Susceptibility of a thin-film spin glass

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We report on measurements on the susceptibility of films of dilute Ag:Mn alloys as a function of applied magnetic field in the temperature range 1.2–60 K. The spin glass temperature T_G was found to have a concentration dependence $T_G \propto C^{0.69}$ for the concentration range $C = 0.61$–7.00 at.% Mn, in good agreement with measurements made in bulk samples. It was also found that T_G shifts to lower temperatures with increasing magnetic field, in qualitative agreement with theory.

I. INTRODUCTION

In recent years there has been extensive interest in the properties of spin glasses.[1] The low-field magnetic susceptibility $\chi(T)$ shows a pronounced cusp at a temperature which is now commonly designated as the glass temperature T_G . Some form of magnetic ordering is present for temperatures below T_G, e.g., there is an onset of the hyperfine-field splitting in Mössbauer data.[2] The puzzling problem associated with the ordering transition is the absence of critical behavior around T_G in specific-heat measurements.[3] Neutron-diffraction studies also fail to exhibit long-range ordering below T_G.[4]

An archetype spin glass is dilute Ag:Mn. To our knowledge, no magnetic susceptibility measurements in the vicinity of T_G in the presence of magnetic fields have been performed on this system. The simple metallurgy of this alloy,[5] and the ease with which proximity-effect sandwiches can be fabricated,[6] make thin-film samples of special interest. Proximity-effect sandwiches are of particular interest since they allow the direct measurement of such microscopic quantities as the spin-flip scattering time. Our report, therefore, is concerned with magnetic-susceptibility measurements of thin-film Ag:Mn samples over a wide range of temperature (1.2–60 K) and magnetic field (500–3000 G). We have also made similar measurements on bulk samples, with no discernible difference in susceptibility observed.

II. EXPERIMENTAL PROCEDURE

Several sample preparation procedures were attempted (coevaporation, electron-beam gun melting and evaporation, and arc melting and evaporation). We found the "best" technique to be the preparation of a master alloy (~15 g) in an induction furnace, with subsequent electron-beam gun evaporation of part of the alloy. In order to obtain samples whose susceptibility did not vary significantly from that of the master alloy, the evaporation was done at a constant rate (~100 Å/sec) and at pressures of $\sim 5 \times 10^{-6}$ Torr. The Mn concentration in the films, as determined from room-temperature susceptibility measurements, did not vary by more than 10% from that of the master alloy. Films 5000–20 000 Å thick (~7.5–30 mg) were evaporated on glass substrates, removed from the substrate, and rolled in cylinders (diameter ~2 mm, length ~6 mm). When the films were evaporated on teflon or sapphire substrates, it was quite cumbersome to remove them from the substrate even after several cyclings to 77 K. To our surprise, the films that were evaporated on glass (the obvious substrate) were easily removable in one piece with the help of a thin glass slide. The susceptibility of the master alloy (a ball of approximately 3 mm diameter) was also measured the same way, for comparison purposes.

III. RESULTS AND DISCUSSION

The spin-glass transition temperature T_G was determined from the maximum in the susceptibility versus temperature data. Figure 1 shows a graph of T_G versus concentration C, in low magnetic field (500 G). The best fit for the data exhibits the power law $T_G \propto C^{0.69}$ in good agreement with the results of Canella and Mydosh[7] for bulk samples in the same concentration rate. The nonlinear dependence of T_G on C is explicit evidence in this concentration regime of strong Mn-Mn interaction.

Figure 2 shows a plot of the reduced magnetization M/C versus the reduced magnetic field at the same reduced temperature T/C (2.5 K/at.% Mn). The slopes of these curves shift systematically with increasing Mn concentration, similar to what was observed by Souletie and Tournier[3] for CuMn. It is suggested[3] that this is possibly because the moment per impurity is not a constant over the relevant concentration re-

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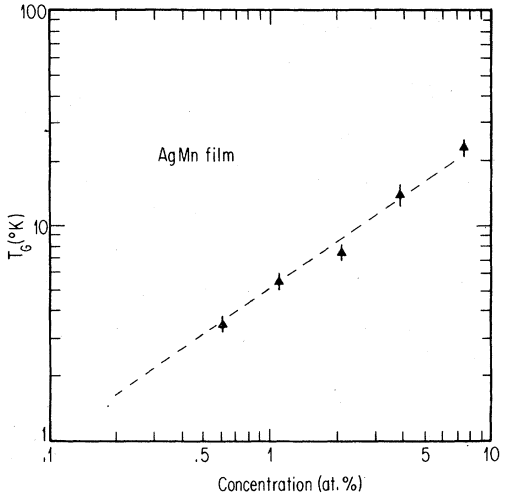

FIG. 1. Glass temperature vs concentration of Mn. The line is a fit to the experimental data.

gime. Fisher[8] showed that for a true antiferromagnet the susceptibility should have a sharp peak at T_N. The disordering influence of an applied magnetic field drives T_N to lower values as the field increases. Figure 3 shows a graph of the transition temperature for various Ag:Mn concentrations versus magnetic field. The results are in qualitative agreement with the predictions of Fisher. Canella and Mydosh[9] find that for gold-iron alloys the shift is opposite to the prediction of Fisher.

It is not clear to us at the present time the reason for the difference in magnetic field dependences between AgMn and AuFe. We feel that more extensive work is needed in order to elucidate this problem.

IV. CONCLUSION

In summary, we have made measurements on the susceptibility of Ag:Mn films in the concentration range 0.61–7 at.%. We find that the susceptibility of these films is in agreement with bulk measurements of Canella and Mydosh. In addition, we have analyzed the behavior of the susceptibility in the presence of an external magnetic field. The temperature dependence of Souletie and Tournier is shown to be obeyed with different slopes for different Mn concentrations along with a shift of T_G to lower values as the external magnetic field is increased.

These measurements demonstrate that thin film Ag:Mn films can serve as archetype spin-glass systems. We have observed superconducting tunneling into (Ag:Mn)Pb proximity-effect sandwiches. Preliminary results do not exhibit an increased conduction spin-flip scattering in the vicinity of T_G, as it is expected theoretically.[10] We shall report further on these measurements in a subsequent publication.[6]

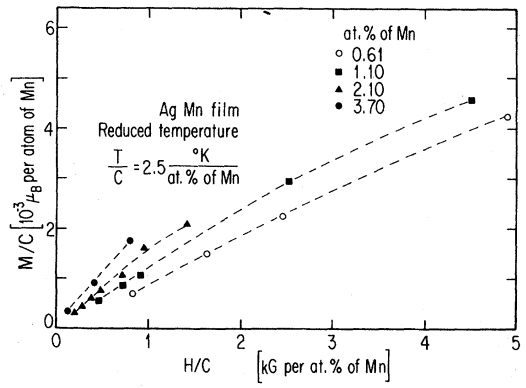

FIG. 2. Reduced magnetization vs reduced magnetic field at constant reduced temperature.

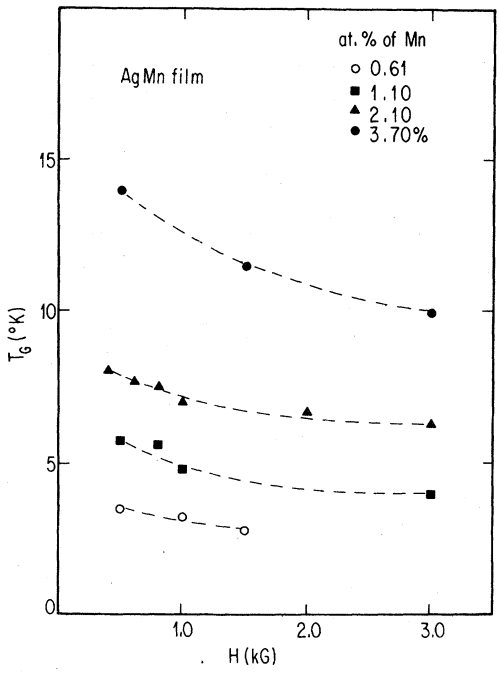

FIG. 3. Transition temperature vs magnetic field. The lines are fit to the experimental data. Notice the decrease on T_G with increasing magnetic field.

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