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Electron Heating Experiments Below the Spin Glass Resistance Maximum

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We report electron heating measurements below the resistance maximum associated with the spin-glass freezing transition. The differential resistance showed features under the application of a dc electric field which cannot be readily interpreted in a simple electron heating picture. We demonstrate that these anomalies are resolved after computation of the resistance by integration of the differential results at various currents. An experiment was designed and carried out to test this procedure through the use of an applied magnetic field. The integration process is applicable to transport measurements carried out under combinations of ac and dc electric fields.

1. INTRODUCTION

The electrical resistance of a metallic film with distributed magnetic impurities exhibits a complex temperature and magnetic field dependence. For large Cr concentrations in Cu films (>1000 ppm), we find that the resistance displays a minimum above 15 K, followed at lower temperature by a logarithmic rise associated with the Kondo effect. At lower temperatures, the resistance can also exhibit a size and concentration dependent maximum associated with the freezing of the interacting impurity spins into the spin glass state. These phenomena were described by Schilling *et al.*,[1] and the interplay between the Kondo temperature and the spin-glass freezing temperature on the resistance was explored theoretically by Larsen.[2] Finite size effects on the resistivity of thin metallic films containing magnetic impurities were observed in this laboratory[3] and elsewhere.[4]

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Resistance measurements that employ ac bridge techniques have been used in several investigations to determine electron relaxation times in metallic films.[5–8] Under the application of a dc electric field, the electron temperature in such a film may be raised above that of the phonons. It is possible to determine the electron temperature from the resistance with the zero heating data serving as the calibration. Spin flip scattering allows the impurity spins to equilibrate to the electron temperature; there is no other mechanism by which the impurity spins lose energy on a comparable time scale. It is important to note that an applied magnetic field should not affect the electron temperature of our heated samples because this temperature will be determined by the electron-phonon scattering and by the eventual transfer of energy from the lattice to the substrate. While conducting such heating measurements, we recorded a resistance anomaly in the spin glass regime. The resistance attained values *above* those seen in the equilibrium (zero heating) case. This observation is inconsistent with the known electron energy relaxation processes discussed, and we wanted to determine the origin of this anomalous resistance. We have found, and will discuss below, an explanation for the anomaly which conforms to expectations for energy exchange out of the electron gas and is specifically related to the technique used. In addition, we have used the application of a magnetic field to confirm the applicability of our analysis.

2. EXPERIMENTAL DETAILS

2.1. Sample Description

The thin film samples (nominally 5000 ppm Cr in Cu) were deposited during a single thermal evaporation onto a silicon wafer. Patterning was carried out using photolithography and lift-off procedures. The films had a thickness of 34 nm, were 90 μm long and had a width of 1.1 μm. Their resistivity at 4.2 K was 8.8 $\mu\Omega$-cm. We carried out measurements using a commercial resistance bridge[9] operating at 17 Hz. Starting from a lattice temperature below that of the resistance maximum, a dc field was applied and we recorded the resistance of the sample as a function of temperature.

2.2. Results and Analysis

We observe a number of anomalous features in our resistance vs. temperature sweeps as seen in Fig. 1. The resistance at high heating levels attains values greater than the zero bias resistance maximum. Also, results obtained while varying the temperature of the substrate, T_0, at a fixed value of electric field, show a local *minimum* in the differential resistance

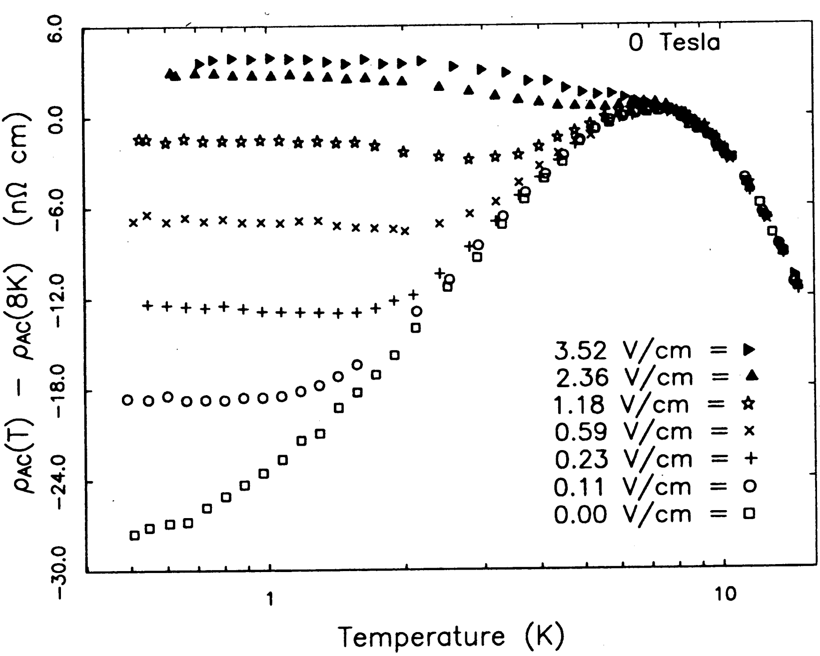

Fig. 1. The normalized differential resistance (dV/dI) of a 5000 ppm, 1.1 μm wide, CuCr film under the application of various dc electric fields in zero magnetic field. Two anomalies are observed. The resistance at high dc electric fields increases above that of the zero-bias maximum, and there is a prominent resistance minimum at lower electric fields (see for example the 1.18 V/cm data).

(for example near 3 K for the 1.18 V/cm dc field). These results are incompatible with the assumption that the resistance measured by the bridge can be directly used to determine the electron temperature. Otherwise, we would be led to conclude that under the action of a fixed electrical heating power, the electron temperature, T_e, decreases as the substrate temperature is raised.

To correctly analyze our data, the differential resistance measured by the ac bridge (dV/dI), has to be converted to resistance (V/I), where I is the applied dc bias current. To explain further, the resistance is usually converted to the electron temperature under the assumption that the metal film is ohmic, or that $dV/dI = V/I$. This equality only holds at zero bias current. The proportionality of V and I yields the resistivity, $\rho = m/ne^2\tau$, where the scattering time, τ, is characteristic of the electron temperature. Thus, the differential resistance can be used as an electron thermometer under zero bias conditions. Application of a dc current to the sample causes a temperature rise and leads to an increased resistivity. In this non-ohmic region (in the presence of a dc current), a discrepancy arises between the temperature inferred from the measured differential resistance dV/dI and the temperature determined from the calibration of the zero bias resistance. To obtain the resistance that is indicative of the electron temperature, $R = V/I_{dc}$, we need to integrate the differential resistance to find V: $V = \int (\Delta V/\Delta I_{dc})\, dI_{dc}$, then divide by I_{dc}. We will discuss the procedure below. The differences between the temperatures inferred using the ac and the dc techniques are illustrated in Fig. 2 where the dashed line is the voltage response of a *hypothetical* sample, with temperature 1 K at zero bias, that is undergoing application of a dc current. For example, suppose that the electrons have been heated from the initial lattice temperature of 1 K to 2 K by the application of a 2.0 mA dc current. The voltage should be on the $T = 2$ K ohmic resistance line (a value of around 4 mV). However, an ac resistance bridge instead measures the tangent to the dashed curve. In this case, the tangent has a slope that corresponds to a resistor at around 3 K. The bridge would give a reading that implies the electrons are at

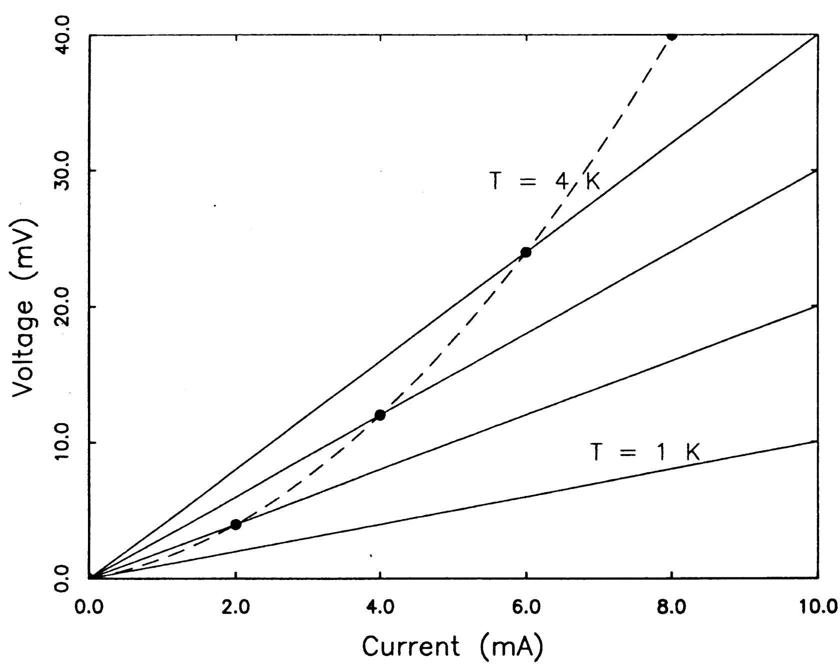

Fig. 2. A schematic of the results of a hypothetical heating experiment on a sample at 1 K with a characteristic (zero bias) resistance (dashed line) that increases with temperature. Upon the application of a dc electric field, the measured ac resistance increases. However, the appropriate electron temperatures correspond to the intersections of the resistance with the zero bias slopes (solid lines) on the V vs. I plot.

about 3 K instead of their actual temperature of 2 K. Thus, in order to infer the true electron temperature from the differential resistance, we perform the integration to determine the actual resistance as follows. We obtain differential resistance data (dI/dV) at a fixed substrate temperature and at a number of values of applied current I_{dc}. We then numerically fit and integrate the differential resistance over the appropriate currents to find the effective dc voltage at each current. From the results of the integration, we determine the dc resistance and use this value to infer the temperature of the electrons.

In the inset to Fig. 3, we illustrate the difference between the dc and differential values of the resistance for a heating experiment on our film at $T_0 = 0.8$ K. Having carried out the integration procedure on the same data as shown in Fig. 1, we obtain the result shown in Fig. 3. We observe that this integrated resistance exhibits none of the anomalous behavior seen in Fig. 1 and is now compatible with the use of the resistance as an electron thermometer.

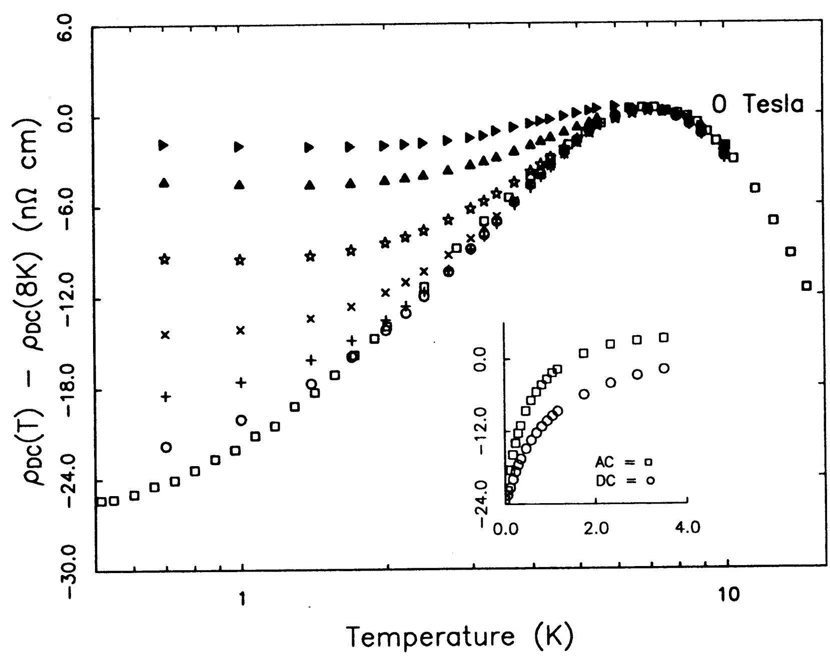

Fig. 3. The data of Fig. 1 following the integration procedure. The symbols are identical to those of Fig. 1. Notice that the anomalies are absent. In the inset, we show the results of the integration for a data set at 0.8 K, plotted as resistivity normalized to 8 K vs. applied dc field in V/cm. The measured differential resistance and the integrated resistance are shown as open squares and circles respectively.

3. DISCUSSION

In order to test the validity of this procedure for thermometry, we carried out a similar set of measurements to those shown in Fig. 1, but in a 5.5 T magnetic field. The magnetic field inhibits the participation of the spins in the electron-impurity spin flip interactions and thus lowers the Kondo resistance term. The increased locking of the spins also leads to an expected shift of the resistance maximum to higher temperatures (from ~7.5 K to ~9 K) in the data taken in a field. However, both anomalies seen in Fig. 1 are still present in the 5.5 T magnetic field. Spin flip processes cannot transfer energy from the electron system directly to the lattice of the thin film or to the substrate. Thus for an equal power input to the film we expect that the temperature rise $T_e - T_0$, would be independent of magnetic field. We find that the electron temperature at low dc fields is magnetic field independent *only* after the integration procedure (Fig. 4).

The characteristics of the electron temperature as a function of applied dc electric field are also evident from Fig. 4. The electron temperature rises

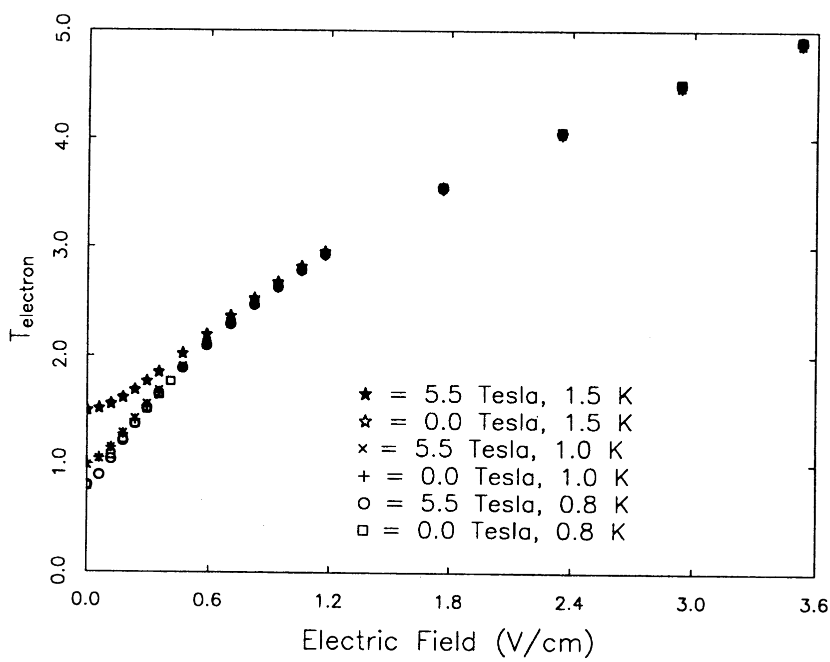

Fig. 4. The results obtained by considering the resistance after integration at three temperatures and in two magnetic fields. The data in different magnetic fields agree well (to within the precision of the measurements). For comparison, at 1.18 V/cm the displayed corrected integrated data has a spread of .03 K in electron temperature at high applied fields, whereas the differential data has a spread of about .3 K (not shown).

above the nominal lattice temperatures for low applied field. At higher applied fields the electron temperature becomes independent of the initial lattice temperature[10] and the curves coalesce. The uncorrected differential data showed a non-physical magnetic and electric field dependence of the electron temperature. This also suggests that the dc or integrated resistance should be used to infer the electron temperature.

Previous workers[6,7] found that the resistance of a heated disordered film decreased below the values seen in their equilibrium resistance. Our procedure may have bearing on the interpretation of their data. An independent measurement reported this effect using purely dc techniques,[11] which should not be subject to ambiguity in interpretation. Consequently, in the case of electron-heating of disordered systems, under the action of a current, the resistance *can* fall below that measured under zero bias conditions. However, the inferred temperature of the electron gas (and any scattering times derived from this temperature), under combinations of heating and differential resistance measurements, will depend on whether ac or dc resistance data was used.

We point out that dc heating with differential resistance bridge measurements was also used in our laboratory to determine electron-phonon scattering rates in thin films under similar conditions.[8] Here, we always used the integration process to convert the differential resistance to resistance.

4. CONCLUSION

In conclusion, we have demonstrated that the use of ac resistance measurement techniques in combination with dc electric fields yields a resistance which is not directly a measure of the electron temperature. The differential resistance must be integrated. Following the procedure outlined in this paper, the inferred temperatures are shown to rise by identical amounts in the same system in different magnetic fields in accord with a simple picture of thermal conduction processes out of the electrical films. These results confirm the validity of ideas set forth by Swartz[5] and implemented in other work in this laboratory.[8,12]

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