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Magnetic and magnetoresistance measurements on iron-based nanoclusters in $In_{0.53}Ga_{0.47}As$

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We have obtained magnetoresistance data on low iron-concentration samples (~1%) showing a large negative magnetoresistance (3.2% at 5 K in 0.5 T) attributed to imbedded superparamagnetic clusters in $In_{0.53}Ga_{0.47}As$. The samples were prepared by ion implanting a p-$In_{0.53}Ga_{0.47}As$ layer with iron followed by a rapid thermal anneal. Magnetic measurements confirm the formation of a cluster size distribution with a mean diameter of 6.2 nm and effective moment of 7000 bohr magnetons. The magnetization of these single domain ferromagnets is 50% saturated in a field of only 0.2 T even at room temperature which is important for device applications. [S0021-8979(97)22308-X]

I. INTRODUCTION

The discovery of giant negative magnetoresistance (GMR), first in multilayers[1] and then in granular metallic systems,[2,3] provides opportunities both for novel new devices and for better understanding of fundamental spin-dependent electronic scattering. The development of a semiconducting system exhibiting GMR would offer many advantages in device design and fabrication. We, as well as other groups, have reported previously on efforts to produce semiconductors containing magnetic clusters.[4–12] Our measurements on iron-implanted GaAs, demonstrated that rapid thermal annealing produces Fe_3GaAs clusters with tunable particle diameters in the critical 2–10 nm size range found to be optimal for GMR in the metallic systems.[4,5] Subsequent magnetic measurements[5,10,11] showed that the precipitates exhibit superparamagnetism which is thought to underlie GMR in the metallic systems.

A difficulty with metallic particles in GaAs is the presence of Schottky wells at the interface due to band offsets which yield semi-insulating material even at high doping levels.[12] In this work we report new measurements on an iron-implanted p-$In_{0.53}Ga_{0.47}As$ sample. Magnetization measurements demonstrate that the nanoclusters in this system exhibit superparamagnetic behavior similar to that reported in related systems such as Fe_3GaAs precipitates in GaAs, Co-Cu, Fe-Cu, and Co-Ag.[5,13–19] $In_{0.53}Ga_{0.47}As$ has a lower band gap (0.74 eV at 300 K) compared to GaAs (1.42 eV at 300 K) and a correspondingly lower Schottky well at the interface. Consequently, the depletion region around each cluster is substantially reduced allowing correspondingly higher carrier concentrations. Additionally, since the mobility is higher in $In_{0.53}Ga_{0.47}As$ then in GaAs, we might expect the spin-coherence length to be greater in $In_{0.53}Ga_{0.47}As$ as well. This would allow the carriers to sample more clusters within a single spin-coherence length which is critical for the GMR effect. In this work we report on evidence for a large negative magnetoresistance in iron-implanted p-$In_{0.53}Ga_{0.47}As$ which we attribute to spin-dependent scattering by the precipitates.

II. EXPERIMENTAL DETAILS

Samples were fabricated by ion-implanting an ~150 nm molecular beam epitaxy (MBE) growth p-$In_{0.53}Ga_{0.47}As$ layer on a commercial InP wafer. Iron was implanted to a concentration of 1×10^{16} ions/cm^2 (1%) using an implantation energy of 170 keV. Because of the low solubility of iron, a rapid thermal anneal at 650°C for 30 s allowed the iron to precipitate into the more stable iron rich clusters.

Magnetic measurements were made in a Cryogenic Consultants Limited (CCL) SQUID magnetometer for temperatures between 5 and 324 K in fields up to 6 T. Samples were thinned to ~70 μm to reduce the magnitude of the background diamagnetic signal due to the substrate. This diamagnetic contribution was obtained from high-field measurements where the superparamagnetic clusters are nearly saturated. We report magnetic data due to the clusters after subtracting the background diamagnetic contribution. Magnetoresistance measurements were made in a Quantum Design physical property measurement system (PPMS) for temperatures between 5 and 300 K in fields up to 7 T. The magnetoresistance was measured in a Van Der Pauw configuration with annealed indium contact pads forming ohmic contacts.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Magnetization versus field measurements taken at 175 K are shown in Fig. 1. The diamagnetic contribution has been

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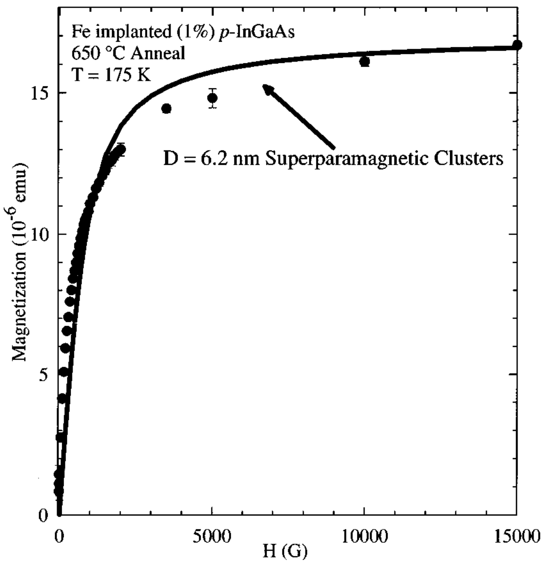

FIG. 1. Magnetization vs field measurements taken at 175 K for iron implanted p-$In_{0.53}Ga_{0.47}As$ sample. The solid line is a theoretical fit assuming a uniform 6.2-nm-diam superparamagnetic response.

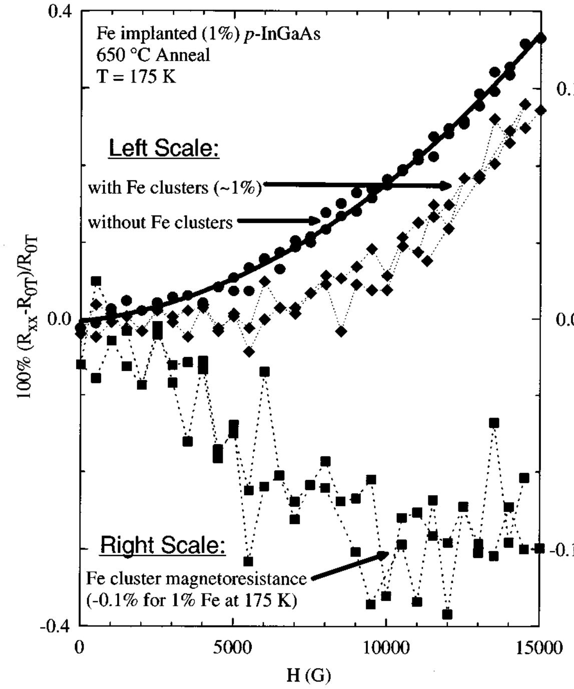

FIG. 2. Magnetoresistance vs field taken at 175 K for iron implanted p-$In_{0.53}Ga_{0.47}As$ sample. The solid line is a second order polynomial fit to the background (no iron-implant) data shown as circles. Data from the sample with superparamagnetic iron-clusters are shown by diamonds. The magnetization shown by the squares is obtained by subtracting the background from the sample with iron-clusters. This negative magnetoresistance saturates in fields above 5000 G and is attributed to the clusters.

subtracted. The magnetization is >75% saturated by 0.5 T. A search for hysteresis was made with a null result within the resolution of the remnant fields in our magnetometer (~30 G). The observed field response was similar to that observed for the Fe_3GaAs nanoprecipitates in GaAs which are known to be superparamagnetic.[5] The data can be approximately fit with a Brillouin function with a single cluster diameter of 6.2 nm as shown by the solid line. However, deviations from this simple model indicates a distribution of cluster size.

Magnetoresistance versus field measurements were taken at 175 K on an $In_{0.53}Ga_{0.47}As$ sample containing superparamagnetic clusters. To obtain a background response for comparison, a sample without implanted iron was prepared from the same $In_{0.53}Ga_{0.47}As$ wafer. Magnetoresistance data taken on this background sample are shown as solid circles in Fig. 2 using the scale on the left axis. The data have been plotted as a percentage change from the zero-field value. The qualitative field dependence is roughly parabolic and was fit with a second order polynomial shown as a solid line which we take as the background magnetoresistance.

The magnetoresistance versus field for the sample containing iron is shown in Fig. 2 as solid diamonds using the scale on the left axis. The qualitative field dependence above 7000 G is roughly parabolic as was observed for the background sample. However, the data flatten in fields below ~7000 G. A subtraction between these two data sets was carried out and is shown as solid squares in Fig. 2 using the expanded scale on the right axis. The resulting negative magnetoresistance ~−0.1% is attributed to the superparamagnetic clusters. A comparison with the magnetic data in Fig. 1, taken at the same temperature, shows that the strongest field response occurs below 7000 G—the region where the negative magnetoresistance is observed. While a signal of −0.1% is small we stress that the magnetic ion concentration of 1% is more than an order of magnitude below that used in the Co-Cu system.[19] In addition our system was measured at a temp of 175 K. Given these two facts, the size of the negative magnetoresistance we observe is reasonable compared to the granular metallic systems.

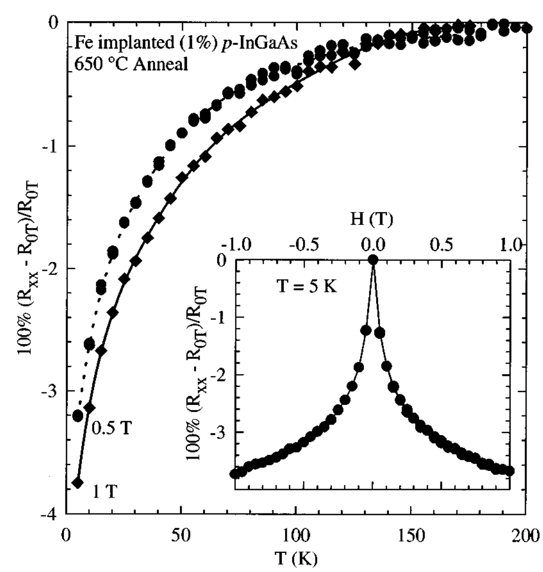

FIG. 3. Percent magnetoresistance vs temperature taken in 0.5 and 1 T with respect to the zero field response for an iron-implanted p-$In_{0.53}Ga_{0.47}As$ sample. The inset shows the raw percent magnetoresistance for an iron-implanted p-$In_{0.53}Ga_{0.47}As$ sample at 5 K.

In an effort to further study this negative magnetoresistance, we plot in Fig. 3 the percent change in the magnetoresistance in fields of 0.5 and 1 T from the zero field values as a function of temperature. As can be seen, the negative magnetoresistance grows roughly as $1/T$ to a maximum negative magnetoresistance of 3.7% at 5 K. We speculate that this dramatic increase in negative magnetoresistance arises from the observed presence of a large population of smaller clusters which remain in the linear regime with magnetization increasing as H/T. The inset shows the raw percent magnetoresistance versus field data at 5 K. As can be seen, the magnetoresistance is already 1/3 of the 10 000 G value in a field of only 500 G. Care must be taken in interpreting these results since it is well know that negative magnetoresistance has been observed in GaAs at low temperature. However, the high temperature at which the negative magnetoresistance appears suggest that the observed negative magnetoresistance in this case is due to the iron clusters.

IV. CONCLUSIONS

We have observed a large negative magnetoresistance which we attribute to superparamagnetic clusters in a semiconductor. The observed magnetoresistance in our low magnetic concentration sample is comparable with the granular metallic systems assuming the magnetoresistance scales linearly with magnetic concentration. Work is underway to increase the magnetic ion concentration to optimize the effects presented here to explore the potential for a semiconducting GMR material.

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