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Spin-dependent localization effects in GaAs:Mn/MnAs granular paramagnetic–ferromagnetic hybrids at low temperatures

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Abstract

We compare the magneto-transport in paramagnetic–ferromagnetic GaAs:Mn/MnAs granular hybrids and paramagnetic GaAs:Mn reference samples. The differences in the hole transport between the two systems at low temperatures arise due to carrier localization effects at the cluster–matrix interface in the hybrids. The localization is caused by a Schottky barrier formation at the interface as well as spin-dependent shifts of the hole bands caused by the stray field of the ferromagnetic clusters. The application of an external magnetic field leads to a delocalization of the carriers and thus a negative magneto-resistance effect. These effects can be simulated using a network model approach.

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1. Introduction

Paramagnetic–ferromagnetic granular hybrid structures (such as a paramagnetic GaAs:Mn matrix with ferromagnetic MnAs clusters) exhibit very pronounced magneto-resistance (MR) effects which differ considerably from those observed in the paramagnetic matrix alone or from those in diamagnetic–ferromagnetic granular hybrids. However, the MR behavior of GaAs:Mn/MnAs granular hybrids grown by different methods (i.e., metal-organic vapor-phase epitaxy [1], ion implantation of Mn into LT GaAs and subsequent annealing [2], or molecular beam epitaxy followed by thermal annealing [3]) is independent of the growth method employed. Therefore, the temperature dependence of the MR effect appears to be an intrinsic feature of the GaAs:Mn/MnAs hybrid system. A dominant negative MR effect at low temperatures $T < 50$ K as well as a dominant strong positive MR effect in an intermediate temperature regime $50 < T < 200$ K are commonly observed and can be related to a spin-dependent interplay of the paramagnetic GaAs:Mn matrix and ferromagnetic MnAs clusters [4]. Here, we will present first steps towards the modelling of the negative MR effects observed at low temperatures. The model is an extension of a network model which was used previously for describing MR effects in paramagnetic dilute magnetic semiconductor alloys (without ferromagnetic inclusions) [5].

2. Results and discussion

The inset of Fig. 1 is a transmission electron microscope (TEM) image of a GaAs:Mn/MnAs hybrid. The ferromagnetic MnAs clusters are embedded almost dislocation-free into the paramagnetic GaAs:Mn matrix. The average Mn concentration in the matrix is about 0.5%. The *c*-axis of the hexagonal MnAs is oriented along the $\langle 111 \rangle$ directions of the zincblende matrix. The basal plane of the clusters is the easy plane of the magnetization [1,6]. The majority carriers are holes in the hybrids as well as in the GaAs:Mn reference sample.

Fig. 1 also depicts a comparison of typical magneto-transport results of paramagnetic GaAs:Mn and paramagnetic–ferromagnetic granular GaAs:Mn/MnAs hybrids. Clear differences can be observed in the temperature dependence of the resistivity. At low temperatures (below 100 K), the resistivity of the hybrids is much bigger than that of the paramagnetic GaAs:Mn reference whereas at higher temperatures the resistivities are comparable. Furthermore, the MR behavior (which is defined as $\mathrm{MR} = (\rho_0 - \rho(H))/\rho_0$ where $\rho_0 = \rho(H = 0)$) is different for the two types of samples. At low temperatures, the MR effects are negative in both cases, but differ in curvature, i.e., the curvature is negative for the hybrids and positive for the paramagnetic GaAs:Mn alloy. In particular, the strong increase of the resistivity of the hybrids at low temperatures is an indication for a trapping of the holes. The strong localization of the holes at low temperatures is due to the MnAs clusters. On the one hand, a band bending (Schottky barrier) can occur at the interface between the metallic or semimetallic cluster and the semiconducting matrix material due to the establishment of a single Fermi level within the hybrid. On the other hand, even at $H_{\mathrm{ext}} = 0$ T, the magnetic field is not zero in the paramagnetic matrix due to the presence of the ferromagnetic clusters. Already an estimation of the dipolar field of a cluster yields

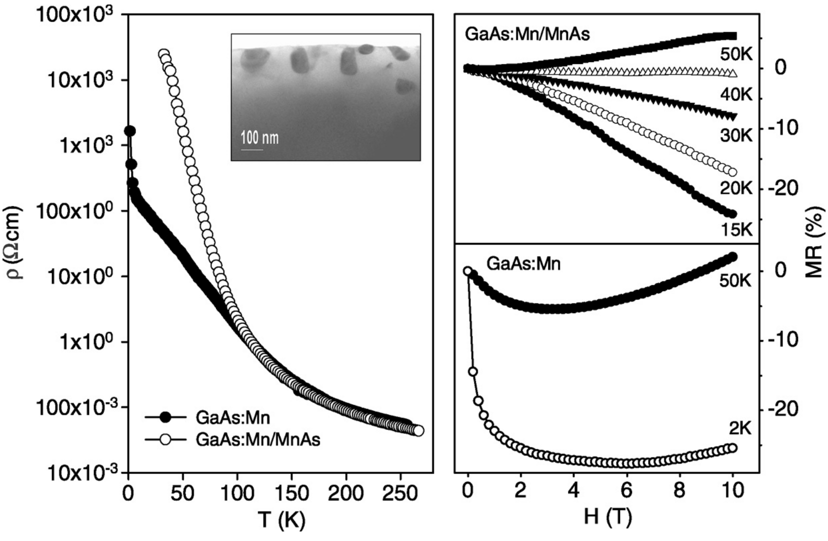

Fig. 1. Left: Temperature dependence of the resistance of paramagnetic GaAs:Mn and GaAs:Mn/MnAs hybrids. Inset: TEM image of the MnAs clusters in a GaAs:Mn matrix. Right: MR curves at various temperatures for GaAs:Mn/MnAs hybrids (top) and GaAs:Mn (bottom).

magnetic fields of about 1 T at the surface of the clusters. At low temperatures, this is almost sufficient to saturate the giant Zeeman splitting in the paramagnetic matrix close to the surface, i.e., lower the energy for one kind of heavy holes by $|\frac{5}{4}N_0\beta x|$. Choosing $|N_0\beta| = 2.5$ eV and assuming $x \approx 0.005$ gives a trap depth at saturation of about 15 meV. The holes of one spin orientation are trapped at the cluster interface at low temperatures due to the local giant Zeeman splitting (left top image of Fig. 2). In an applied external field H_{ext} the giant Zeeman splitting (which saturates at high fields) occurs throughout the entire paramagnetic GaAs:Mn matrix and releases the trapped holes (left bottom image of Fig. 2) leading to a negative MR effect. With increasing temperature, the magnetic field at the cluster surface of about 1 T is no longer sufficient to saturate the giant Zeeman splitting, and the trap depth will decrease following the Brillouin function. In addition, the thermal energy of the holes k_BT will increase. Therefore, this negative MR effect will disappear with increasing temperature.

A first quantitative insight can be gained by performing calculations using an extension of the network model developed previously for describing MR effects in paramagnetic wide-gap dilute magnetic semiconductors such as GaAs:Mn [5]. At this stage of the investigation, a single MnAs cluster is centered in a 25 × 25 network of cubic cells. Its size comprises 10% of the total system. The cells representing the metallic cluster have a much lower resistance than the average cell of the semiconducting GaAs:Mn matrix. For numerical reasons, we assume an average Mn concentration of 3% in all calculations. The resistivities of the hole bands in the matrix cells are basically calculated as in the case without clusters. The effects of the clusters on the matrix cells are added as follows. The local band bending in the matrix near the cluster arises from the formation of a (spin and

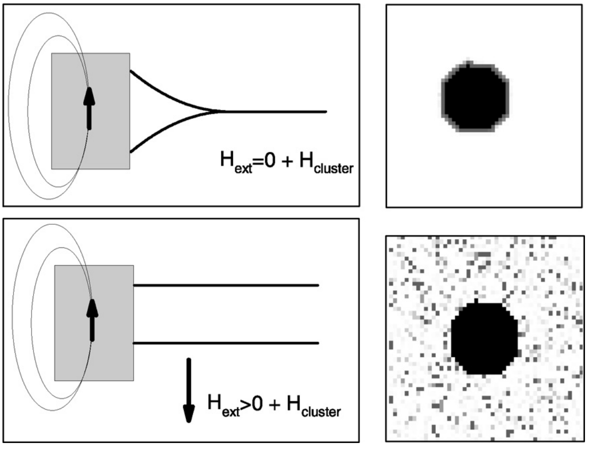

Fig. 2. Left: Schematic images of the carrier localization at $H_{\text{ext}} = 0$ (top) and $H_{\text{ext}} \neq 0$ (bottom). Right: Network calculations for a single cluster at $H_{\text{ext}} = 0$ (top) and $H_{\text{ext}} \neq 0$ (bottom).

H-field independent) Schottky barrier as well as from a local (spin and H-field dependent) giant Zeeman splitting of the hole bands caused by the p–d exchange between the hole spins and the $S = 5/2$ spins of the Mn ions. The Mn ions are aligned by the sum of external field H_{ext} and dipolar cluster field H_{cluster}. As the electronic structure of the MnAs is basically unknown, we model the Schottky barrier as temperature independent and decreasing with increasing distance d from the cluster as d^{-5}. This dependence was chosen to make sure that the influence of the Schottky barrier is restricted to the matrix cells directly adjacent to the cluster only. On the digital length scale of the network model it causes a square potential trap in these matrix cells. For simplicity, we assume that the cluster field is isotropic and decreases with d^{-3}. The corresponding energy shifts are added to each cell.

The top and the bottom grey scale images on the right of Fig. 2 depict the carrier occupations at $T = 30$ K in the GaAs:Mn matrix surrounding an MnAs cluster (black colored cells) at $H_{\text{ext}} = 0$ T and $H_{\text{ext}} = 10$ T, respectively. The cluster field at the interface between MnAs and GaAs:Mn was set to $H_{\text{cluster}} = 1$ T and the Schottky barrier was 20 meV. A dark grey corresponds to a high carrier concentration in the matrix. At zero-field all holes are localized at the cluster interface and are released with increasing magnetic field as discussed above.

The left graph of Fig. 3 shows calculated temperature dependences for GaAs:Mn alloys and GaAs:Mn/MnAs hybrids where, in the case of the hybrids, the Schottky barrier was 20 meV and the cluster field was varied between 1 and 3 T. The calculations are in qualitative agreement with the experimental results shown in Fig. 1. The right graph of Fig. 3 is a comparison of calculated MR curves at $T = 30$ K taking into account field-independent disorder due to alloying represented by m_{dis}, which is the slope of the valence band edge with x [5]. For example, $m_{\text{dis}} < 0$ means that cells with $x_{\text{loc}} < x$ are shifted towards the acceptor which leads to a spatial smoothing of the hole subband dominating the transport. As described in detail in Ref. [5], the small positive MR effect at low fields

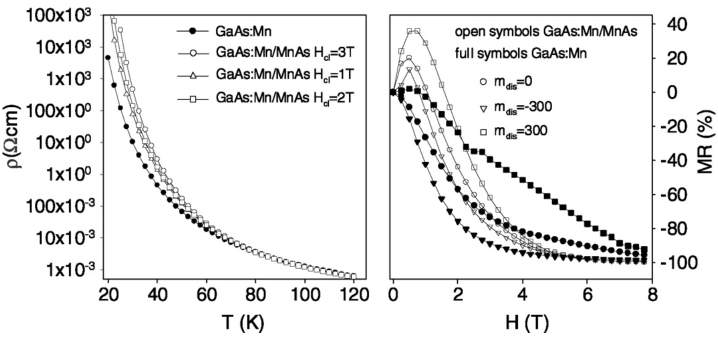

Fig. 3. Left: Calculated temperature dependence of the resistivity of paramagnetic GaAs:Mn and GaAs:Mn/MnAs hybrids. Right: Calculated MR curves for paramagnetic GaAs:Mn and GaAs:Mn/MnAs hybrids for various field-independent disorder parameters at $T = 30$ K.

in the paramagnetic GaAs:Mn is disorder induced whereas the strong negative MR effect at high fields is population induced, i.e., due to the giant Zeeman splitting the density of states approaches the acceptor. For $m_{\text{dis}} < 0$ the curves are in reasonable agreement with the experiment. The positive MR effects in the calculated curves for the hybrids are enhanced. This is simply a population effect, i.e., disorder-induced effects are more significant at low populations and the population in the bulk of the matrix of the hybrid is much lower than in the corresponding paramagnetic alloy due to the trapping of holes at the cluster surface. This effect somewhat corresponds to the difference in curvature of the experimental MR curves in Fig. 1. In addition, it can be seen that the negative slope of the MR curves calculated for the hybrids at intermediate fields is bigger than that in the paramagnetic case. This reflects the release of the holes with increasing external magnetic field in the hybrids discussed above.

3. Conclusions

We have demonstrated that the low-temperature magneto-transport in paramagnetic–ferromagnetic GaAs:Mn/MnAs granular hybrids is dominated by spin and magnetic-field dependent localization phenomena at the cluster–matrix interface. These phenomena arise due to a band bending because of a Schottky barrier formation at the interface as well as local giant Zeeman splittings in the matrix caused by the magnetic stray fields of the clusters. The effects can be successfully described theoretically using a network model approach.

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