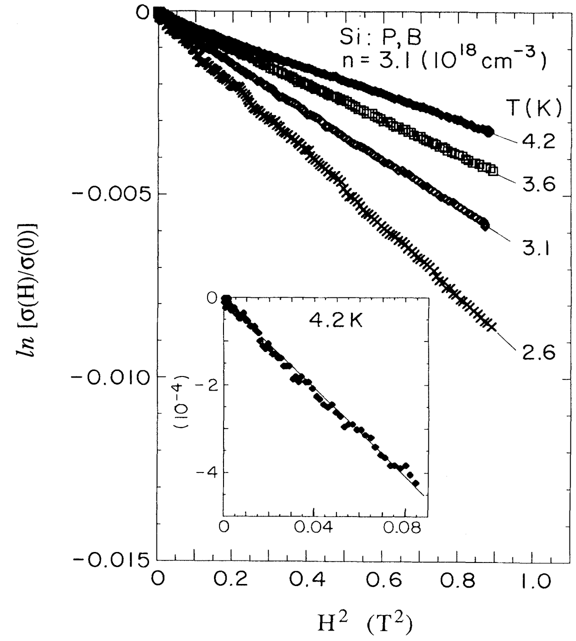

FIG. 3. The logarithm of the ratio of the conductivities, $\ln[\sigma(H)/\sigma(0)]$, vs H^2 at several different temperatures for compensated n-type Si:P,B. The inset shows data at small magnetic fields.

Figures 1–3 show that the conductivity is consistent with the exponential form, $\ln[\sigma(H)/\sigma(0)] \propto H^2$, within the range of magnetic fields and temperatures of our measurements. We note that the conductivity changes little with field (at most 2% or 3% in a field of 1 T). Thus, since $\ln[\sigma(H)/\sigma(0)] = \ln[1+\Delta\sigma/\sigma] \approx \Delta\sigma/\sigma$, the expression $\Delta\sigma/\sigma \propto H^2$ provides an equally good fit. The exponential form is consistent with a negative magnetoconductance due to field-induced modifications of the wave functions, an effect which is expected to be important only at substantially higher magnetic fields. However, it is possible that this contribution becomes measurable at small fields in the absence of a competing positive term.

Field-induced modifications of the dopant wave functions are expected to give a conductivity

$$\ln[\sigma(H)/\sigma(0)] = -\mathcal{H}H^2 \propto H^2(T^*/T)^y \,, \tag{1}$$

with $y = \frac{3}{4}$ for Mott variable-range hopping, and $y = \frac{3}{2}$ for variable-range hopping in the presence of a Coulomb gap due to electron-electron interactions.[1] The slopes obtained from the best fits to the data of Figs. 1–4 are plotted as a function of temperature on a double-logarithmic scale in Fig. 4. Despite the fact that in this range of temperature the zero-field conductivity was found to exhibit Mott hopping in Si:P and some intermediate form in Si:As and Si:B, the slopes of Fig. 4 yield $y=\frac{3}{2}$ for all the uncompensated materials. The slope for compensated Si:P,B yields $y=2$, which fits neither form. Our results are thus inconsistent with this theory in detail, and the negative magnetoconductance we observe may in fact be due to a different mechanism.

The presence of a positive magnetoconductance in many materials and its absence in others is currently not understood. A positive term has been measured at small fields in doped germanium while it appears to be absent in doped silicon. We suggest that the apparent absence at temperatures between 1.6 and 4.2 K of a positive component in the magnetoconductance of silicon may be due to spin-flip scattering. The magnetic susceptibility of insulating doped semiconductors is a strong function of temperature, and static and ESR measurements have established that there are on the order of 10^{18}-cm^{-3} magnetic moments in Si:P,[21] Si:B,[22] and Si:P,B (Ref. 23) at dopant densities comparable to those in our samples. Similar behavior[24] is found for Ge:Sb, which has an order of magnitude fewer spins for equivalent values of n/n_c ($n_c \approx 10^{17}$ cm^{-3}). There is recent evidence that the $\approx 10^{18}$-cm^{-3} spins in Si:B have a measurable effect on its magnetoconductance below about 300 mK, where they appear to be responsible for the presence of a "hard" gap in the density of states.[16] Quantum interference requires that phase memory be retained during the intermediate virtual scattering events between the initial and final states of a hop. Spin-flip scattering may suppress the phase memory required for the quantum interference process. We suggest that strong spin-flip scattering may thus be responsible for the absence of a positive magnetoconductance in silicon-based doped semiconductors in the temperature range between 1.6 and 4.2 K.

To summarize, we have measured the magnetoconductance to 2 T between 1.6 and 4.2 K of uncompensated n-type Si:P and n-type Si:As, uncompensated p-type Si:B, and compensated n-type Si:P,B. For both signs of the dopant, and in compensated as well as uncompensated samples, the magnetoconductance is small and negative and consistent with that expected due to changes of the electron wave functions in a magnetic field. Quantum interference, which is generally expected to give a positive contribution, appears to be absent or negligibly small at these fields and temperatures. The reason for the apparent absence of this term is not understood, and requires further study. We suggest that it may be due to strong spin-flip scattering in doped silicon.

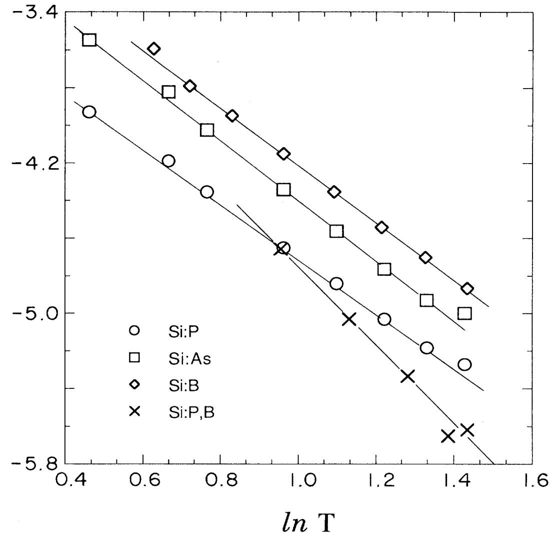

FIG. 4. $\{-\ln[\sigma(H)/\sigma(0)]\}/H^2=\mathcal{K}\propto(T^*/T)^y$ vs T (in K) plotted on a log-log scale [see Eq. (1)]. $\mathcal{K}$ (in T^{-2}) is obtained from the slopes of the curves of Figs. 1–3, and equivalent data for Si:As.

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[1] B. I. Shklovskii and A. L. Efros, *Electronic Properties of Doped Semiconductors* (Springer-Verlag, Berlin, 1984).

[2] V. I. Nguyen, B. Z. Spivak, and B. I. Shklovskii, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 35 (1985) [JETP Lett. **41**, 42 (1985)]; Zh. Eksp. Teor. Fiz. **89**, 1770 (1985) [Sov. Phys. JETP **62**, 1021 (1985)].

[3] U. Sivan, O. Entin-Wohlman, and Y. Imry, Phys. Rev. Lett. **60**, 1566 (1988); O. Entin-Wohlman, Y. Imry, and U. Sivan, Phys. Rev. B **40**, 8342 (1989).

[4] W. Schirmacher, Phys. Rev. B **41**, 2461 (1990).

[5] O. Faran and Z. Ovadyahu, Phys. Rev. B **38**, 5457 (1988).

[6] F. Tremblay, M. Pepper, D. Ritchie, D. C. Peacock, J. E. F. Frost, and G. A. C. Jones, Phys. Rev. B **39**, 8059 (1989); F. Tremblay, M. Pepper, R. Newbury, D. Ritchie, D. C. Peacock, J. E. F. Frost, and G. A. C. Jones, *ibid.* **40**, 10051 (1989).

[7] Qiu-yi Ye, B. I. Shklovskii, A. Zrenner, and F. Koch, Phys. Rev. B **41**, 8477 (1990); M. E. Raikh, J. Czingon, Qui-yi Ye, F. Koch, W. Schoepe, and K. Ploog, *ibid.* **45**, 6015 (1992).

[8] A. N. Ionov, I. S. Shlimak, and A. L. Efros, Fiz. Tverd. Tela (Leningrad) **17**, 2763 (1975) [Sov. Phys. Solid State **17**, 1835 (1976)]; I. S. Shlimak, A. N. Ionov, and B. I. Shklovskii, Fiz. Tekh. Poluprovodn. **17**, 503 (1983) [Sov. Phys. Semicond. **17**, 315 (1983)].

[9] T. Dietl, L. Swierkowski, J. Jaroszynski, M. Sawicki, and T. Wojtowics, Phys. Scr. **T14**, 29 (1986).

[10] Y. Zhang and M. P. Sarachik, Phys. Rev. B **39**, 8059 (1989); Y. Zhang, P. Dai, and M. P. Sarachik, *ibid.* **45**, 9473 (1992).

[11] Y. Shapir and Z. Ovadyahu, Phys. Rev. B **40**, 12 441 (1989).

[12] J. L. Pichard, M. Sanquer, K. Slevin, and P. Debray, Phys. Rev. Lett. **65**, 1812 (1990).

[13] E. Medina, M. Kardar, Y. Shapir, and X. R. Wang, Phys. Rev. Lett. **62**, 941 (1989); **64**, 1816 (1990).

[14] Y. Meir, N. S. Wingreen, O. Entin-Wohlman, and B. L. Altshuler, Phys. Rev. Lett. **66**, 1517 (1991).

[15] E. Medina and M. Kardar, Phys. Rev. Lett. **66**, 3187 (1991).

[16] P. Dai, Y. Zhang, and M. P. Sarachik, Phys. Rev. Lett. **69**, 1804 (1992).

[17] I. Terry, T. Penney, S. von Molnar, and P. Becla, Phys. Rev. Lett. **69**, 1800 (1992).

[18] U. Thomanschefsky, Ph. D. thesis, Cornell University, 1990; U. Thomanschefsky and D. F. Holcomb, Phys. Rev. B **45**, 13 360 (1992); D. F. Holcomb (private communication).

[19] A. N. Ionov, M. N. Matveev, R. Rentzsch, and I. S. Shlimak, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 330 (1985) [JETP. Lett. **42**, 406 (1985)].

[20] W. N. Shafarman, T. G. Castner, J. S. Brooks, K. P. Martin, and M. J. Naughton, Solid-State Electron. **28**, 93 (1985).

[21] J. P. Quirt and J. R. Marko, Phys. Rev. Lett. **26**, 318 (1971); Phys. Rev. B **7**, 3842 (1973); H. Ue and S. Maekawa, *ibid.* **3**, 4232 (1971); S. Ikehata and S. Kobayashi, Solid State Commun. **56**, 607 (1985); M. A. Paalanen, S. Sachdev, R. N. Bhatt, and A. E. Ruckenstein, Phys. Rev. Lett. **57**, 2061 (1986); K. Andres, R. N. Bhatt, P. Goalwin, T. M. Rice, and R. E. Walstedt, Phys. Rev. B **24**, 244 (1981); Y. Ootuka and N. Matsunaga, in *Anderson Localization,* edited by T. Ando and H. Fukuyama (Springer-Verlag, Berlin, 1988).

[22] M. P. Sarachik, D. R. He, W. Li, M. Levy, and J. S. Brooks, Phys. Rev. B **31**, 1469 (1985).

[23] M. J. Hirsch, D. F. Holcomb, R. N. Bhatt, and M. A. Paalanen, Phys. Rev. Lett. **68**, 1418 (1992).

[24] N. Matsunaga and Y. Ootuka, Solid State Commun. **75**, 255 (1990).