The Hall Effect in a-Gd_xSi_{1-x} at the Metal-Insulator Transition

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Abstract

We have measured the Hall Effect in 3-d amorphous Gd_xSi_{1-x} films in the critical regime of the Metal-Insulator transition at T=400mK. a-Gd_xSi_{1-x} exhibits a large negative magnetoresistance which is independent of the orientation of the magnetic field H with respect to the film and allows an in-situ tuning of the conductivity through the metal-insulator transition with H. We find an electron-like Hall coefficient R_H. As the material becomes less metallic, R_H increases. We find that R_H is a critical quantity with critical exponent ~ -1 ($R_H \sim (H - H_C)^{-1}$).

Key words: Metal-Insulator transition; Hall Effect; Correlation; Localization

1. Introduction

The investigation of the electronic properties at the Metal-Insulator transition (MIT) is a topic of current interest because the MIT displays characteristics of a T=0K quantum phase transition. [1] To probe the MIT in the critical regime it is important to be able to control the transition in a continuous way. In the past, most studies have relied upon the systematic investigation of a series of samples in which the doping density has been varied through a concentration range that spans the MIT. It is implicitly assumed that all other parameters are kept constant in the preparation of these materials where n, the mobile electron concentration is varied. A systematic quantitative investigation of this kind suffers from the ambiguity that materials from different doping runs are quantitatively compared, introducing uncertainties due to inhomogeneities and irreproducibility in the sample preparation process. An elegant solution to these shortcomings arises from using a single sample, which can be reversibly tuned by an external parameter, like stress, [2] magnetic field [3] or illumination. [4] Such a tunable transition can substantially improve the quality of transport measurements. We have also shown [5] that in addition, for a quantitative study it is of great value to determine the electronic density of states by electron tunneling, since tunnel junctions can determine the density of states away from the Fermi level and display the effect of strong coulomb interactions. Here, we present Hall effect measurements in the case of the 3-dimensional system of a-Gd_xSi_{1-x}, which can be reversibly tuned through the MIT by application of a magnetic field H. [6] In this system we have measured transport conductivity, [5–7] density of states, [5] magnetization [8] and specific heat [9] in the critical regime. Here, we determine the Hall coefficient for values of H where the system is well into the metallic state to values of H where the system is deep into the quantum critical regime.

There is significant debate as to what constitutes the quantum critical regime (QCR). In three dimensions, the Ioffe-Regel [10] limit ($k_F \times l \sim 1; k_F$: Fermi wave vector, l: mean free path) results in a conductivity, $\sigma = n \times e^2/(\hbar \times k_F^2)$ (n: electron concentration, e: elementary charge, $\hbar$: Planck's constant), below which a classical Fermi liquid description fails to make sense. This conductivity is material dependant (due to n/k_F^2) and may be considered a phenomenological upper limit for the conductivity σ of the QCR.

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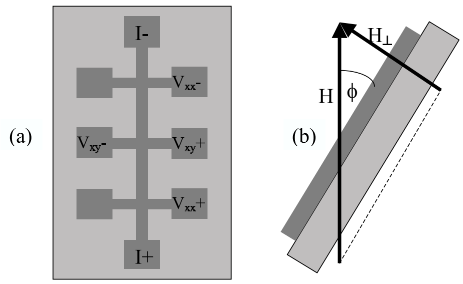

Fig. 1. (a) Schematic top view of sample, (b) Schematic on-edge view of sample rotated at angle ϕ with respect to the applied magnetic field H. $H_\perp = Hsin\phi$ is the magnetic field contributing to the measurement of the Hall coefficient.

Since Gd_xSi_{1-x} is amorphous, its disorder is large compared to crystalline doped semiconductor systems (e.g. Si:P). Consequently, a-Gd_xSi_{1-x} has a significantly enhanced electron density at the MIT ($n \sim 10^{22}cm^{-3}$) leading to a high conductivity at the Ioffe-Regel limit ($\sim 500\Omega^{-1}cm^{-1}$). This is about 40 times larger than the equivalent value in Si:P. [2] A material with a higher electron density and therefore a higher Fermi energy E_F and conductivity at the Ioffe-Regel limit allows for experimentally probing the MIT deeper into the QCR.

The ability to measure the Hall coefficient R_H in a tunable system deep in the quantum critical regime allows an answer to the question if R_H is a critical quantity. According to Altshuler, [11] a system that is dominated by e-e-interactions should exhibit critical behavior for R_H. On the other hand, Fukuyama has suggested [12] that corrections due to localization should leave R_H unchanged. The material used in this study has a very large carrier concentration at the MIT and therefore should exhibit very strong e-e-interactions. Close to the MIT, localization effects should also be present. It is the goal of this study to determine if R_H is critical in the presence of both effects.

2. Methods

To fabricate the Hall bars, we used a lithographic lift-off technique. A film of ∼200nm of Cu was deposited on a SiN covered Si surface. Using optical lithography, a pattern of the desired Hall bar was then defined on this Cu substrate. The exposed Cu in the Hall bar region was then etched in a FeCl solution and the remaining photoresist was removed. Onto the resulting inverted Cu pattern ∼100nm of a-Gd_xSi_{1-x} was deposited, using a simultaneous double e-beam evaporation of Gd and Si. In a lift-off step the remaining Cu was then etched in a FeCl solution, leaving the desired a-Gd_xSi_{1-x} Hall bar. The Hall bars have a current carrying strip as shown in Fig. 1a, and they have three pairs of voltage probes at three different locations along the strip, thus allowing for simultaneous measurements of the longitudinal $R_{xx} = V_{xx}/I$ and transverse $R_{xy} = V_{xy}/I$ resistance. All resistances are measured using a low frequency ($f < 30Hz$) AC method.

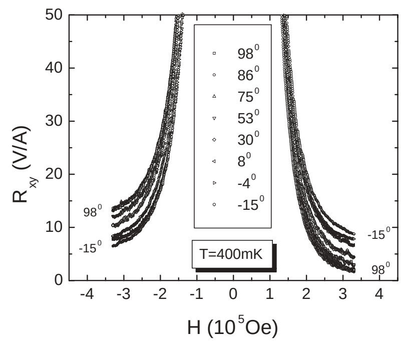

Fig. 2. Measured data: Transverse resistance R_{xy} versus the applied magnetic field H for various angles ϕ.

We measured the samples in a ^{3}He cryostat at T=400mK in applied magnetic fields $|H| < 33T$ at the National High Magnetic Field Lab in Tallahassee, Florida. Since we have already shown that a-Gd_xSi_{1-x} shows a very large magnetoresistance [7] and H drives the system through the MIT, [6] we cannot use the conventional method to measure the Hall coefficient. Instead, we developed a technique to measure the Hall coefficient in constant applied magnetic field. To measure R_{xy} in fixed H, we adjust the angle between H and the sample plane in situ by means of a rotating stage (Fig. 1a, reproducibility of stage angle $\sim 1^o$). We have experimentally verified that the change in longitudinal resistance R_{xx} of 3-dimensional a-Gd_xSi_{1-x} is independent of the direction of the applied magnetic field. The transverse voltage due to the Hall effect, however, depends on the normal magnetic field $H_\perp = Hsin\phi$, where ϕ is the angle between the applied field H and the sample plane (see Figure 1b). Thus, by measuring the transverse resistance in a fixed applied magnetic field at different angles ϕ the Hall coefficient can be determined.

3. Results

Fig. 2 shows the results of a measurement of the transverse resistance R_{xy} versus the applied magnetic field H for various angles ϕ. The very large variation of R_{xy} as a function of applied field H illustrates the complication of these measurements as a function of H, as discussed above. The data at angles close to $\phi = 0^o$ apparently diverge and without careful scrutiny could be interpreted as represented by an even function of ap-

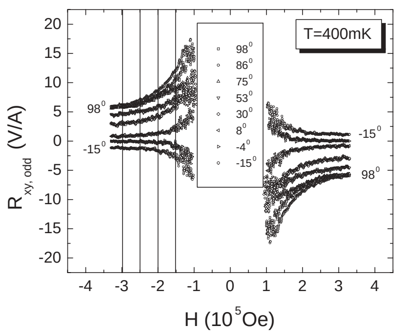

Fig. 3. Odd component of the transverse resistance, $R_{xy,odd}$, versus the applied field H for various angles ϕ.

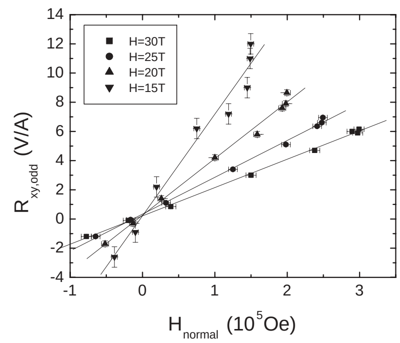

Fig. 4. Odd component of the transverse resistance, $R_{xy,odd}$, versus normal magnetic field, $H_\perp$, for various applied magnetic fields H.

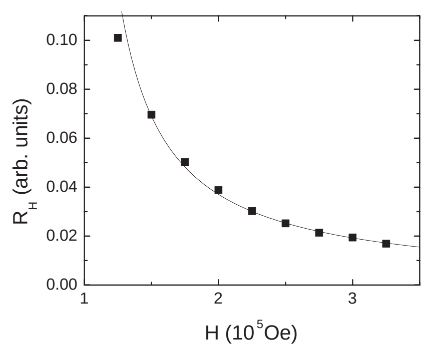

Fig. 5. Hall coefficient R_H versus magnetic field H. Also shown is a function $R_H \sim (H - H_C)^{-1}$ ($H_C = 92kOe$) which describes the data well.

plied field H. For larger angles, it is clearer that there is an asymmetry about H=0. Since the Hall voltage is an odd function of applied field H and yet there appears to be a divergent even component, present for all angles, a more careful analysis of these data is necessary. In order to extract the pure contribution from the Hall effect, we determine the antisymmetric (odd) component of the data in Fig. 2, $R_{xy,odd}(H) = 1/2[R_{xy}(H) - R_{xy}(-H)]$.

Fig. 3 shows the odd component of the transverse resistance, $R_{xy,odd}$, versus the applied field H for various angles ϕ. For $H < H_C = 92kOe$, the sample becomes insulating and the measurement breaks down. As expected, we find almost no odd contribution at angles close to $\phi = 0^o$, since we expect the Hall effect to disappear for a magnetic field H parallel to the film. For larger ϕ, however, we find a significant odd contribution. For positive H, the voltage due to Hall effect in the data close to $\phi = 90^o$ is negative, which indicates that R_H is negative (electron-like). We note that the largest odd contribution occurs for $\phi = 86^o$ and the magnitude of the contribution declines from that value at $\phi = 98^o$ as may be expected, as the maximum should occur at $\phi = 90^o$. Data at the same applied magnetic field H, but at different angles (indicated by the vertical lines) has been acquired at different $H_\perp = Hsin\phi$.

To determine the Hall coefficient R_H, $R_{xy,odd}$ is plotted versus $H_\perp$ for various applied magnetic fields H in Fig. 4. The Hall coefficient R_H is related to the slope $\Delta R_{xy,odd}/\Delta H_\perp$ in this Figure according to $R_H = t \times \Delta R_{xy,odd}/\Delta H_\perp$, where t=100nm is the sample thickness. As H is reduced and the material approaches the insulating regime we observe a concomitant increase in R_H.

Fig. 5 shows R_H versus the magnetic field H. Below the critical field $H_C = 92kOe$ the sample is insulating. Also shown is a function $R_H \sim (H - H_C)^{-1}$ which fits the data very well. We conclude that R_H is not constant in the QCR and shows, in agreement with the prediction of Altshuler, [11] critical behavior. The critical exponent is approximately -1. This is further evidence that the electronic properties of a-Gd_xSi_{1-x} are strongly influenced by e-e interactions, as has been seen in prior transport [6] and tunneling [5] measurements.

4. Conclusion

While the precise conditions for an experimental realization of a system in the QCR are under debate, [2] we have investigated a tunable system with conductivities up to two orders of magnitude below the Ioffe-Regel limit. [5,6] In this system, we have measured transport, [5–7] tunneling, [5] magnetization [8] and specific heat. [9] Adding to this body of information we have shown here that the Hall coefficient R_H is a critical quantity, with critical exponent -1 ($R_H \sim (H - H_C)^{-1}$). This is in agreement with theoretical expectation for a system influenced by e-e-interaction.

In the data presented here we do not see any evidence for anomalous Hall effect. Though we investigate a magnetically doped semiconductor, we believe this to be a reasonable result in this interesting case at the MIT. For concentrated magnetic materials that are conventional metals, the voltage due to anomalous Hall effect is typically a factor of 10-100 larger than the voltage due to ordinary Hall effect. In the material investigated here, the carrier concentration is found to be between 2 and 3 orders of magnitude lower than traditional metallic densities. Furthermore, the Gd density is x=0.14 close to the MIT, which implies a reduced density of magnetic scatterers, compared to a concentrated magnetic material. These two factors together result in a reduction of the anomalous Hall term of 3 orders of magnitude or more. Therefore we expect that the anomalous Hall Effect is small on the scale of the ordinary Hall effect observed in Fig.3.

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