ELECTRON SPIN RESONANCE IN Si:P NEAR THE METAL-INSULATOR TRANSITION

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ABSTRACT

ESR measurements on phosphorus doped silicon have been carried out in the vicinity of the MI transition for a temperature range T = 10 mK - 10K. A strong T dependence is observed in the spin susceptibility and diffusion constant. This is interpreted in light of the scaling theory of the amorphous antiferromagnet (insulating phase) and the scaling theory of localization with electron-electron interactions (metallic phase).

1. INTRODUCTION

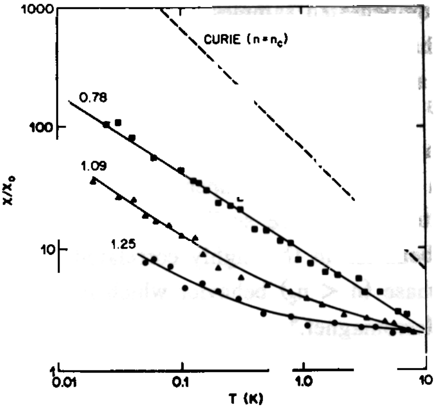
The Metal-Insulator (MI) transition has been studied extensively in doped semiconductors.[1] A major puzzle is that the exponent ν governing the critical onset of the $T = 0$ dc conductivity $[\sigma \propto (n-n_c)^\nu]$ is around 0.5 for uncompensated semiconductors, while compensated samples behave like metal-semiconductor alloys[2] with $\nu \simeq 1$. It has been suggested that this difference may be due to spin scattering, which alters the universality class within the scaling picture of the MI transition.[3] In this paper we use electron spin resonance (ESR) to investigate the spin dynamics of electrons close to the MI transition in uncompensated Si:P down to millikelvin temperatures. This not only provides a clue to the appropriate perturbative scaling scheme on the metallic side, but also shows how the behavior in the highly correlated metal $(n \gtrsim n_c)$ connects with the insulating phase $(n < n_c)$ behavior which has been modelled in terms of an amorphous antiferromagnet.[4]

2. EXPERIMENTS AND RESULTS

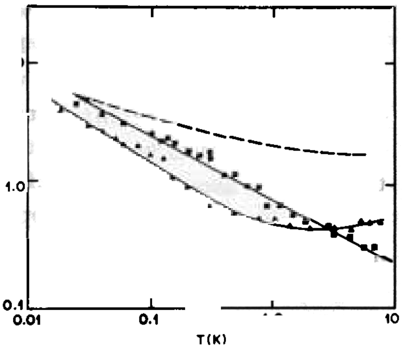
Three Si:P samples with P-doping levels $n = 2.76$, 4.09 and $4.70 \times 10^{18}/\mathrm{cm}^3$, spanning both sides of n_c $(= 3.75 \times 10^{18}/\mathrm{cm}^3)$ were studied. Doping levels were determined using the room temperature resistivity and resistivity ratios $\rho(4.2\mathrm{K})/\rho(300\mathrm{K})$ of neighboring samples cut from the same boule. They were found to be uniform to within ±2% for each sample. The ESR spectrometer was a standard continuous wave Q meter working at f = 18.4 MHz. The absorption signal was recovered by signal averaging about 200 static magnetic field sweeps over the resonance peak. At the higher T, the ESR line was found to be a narrow Lorentzian, while at the lowest T the linewidth became comparable to the resonance field, and additional absorption was detected on the low field side. Consequently we show data only down to 50 mK.

Figure 1 shows the T-dependence of the spin susceptibility χ (relative to the Pauli χ_0) down to T = 50 mK. An absolute determination was possible by an *in situ* calibration against the known susceptibility of ^{29}Si nuclei. Absolute accuracy is estimated as ±25% (relative accuracy ±10%). χ for the insulating sample ($n/n_c = 0.78$) follows quite well the $T^{-0.65}$ behavior seen earlier[5,6] and explained in terms of a scaling theory of hierarchically coupled spins.[4] Interestingly, the metallic samples ($n/n_c = 1.09$ and 1.25) show a similar T-dependence at low T, and a χ up to 30 times the Pauli value.

Figure 2 exhibits the ESR linewidth $\Delta H_{1/2}$ for the same T. Also shown are the results of Murayama et al,[6] for their $n/n_c = 0.55$ sample at 11 MHz. There is a general agreement between the data: the line narrows with increasing n and broadens significantly with decreasing T.



Normalized susceptibility χ/χ_0 as a function of temperature for three Si:P samples near the MI transition ($n = n_c$).



2. ESR linewidth as a function of T at 18.4 MHz for two samples near the MI transition (■ for $n/n_c = 0.78$ and ▲ for $n/n_c = 1.09$). For comparison the broken line shows the linewidth from Ref. 6 at 11 MHz and $n/n_c \simeq 0.55$.

3. *DISCUSSION AND CONCLUSIONS*

In light of the gradual change in the behavior of both χ and $\Delta H_{1/2}$ as n goes through n_c, it is tempting to interpret the results in the metallic phase as an extension of the insulating phase behavior. The scaling calculation[4] for the amorphous antiferromagnet, which neglects charge fluctuations but takes into account quantum spin fluctuations, predicts the T-dependence of χ as well as the (non-linear) magnetization.[5] An extension, including the hyperfine coupling to the P nuclei, accounts for the T and f-dependence of $\Delta H_{1/2}$ seen by Murayama et al.[6] In this picture, spin diffusion is restricted to smaller clusters within a dephasing time as T is reduced. Thus, the exchange narrowing of the ESR line becomes less effective at low T, and a broader line ensues. The effective cluster sizes in this model vs $\Delta H_{1/2}$ are given in Table I. Note that linewidths on the metallic side interpreted thus would correspond to rather small spin clusters at low T.

Table I

N	6	8	20	50	100	450
$\Delta H_{1/2}$ (Oe)	3.9	3.4	3.0	2.6	2.1	1

An alternative approach[8] is the scaling theory of localization with electron-electron interactions, starting from the metallic phase. A perturbative calculation to lowest order in disorder (but all orders in interaction) shows the importance of spin fluctuations,[9] and predicts proportional enhancements of χ and $\Delta H_{1/2}$ (decreased spin diffusion). This is quite well obeyed by all three samples as a function of T (see Figs. 1 & 2); the proportionality constant varies smoothly across n_c. With enhanced spin fluctuations, uncompensated Si:P could belong to a different universality class from the metal-semiconductor alloys and this may account for their different conductivity exponents.

In conclusion, we see a strongly enhanced spin susceptibility (relative to the Pauli value) and suppressed diffusion (compared to charge diffusion) as the MI transition is approached from the metallic phase. Both are T-dependent and merge smoothly on to the insulating phase behavior. These effects are in agreement with scaling pictures of the magnetic behavior of the insulating[4] (no charge diffusion) and metallic[9] (weak disorder) phases. Other experimental probes (such as specific heat, thermopower and thermal conductivity) would be useful in deciding between the relative merits of the two models.

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REFERENCES

1. See e.g., R. F. Milligan, T. F. Rosenbaum, R. N. Bhatt and G. A. Thomas, in "Electron-electron Interactions in Disordered Systems," A. L. Efros and M. Pollack eds. (North Holland, 1985) p. 231 ff.
2. See e.g., G. A. Thomas, Phil. Mag. B*52*, 479 (1985).
3. P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. *57*, 287 (1985).
4. R. N. Bhatt and P. A. Lee, Phys. Rev. Lett. *48*, 344 (1982), and references therein.
5. K. Andres, R. N. Bhatt, P. Goalwin, T. M. Rice and R. E. Walstedt, Phys. Rev. B*24*, 244 (1981); M. P. Sarachik, A. Roy, M. Turner, M. Levy, L. L. Isaacs, D. He and R. N. Bhatt, Phys. Rev. B*34*, 387 (1986).
6. C. T. Murayama, W. G. Clark and J. Sanny, Phys. Rev. B*29*, 6063 (1984).
7. Subir Sachdev and R. N. Bhatt, Phys. Rev. B (to be published).
8. M. A. Paalanen, S. Sachdev, R. N. Bhatt and A. E. Ruckenstein (to be published).
9. Subir Sachdev (to be published).