PROGRESS REPORT

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"Magnetic Properties and Critical Behavior of the
Conductivity Near the M-I Transition"

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PROGRESS REPORT

I - EXPERIMENTS IN THE METALLIC PHASE - CRITICAL BEHAVIOR

Our studies of the resistivity, the magnetoresistance and the Hall coefficient of Si:B have yielded some significant results:

(1) Electrical Conductivity of Metallic Si:B. A detailed report of our results for the electrical conductivity of metallic Si:B between 55 mK and 4.2 K in magnetic fields to 7.5T, and a full comparison with the conductivity of Si:P, were published in Phys. Rev. B **45**, 3984 (1992).

(2) Magnetoresistance of Metallic Si:B. We have studied the magnetoresistance of Si:B at temperatures between 0.05 to 10K in magnetic fields to 9T. The magnetoresistance is positive everywhere within this range of experimental parameters, including in very small magnetic fields where we have done careful and extensive measurements. In contrast to the usual case where the low field magnetoresistance has a negative component associated with the dephasing by a magnetic field of the single particle backscattering process which leads to weak localization, materials in which spin-orbit scattering is important exhibit antilocalization so that the dephasing effect of a magnetic field yields a positive magnetoresistance.¹ We attribute the absence of a negative magnetoresistance to the importance of spin orbit effects in Si:B. A reliable separation into components associated with the dephasing and with electron-electron is more difficult here than for Si:P interactions, since both are of the same sign. Reasonable assumptions regarding the relative size of the contributions at low and at high fields allow an approximate separation from which we deduce the inelastic scattering times, the interaction constant F , and other interesting parameters. Details are contained in Phys. Rev. B **46**, 6724 (1992).

(3) Critical Conductivity Exponent of Si:B. The critical exponent μ which characterizes the approach of the zero-temperature conductivity, $\sigma(0)=\sigma[(n/n_c)-1]^\mu$, to the metal-insulator transition has been found experimentally to be equal to 1 in almost all cases. With the possible

exception of Ga:Ar,² this is true for all semiconductor-metal alloys (e.g. Ge:Au³) measured to date, and for compensated doped semiconductors such as Si:(P,B),⁴ as well as uncompensated Ge:Sb.⁵ The exceptions to this are the "prototypical" uncompensated n-type Si-based semiconductors Si:P,⁶ Si:As,⁷ Si:Sb⁸ and the double-doped system Si:(P,As),⁹ where the critical conductivity exponent has instead an "anomalous" value near 1/2. Among others, spin orbit scattering has been suggested as a factor which could possibly account for the observed difference. Based on Fermi liquid theory, Castellani, Kotliar and Lee¹⁰ suggested that in the presence of spin-orbit scattering the transition is not a true localization transition and is instead due to electron-electron interactions with a critical exponent $\mu=1$. Through a series of measurements of Si:B, a system in which spin-orbit effects are known to be strong, we found that the critical conductivity exponent of Si:B is close to 1/2 despite strong spin-orbit scattering. This appears to rule out spin-orbit effects in establishing the universality class, at least in Si:B, leaving the puzzle of the anomalous critical exponent of 1/2 unresolved and of greater interest than ever. Details are contained in Phys. Rev. Letters **66**, 1914 (1991).

(4) Critical Conductivity Exponent of Si:B in a Magnetic Field.

Subsequent measurements on the same samples of Si:B in a magnetic field have yielded another important result. In addition to finding that μ should be unity for the universality class appropriate to spin-orbit scattering, Castellani, Kotliar and Lee¹⁰ showed that the critical exponent should also be close to 1 in the presence of a magnetic field and for magnetic impurity scattering. Our experimental results in a magnetic field demonstrate that the critical exponent does indeed change from the "anomalous" value close to 1/2 which it has at zero field for reasons which are not understood, to the expected value 1 in a magnetic field of 7.5T. To our knowledge, this is the first clear experimental evidence for a change in universality class at the metal-insulator transition caused by the application of a magnetic field. (However, see (5) below.) Details of this work are contained in Phys. Rev. Letters, **67**, 136 (1991).

(5) Exponent in the Magnetic-Field-Universality Class. Belitz and Kirkpatrick¹¹ have recently pointed out that for a material which is in the SO (spin-orbit) universality class in the absence of a magnetic field, the

application of a large magnetic field places it in the universality class corresponding to MI (magnetic impurities) even though there are no magnetic impurities present in the system. Thus, SO (spin-orbit) + MF (magnetic field) = MI (magnetic impurities). This implies that if Si:B does indeed have strong spin-orbit effects, our earlier finding of $\mu=1$ in this material in a large magnetic field corresponds to the MI class rather than the MF universality class. According to Belitz and Kirkpatrick¹¹ the MF class is obtained in a high magnetic field only for a material which is in the generic class in the absence of a magnetic field. This implies that the critical exponent for the MF class can be determined from measurements in high magnetic field in Si:P, which is in the generic class at $H=0$. Indeed, we have recently finished measurements of the critical conductivity exponent at 8T in Si:P, and find that it is approximately 1, in agreement with theory. This is the first determination of the critical conductivity exponent in the MF universality class. These results were present at the March 1993 APS meeting, and a manuscript is currently in preparation.

(6) Hall Coefficient of Metallic Si:B. A rather important issue which remains unresolved is whether or not the Hall coefficient diverges as the metal-insulator transition is approached from the metallic side. When the transition is driven by interactions, the density of states vanishes at the Fermi energy and the Hall coefficient diverges.¹² On the other hand, at a localization transition the charge diffusion D vanishes, and a scaling calculation for non-interacting electrons by Shapiro and Abrahams¹³ predicted that the Hall coefficient should remain finite. Consequently, finite Hall coefficients have been attributed to localization, while diverging coefficients have been attributed to strong electron-electron interactions. These assumptions have been called into question by recent calculations of Wang, Wang, Kotliar, and Castellani¹⁴ who claim that the Hall coefficient should diverge even at a localization transition or, in effect, that the coefficient $R_H \approx (ne)^{-1}$ probes only the extended states.

Two systematic studies of R_H in nominally uncompensated crystalline doped semiconductors have yielded different results. The Hall coefficient was found by Field and Rosenbaum¹⁵ to diverge in Ge:Sb. In contrast, Koon and Castner¹⁶ have measured a finite Hall coefficient in Si:As. Based on a reinterpretation of earlier data of Yamanouchi et al.¹⁷ Koon and Castner

have also claimed that Si:P exhibits non-critical behavior.¹⁶ Strong spin-orbit scattering has been advanced as a possible reason for a diverging R_H . Based on the limited experimental data available, it has been also been suggested^{14,18} that the Hall coefficient diverges in all materials except those where the conductivity exponent $\mu \approx 1/2$. The first hypothesis implies that the Hall coefficient should diverge in Si:B due to strong spin-orbit effects. On the other hand, it should remain finite according to the second hypothesis since the critical conductivity exponent¹⁹ was found to be $\approx 1/2$ to $2/3$ in Si:B. Our recent measurements, just published, indicate that R_H diverges at the transition. This may indeed be due to spin-orbit effects. We point out, however, that the critical exponent for the longitudinal conductivity of Si:B is not equal to 1, as expected in the presence of strong spin-orbit scattering. It is unlikely that spin-orbit effects determine the behavior of the transverse conductivity without also determining that of the longitudinal transport. This work just appeared in Phys. Rev. Letters **70**, 1968 (1993).

II- EXPERIMENTS IN THE INSULATING PHASE -HOPPING CONDUCTION

(1) Universal Crossover Behavior. On the basis of earlier measurements²⁰ of the resistivity of five samples of n-type CdSe containing different dopant concentrations, we reported a crossover with decreasing temperature from Mott variable range hopping, $\sigma = \sigma_0 \exp[-(T_0/T)^{1/4}]$, to the form of variable range hopping expected in the presence of a "Coulomb gap" in the density of states due to electron correlations, $\sigma = \sigma_0' \exp[-(T_0'/T)^{1/2}]$. With Amnon Aharony, we have recently shown that the data for all five samples collapse onto a single scaling form, $\ln(\rho/\rho_0) = Af(T/T_x)$, where $f(x)$ is a universal function, and A and T_x are sample-dependent constants. This work appeared in Physical Review Letters **68**, 3900 (1992).

(2) Evidence of Correlations due to Exchange. Measurements in nominally uncompensated p-type insulating Si:B indicate that the resistivity in the absence of a magnetic field exhibits activated behavior at very low temperature rather than variable range hopping. Similar behavior had been reported in Si:As,²¹ transmutation-doped n-type Ge,²² GeCr²³ and irradiated

polymer films.²⁴ By applying a magnetic field, we found that the behavior reverts back to Efros-Shklovskii variable-range-hopping at 1 T or higher. Very similar results were found at essentially the same time by Terry, Penney, von Molnar and Becla²⁵ in the dilute magnetic semiconductor HgCdTe. That there is a crossover to a qualitatively different regime when a magnetic field is applied indicates that the zero-field gap is of magnetic origin, as first suggested by Shlimak.²² The form of variable range hopping observed in a magnetic field implies that the density of states has a "soft" parabolic Coulomb gap, which is a manifestation of correlations between electrons due to their charges. Our experimental results imply that in the absence of a magnetic field there exists either a "hard" gap or a sharp decrease in the density of states near E_F due to correlations among the electrons not only due to their charges but also by virtue of their spins. These results were reported in Physical Review Letters **69**, 1804 (1992).

(3) Positive Magnetoconductance due to Quantum Interference.

Quantum-mechanical interference gives rise to a positive magnetoconductance which has been observed and studied in some detail in various materials, including InO,²⁶ n-type GaAs,²⁷ delta-doped GaAs,²⁸ n-type Ge²⁹ and n-type CdSe³⁰ and CdMnSe.³¹ There has been some debate regarding the field dependence of the magnetoconductance. Most experimental studies have yielded either quadratic behavior for all samples of a given material within the measured range of field and temperatures, or linear dependence over the entire range studied. By taking measurements over a very broad range of temperature and magnetic field, we were able to demonstrate that both linear and quadratic dependence on magnetic field are observed in n-type CdSe depending on the temperature of the measurement. Further, the magnetic field at which the crossover from quadratic to linear behavior occurs was shown to be consistent with theoretical expectations. This work was published in the Rapid Communications section of Phys. Rev. **B45**, 9473 (1992).

(4) Apparent Absence of Quantum Interference in Silicon-based Material.

The conductivity of materials in the hopping regime is influenced by magnetic fields in several interesting ways. A magnetic field reduces the conductivity (negative magnetoconductance) by changing the asymptotic

form of the wavefunctions at moderate fields and by reducing wave-function overlap at high fields. As discussed above, quantum-mechanical interference gives rise to a positive magnetoconductance. There has been an interesting debate³²⁻³⁶ 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 results (see 2 above) suggest that the conductivity is partly determined by correlations between electrons due to exchange in ways that have yet to be studied in detail, either theoretically or 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. In order 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, we undertook a study of several different silicon-based semiconductors, including insulating, uncompensated n-type Si:P and Si:As, uncompensated p-type Si:B and compensated Si:P,B. Our results indicate that, regardless of the sign of the dopant impurity, and of the presence or absence of compensation, all these systems have negative magnetoconductances of comparable size between 1.6 and 4.2K. The positive component expected for quantum interference in the hopping regime is absent or undetectably small even in magnetic fields as small as 200 gauss. A paper describing this work has been submitted to Physical Review.

(5) The Hall coefficient of n-type CdSe in the Hopping Regime.

Following Koon and Castner's first measurements³⁷ of a Hall coefficient in the insulating phase in Si:As, we took detailed measurements of the coefficient in n-type CdSe over a wide range of temperature and magnetic field.³⁸ We found a temperature-dependence consistent with the variable-range-hopping form, quite similar to (but weaker than) for the longitudinal resistivity. We also found that, unlike the usual behavior found in the metallic phase, the Hall voltage in an insulator is not linear with magnetic field. For a series of CdSe samples with varying In dopant concentrations, we observed three distinct magnetic field regimes at all temperatures between 0.05 and 4.2K. The Hall coefficient increases linearly at low fields up to some field which depends on the temperature. This is followed by a plateau, above which the Hall coefficient increases again with magnetic field. These

measurements provide the first detailed mapping of R_H in the hopping regime over a broad range of temperature and magnetic field. The results appeared in Rapid communications, Phys. Rev. B **45**, 6301 (1992).

(6) Empirical Scaling in Transverse and Longitudinal Transport in Insulating n-type CdSe. Based on the data that we have obtained between 0.05 and 4.2K for four samples of compensated n-type CdSe, we have proposed (with Mark Ya. Azbel) that in magnetic fields above 3T (up to the highest field of 9T available in our laboratory) an empirical relation holds between the longitudinal and transverse components of the hopping transport, given by $\sigma_{xy} = \mathcal{A} H \sigma_{xx}^{3/2}$. Variations in the prefactor $\mathcal{A}$ are within the $\pm 12\%$ uncertainty of our measurements over the available range of dopant concentrations, $0.75 \leq n/n_c \leq 0.95$. This relation between the longitudinal and transverse conductivities appears to hold independently of the details of the temperature dependence of either component, be it Mott or ES variable-range-hopping. We note that similar results were obtained in Si:As, $\sigma_{xy} \approx \sigma_{xx}^\alpha$, where Koon and Castner³⁷ claimed, however, that the exponent α varies with dopant concentration and extrapolates to 1.375 at the metal-insulator transition. We propose that the relation between the transverse and longitudinal components is universal with an exponent of 3/2 and that small variations that may occur with magnetic field, with dopant concentration, and with material parameters, can be associated instead with changes in the prefactor $\mathcal{A}$. It is important to test the proposed scaling in other materials and for a wide range of parameters and dopant densities in order to establish its range of validity and to determine whether it is, in fact, a fundamental law of hopping conduction. A paper has been submitted to Physical Review Letters.

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