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PROGRESS REPORT

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

For the Period 12/1/90 through 11/30/91

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PROGRESS REPORT

I - THE METAL-INSULATOR TRANSITION - Metallic Behavior and the Approach to the Transition.

Our studies of the resistivity and the magnetoresistance of Si:B have yielded some surprising and significant results:

(1) The critical exponent ν which characterizes the approach of the zero-temperature conductivity, $\sigma(0)=\sigma_0[(n/n_c)-1]^\nu$, 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, this is true for all semiconductor-metal alloys (e.g. Ge:Au) measured to date, and for compensated doped semiconductors such as Si:(P,B), as well as uncompensated Ge:Sb. The exceptions to this are the "prototypical" uncompensated n-type Si-based semiconductors Si:P, Si:As, Si:Sb and the double-doped system Si:(P,As), where the critical conductivity exponent has instead an "anomalous" value of 1/2. The difference between these two apparently distinct types of behavior is not understood, and various conjectures and possible explanations have been advanced to resolve it.

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 Lee considered the critical behavior within different universality classes determined by the presence of various symmetry-breaking fields. They find 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 $\nu=1$.

Our choice of p-type Si:B as an interesting material for study was prompted by the fact that, on the one hand, it is an uncompensated silicon based material for which $\nu=1/2$ in all other cases measured to date while, on the other hand, spin-orbit effects are known to be important so that theory predicts that the critical exponent should be unity. Our measurements established that the exponent of Si:B is in fact close to 1/2 despite the strong spin-orbit scattering. This appears to rule out spin-orbit effects in establishing a particular universality class to describe the transition, leaving the puzzle of the anomalous critical exponent of 1/2 unresolved and of greater interest than ever. Details are contained in *Physical Review Letters* **66**, 1914 (1991).

(2) Subsequent measurements on the same samples of Si:B in a magnetic field have yielded yet another important result. In addition to finding that ν should be unity for the universality (symplectic) class appropriate to spin-orbit scattering, Castellani, Kotliar and Lee showed that the critical exponent should also be 1 in the presence of a magnetic field (the unitary class). 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 $\nu=1$ 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. These results are published in *Physical Review Letters*, **67**, 136 (1991).

(3) We have studied in detail the conductivity between 55mK and 4.2K in zero field and in magnetic fields to 7.5T, and have analyzed in light of current theory. The corrections to the zero-temperature con-

ductivity arising from electron-electron interactions is comparable in size, and the temperature-dependence is quite similar, to those found in Si:P. This is surprising, in light of some marked differences between the two systems due to the differences associated with valence bands versus conduction bands. For the range of concentrations and experimental parameters of these investigations, the only important experimental difference between the two materials is the sign and size of the magnetoresistance. In contrast with Si:P which has both positive and negative components, the magnetoresistance of Si:B is positive for all temperatures and magnetic fields studied. We attribute this to the strong spin-orbit scattering in p-type silicon associated with the degenerate valence bands. A manuscript describing these results has been submitted to *Physical Review*.

(4) Detailed analysis of the field dependence is currently underway. The magnetoresistance associated with electron-electron interactions is known to be positive. The component associated with the (anti)localization process is also positive, however, in contrast with Si:P where the contribution due to localization is negative. This makes it more difficult to effect a reliable separation into components associated with the two contributions. Reasonable assumptions regarding the relative size of the contributions at low and at high fields allow a tentative separation from which we deduce the inelastic scattering times, the interaction constant F , and other interesting parameters. A manuscript is in preparation which will be submitted to *Physical Review*.

II - THE HOPPING REGIME - Experiments on the Insulating Side

(1) From extensive measurements of the resistivity of a series of samples of n-type CdSe in the absence of a magnetic field, we reported the first experimental finding of a crossover with decreasing temperature from Mott variable range hopping, $\rho = \rho_0 \exp(T_0/T)^{1/4}$, to a form of variable range hopping expected in the presence of a "Coulomb gap" due to electron correlations, namely $\rho = \rho_0' \exp(T_0'/T)^{1/2}$. Detailed analysis of these data also contained the surprising implication that the critical exponent ζ for the dielectric constant and the critical exponent μ which characterizes the approach to the transition of the localization length are approximately equal to each other rather than being in the expected ratio 2:1. It should be noted, however, that the values deduced for $(\epsilon \xi)$ were surprisingly large. (Here ϵ is the dielectric constant and ξ is the localization length.) We plan to measure the dielectric constant of these samples to shed further light on this matter (see below). These results appeared in Physical Review Letters 64, 2687 (1990).

(2) Our most interesting and potentially significant finding to date is an unusual and totally unexpected and unexplained field dependence for the Hall coefficient in the hopping regime. For a series of CdSe samples with varying In dopant concentrations, we have observed three distinct regimes at all temperatures between 0.05 and 4.2K, as follows: At low fields, region I, the Hall coefficient increases linearly with magnetic field up to some field which depends on the temperature (below 0.5T in the mK range and up to fields on the order of 2T at 4.2K). This is followed in region II by a plateau, above which (region III) the Hall coefficient increases again linearly with magnetic field. Not unexpectedly, the range of magnetic fields over which each type of

behavior is observed depends on the temperature, with the low field behavior most apparent at high temperature, and the high field behavior dominant over most of the available field range at low temperatures. We have repeated these measurements using different measuring techniques, different sample and contact geometries, and after etching samples to eliminate surface effects as a possible source for the observed behavior; our results have survived every test. A manuscript has been submitted to Physical Review.

(3) We have measured the magnetoresistance in small magnetic fields in a temperature range between 1.6 and 6K. An analysis of these data in light of current theory yields the interesting and puzzling result that the length scale which determines the coherent forward scattering process which presumably determines the magnetoresistance has a temperature dependence which is not related in any way to the temperature dependence of the hopping length deduced from the zero field resistivity. Very similar results were obtained by Tremblay et al. in n-type GaAs, and pose an intriguing problem for the theory in its present form. This is published in Physical Review **43**, 7212 (1991).

(4) We have also made extensive measurements of the magnetoresistance over a wider range of temperature (down to 50mK) and in magnetic fields up to 9T. A negative component which derives from quantum interference effects dominates at low fields, while at higher magnetic fields the magnetoresistance becomes net positive, due presumably to field-induced modifications of the dopant wavefunctions, as discussed in detail by A. Efros and B. Shklovskii. A reliable separation into the two different contributions has been a non-trivial enterprise, and work is continuing.

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