Low Temperature Quantum Corrections to the Anomalous Hall Conductivity in Ultra-thin Fe Films

P. Mitra and A.F. Hebard

Department of Physics, University of Florida, Gainesville FL 32611, USA

Abstract. *In situ* transport measurements on disordered polycrystalline Fe films reveal a logarithmic temperature dependence of the longitudinal R_{xx} and anomalous Hall R_{xx}^{AH} resistances at low temperatures and a heretofore-unobserved scaling behavior in which the relative changes in R_{xx} and R_{xy} are found to be equal. Accordingly, the anomalous Hall conductivity is non-zero with a logarithmic temperature dependence that is believed to be a manifestation of quantum effects due to enhanced e-e interactions and magnetic scattering in itinerant ferromagnets.

Keywords: Ferromagnetism, Anomalous Hall effect, electron-electron interaction
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INTRODUCTION

Ferromagnetism in bulk Fe, Co and Ni is explained by splitting of the conduction bands, which leads to unequal population of up and down spin electrons at the Fermi level resulting in a spontaneous magnetization M. The impurity scattering in these so called band ferromagnets is modified due to a strong spin orbit interaction that manifests itself in a transverse charge current perpendicular to an applied electric field and M. This is the anomalous Hall effect [1], which is described by a phenomenological expression for the corresponding Hall resistivity, which is proportional to M, i.e. $\rho_{xy}^{AH} = R_s M$. The anomalous Hall coefficient R_s depends on transport parameters, unlike the ordinary Hall coefficient, which depends only on the effective carrier density.

The low temperature transport properties of thin films of ferromagnetic metals are modified by quantum corrections arising from weak localization and electron-electron interactions [2]. Interestingly, theoretical calculations predict that the quantum corrections to the anomalous Hall conductivity due to e-e interactions are negligible [3] compared to those of the longitudinal conductivity. Weak localization effects are suppressed by applying a magnetic field normal to the sample. Experiments on quench condensed amorphous Fe films on Sb substrates [4] showed that the anomalous Hall conductivity doesn't change appreciably with temperature in the range of 5-20K, confirming the theoretical prediction that L_{xy} doesn't have quantum corrections. However, our experimental results on polycrystalline Fe films are different, showing finite low temperature quantum corrections to the anomalous Hall conductivity and a new scaling behavior, which holds in a wide range of sheet resistances (100-3000Ω).

EXPERIMENTAL SETUP

We used a unique custom-built high vacuum system consisting of a growth chamber and a cryostat connected by mechanical 'arms' to transfer samples without breaking vacuum. The Fe films were sputtered at room temperature onto glass substrates with pre deposited gold pads. The samples were grown in the Hall bar geometry using a shadow mask and then transferred to the cryostat for magneto-transport measurements at low temperatures down to 4.2K and magnetic fields up to 7T oriented perpendicular to the substrate. The longitudinal resistance R_{xx} and Hall resistance R_{xy} were measured simultaneously using two SR830 lock-in amplifiers. We also treated some of our samples by exposing them to a low energy (200eV) Ar ion beam to reduce the surface roughness of the films [5]. However, we find the low temperature transport properties to be unaffected by this smoothening process, confirming that the low temperature sheet resistance is an appropriate measure of disorder in both ion-exposed and pristine films.

RESULTS & DISCUSSION

We investigated several Fe films in the thickness range of 30-100Å, which is well below the thickness regime where bulk scaling behavior of the resistivity holds. We characterize our films by their sheet resistance R_0 at $T = 5$K. Films with $R_0 < 400\Omega$ show a metallic behavior at high temperatures with a linear decrease of resistance with temperature. The R vs T curves have a minimum at a lower temperature ~20K, and the resistance increases thereafter. For films with higher sheet resistances (600-3000Ω), R vs T curves have no minimum, and the resistance increases monotonically as temperature decreases. However, for all the films under consideration, at low temperatures in the range 5-20K, the resistance diverges as ln(T). The results of fitting the low temperature data to the equation,

$$\sigma_{xx} = 1/R_{xx} = A_R L_{oo} \ln(T) + \sigma_o \quad , \qquad (1)$$

with $L_{oo}=e^2/(2\pi^2\hbar)$, the quantum of conductance, reveal that the prefactor attains a constant value of $A_R = 1.0\pm0.2$. The logarithmic behavior can be explained by electron-electron interactions [2], and the constant prefactor implies that the screening length does not change much for the samples considered.

Hall measurements on these films exhibit typical anomalous behavior as seen in ferromagnetic samples, with a steep linear increase of Hall resistance at low applied magnetic fields, saturating sharply at characteristic fields in the range of ~1.2-1.7T. To find the temperature dependence of the anomalous Hall conductivity L_{xy}^{AH}, constant fields of B = +4T and –4T perpendicular to the sample, were applied separately, and the longitudinal and transverse resistances measured simultaneously as the temperature was varied slowly. R_{xx} and R_{xy} were extracted as the even and odd parts respectively. Typical results for a film with $R_0 = 3000\Omega$ are shown in Fig. 1. At low temperatures (T < 20K), the relative changes in both R_{xx} and R_{xy} (with respect to a reference temperature of $T_0 = 5$K) decrease logarithmically with the same slope as the temperature increases. Hence the two curves overlap each other. At higher temperatures ($T > 20$K), R_{xy} decreases at a faster rate compared to R_{xx}. The anomalous Hall conductivity, as calculated by the formula $L_{xy} = R_{xy}/(R_{xx}^2 + R_{xy}^2)$ is found to increase as ln(T), as shown in Fig. 1, with a slope equal to but opposite in sign to that of R_{xx} and R_{xy}. The low temperature scaling behavior, summarized as

$$\frac{\partial R_{xy}^{AH}}{R_{xy}^{AH}} = \frac{\partial R_{xx}}{R_{xx}} = -\frac{\partial L_{xy}^{AH}}{L_{xy}^{AH}} \quad , \qquad (2)$$

applies uniformly to all of our films in the resistance range 100-3000Ω.

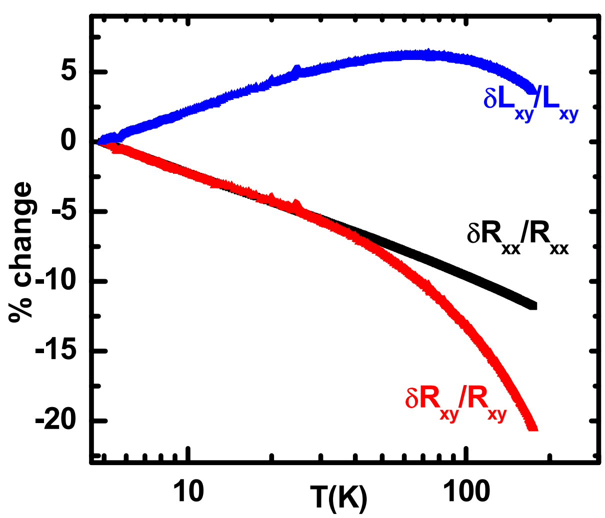

FIGURE 1. Temperature dependence of relative changes in R_{xx}, R_{xy} and L_{xy} for an Fe film of R_0=3kΩ.

To conclude, our experiments on polycrystalline Fe on glass substrates provide convincing evidence for quantum corrections to the anomalous Hall conductivity. These results are in contradiction to a previous investigation of amorphous Fe on Sb [4] and indicate that Fe films on polarizable host substrates (Sb) behave differently than Fe on insulating substrates (glass). Since we are dealing with ultra thin films, interfaces play an important role and the nature of the substrate could drastically affect the strength of the electron-electron interaction for thin films. Previous theoretical calculations [3] take into account only the short-range exchange term and neglect the direct term that is important for long-range interactions. A more rigorous theoretical formulation is desirable to fully understand the results.

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