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Domain-wall contribution to magnetoresistance in ferromagnetic (Ga,Mn)As film

T. WOSIŃSKI*, O. PELYA, T. FIGIELSKI, A. MĄKOSA, A. MORAWSKI, J. SADOWSKI, W. DOBROWOLSKI, R. SZYMCZAK, J. WRÓBEL

Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warsaw, Poland

Simple magnetoresistive nanodevices formed by narrow constrictions of submicron width in the epitaxial film of a ferromagnetic (Ga,Mn)As semiconductor have been fabricated employing the electron-beam-lithography patterning and low-energy low-dose oxygen ion implantation. Low-temperature charge-carrier transport through the constrictions has been investigated and correlated with magnetic properties of the film. The constricted devices revealed abrupt jumps of a reduced resistance that appeared when the sweeping magnetic field crossed the regions of the coercive field of the film magnetization. In contrast, the non-constricted reference device displayed abrupt jumps of an enhanced resistance at the same values of magnetic field. We interpret the both features, whose positions on the magnetic-field scale reflect the hysteresis loop of magnetization, as manifestation of domain wall contribution to the (Ga,Mn)As film resistance. Presumably, the suppression of the weak localization effects by a domain wall located at the constriction results in a negative contribution of a domain wall to the resistance, while the spin-orbit interaction can be responsible for its positive contribution to the resistance.

Key words: *ferromagnetic semiconductor; nanostructure; domain wall; magnetoresistance*

1. Introduction

Electron transport through domain walls (DWs) in ferromagnetic nanowires and constrictions became the subject of great current interest stimulated by possible applications of the magnetoresistance associated with DWs in magnetoelectronic devices. On the other hand, recent advance in the growth of ferromagnetic semiconductors based on III–V compounds gives rise to a possible integration of electronic and magnetoelectronic devices providing a basis for future spin electronics. In particular, homogeneous films of $Ga_{1-x}Mn_xAs$ containing up to 8% of Mn atoms can be grown by a low-temperature molecular-beam epitaxy (LT-MBE) [1]. When intentionally undoped, the films are of p-type where Mn atoms, substituting the Ga lattice atoms, sup-

*Corresponding author, e-mail: wosin@ifpan.edu.pl

ply both mobile holes and magnetic moments. Below the Curie temperature, T_C, the films become ferromagnetic due to the hole-mediated ordering of Mn spins ($S_{Mn} = 5/2$ for Mn^{2+} charge state) [2]. Although the highest T_C in the as-grown (Ga,Mn)As films remains so far at 110 K, it has been increased up to 173 K till now [3] by means of post-growth low-temperature (180–250 °C) annealing treatments [4–6]. The main effect of annealing, leading to the efficient increase in both the hole density and T_C, is outdiffusion from the (Ga,Mn)As films of Mn interstitials that act as double donors in GaAs. It is expected that further optimization of the MBE-growth conditions and the post-growth annealing will succeed in obtaining (Ga,Mn)As films of about 10% Mn content showing room-temperature ferromagnetism [7].

In the present study, we fabricated and investigated simple magnetoresistive nanodevices formed by narrow constrictions in the epitaxial film of a ferromagnetic (Ga,Mn)As semiconductor with the aim to explore the impact of a domain wall pinned at the constriction on the charge-carrier transport across it.

2. Experimental

Ferromagnetic $Ga_{0.99}Mn_{0.01}As$ film has been grown on a semi-insulating (001) GaAs substrate by means of LT-MBE in a dedicated III–Mn–V MBE system located at MAX-Lab, Lund University, Sweden; see Ref. [8] for more details. The film 50 nm thick was covered with a 10 nm thick GaAs cap layer. Magnetization of the film, which exhibits an in-plane easy axis of magnetization and the Curie temperature of 50 K, was measured using a superconducting quantum interference device (SQUID) magnetometer with a magnetic field applied parallel to the film plane, along the

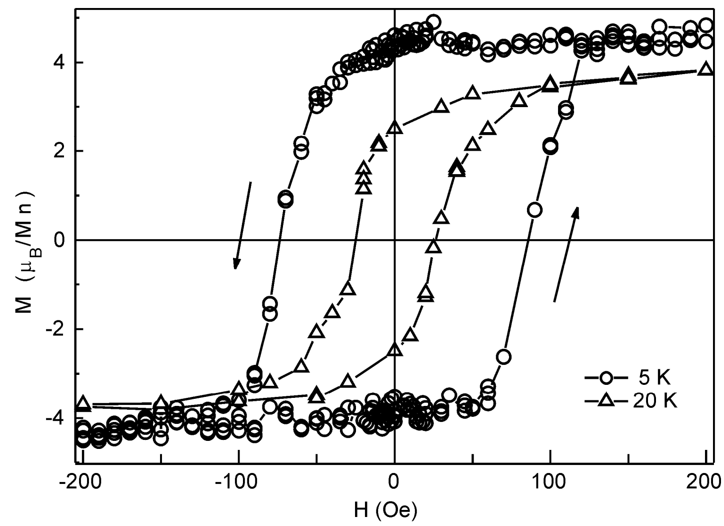

Fig. 1. Magnetization hysteresis loops for $Ga_{0.99}Mn_{0.01}As$ film recorded with SQUID magnetometer at 5 K and 20 K after subtraction of diamagnetic contribution from the GaAs substrate

cleavage edge, i.e. the ⟨110⟩ crystallographic axis. Figure 1 presents the magnetization hysteresis curves recorded at 5 and 20 K, showing a strong dependence of the hysteresis loop width on temperature. A large value of the low-temperature saturation magnetization of the film, of 4.5μ_B per Mn atom, and a relatively high Curie temperature evidence a high quality of the investigated ferromagnetic film.

We fabricated constrictions of submicron width in the (Ga,Mn)As film by the method of low-energy (25 keV) low-dose (5×10^{13} ions/cm^2) oxygen ion implantation through a mask consisting of a thick resist deposited on the top of the film and containing windows patterned by the electron-beam lithography. Previously, we have found that such an implantation destroys both the conductivity and ferromagnetism in the layer [9]. The lithographic widths of the constrictions were in the range of 200–1000 nm. Individual devices, of an outline 2.5×1 mm^2 and the shape shown in the inset of Fig. 2, were defined in the film and their distant terminals were supplied with Ohmic contacts. All the results presented in this paper refer to the constriction with lithographic width of 400 nm, whose microscopic image is shown in the inset in Fig. 4, and, additionally, to a reference (non-constricted) device of a bar (1.5×0.5 mm^2) shape. The contribution of the constricted part of the device to its total resistance is comparable to that carried in by the wide leads.

3. Results

We measured the sample resistance, *R*, as a function of a magnetic field, *H*, using the pseudo-four-probe method and lock-in technique with a sensing voltage of a few mV

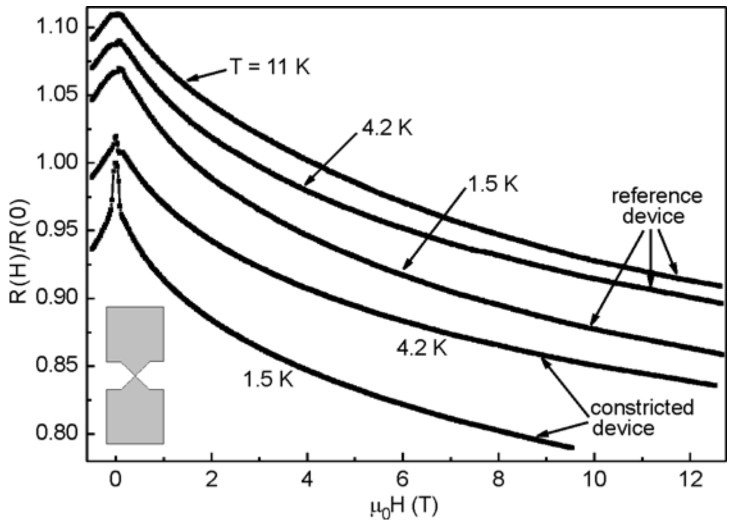

Fig. 2. Relative magnetoresistance vs. in-plane (perpendicular to the current) magnetic field for the reference and constricted devices measured at various temperatures. The curves are vertically offset for clarity. Inset: constricted device design

at 770 Hz. Relative magnetoresistance, $R(H)/R(0)$, plotted as a function of magnetic field applied parallel to the film plane (perpendicular to the current) is shown in Fig. 2. Both the reference and constricted devices investigated by us exhibit a large negative magnetoresistance (MR) at low temperatures, extending far outside the field of ferromagnetic hysteresis loop. Such a behaviour of MR, which has been also observed by us for the perpendicular orientation of magnetic field with respect to the film plane [10, 11], is typical of (Ga,Mn)As films. It has been commonly attributed to the reduction of spin-disorder scattering of charge carriers caused by the ordering of localized Mn spins in an external magnetic field – a mechanism well known in ferromagnetic metals. Another mechanism, which possibly dominates at the lowest temperatures, is the suppression of carrier quantum localization by an external magnetic field [10–14]. In fact, we have recently shown [11] that the low-temperature MR of our (Ga,Mn)As film under perpendicular magnetic field can be successfully described within the weak localization theory for two-dimensional ferromagnetic systems developed by Dugaev et al. [15]. The inelastic scattering length derived from the fitting of our MR results to this theory was about 90 nm [11], while the hole mean free path in the (Ga,Mn)As film is of the order of 1 nm.

A striking difference has been revealed between MR measured in the reference and constricted devices in a narrow range of a magnetic field around $H = 0$ (Figs. 3 and 4). At the magnetic field corresponding to the coercive fields of the film magnetization, MR of the reference device exhibits abrupt jumps followed by regions of an enhanced resistance (Fig. 3). With increasing temperature, the spacing between the jumps corresponding to the field swept in opposite directions narrows similarly as does the width of the magnetization hysteresis loop.

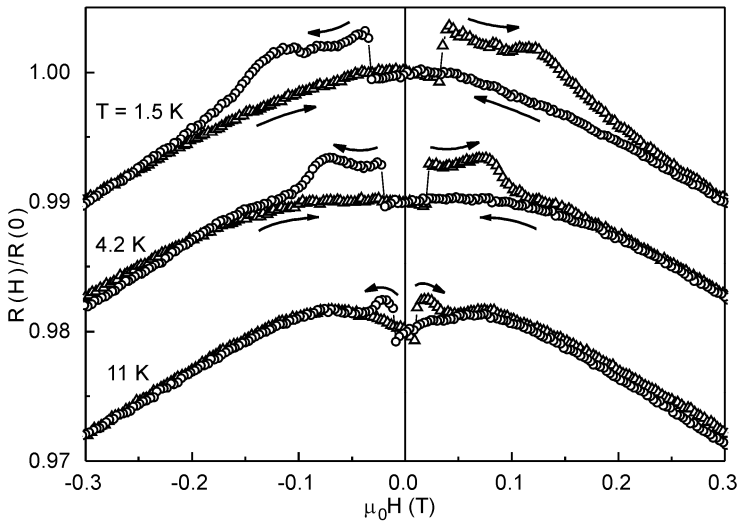

Fig. 3. Relative magnetoresistance for the reference device vs. in-plane (perpendicular to the current) magnetic field swept in opposite directions measured at 1.5, 4.2 and 11 K. The sweep directions are indicated by the arrows. The data for the two latter temperatures have been vertically offset for clarity

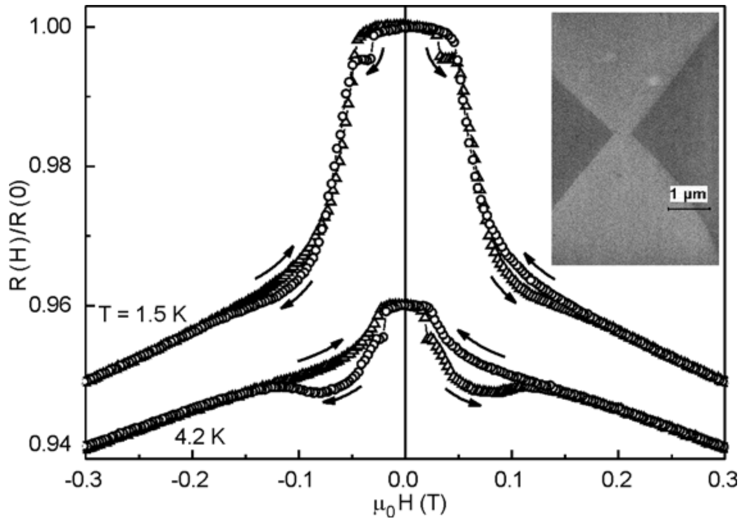

Fig. 4. Relative magnetoresistance for the constricted device vs. in-plane (perpendicular to the current) magnetic field swept in opposite directions measured at 1.5 and 4.2 K. The sweep directions are indicated by the arrows. The data for the latter temperature have been vertically offset for clarity. Inset: secondary electron image in a scanning electron microscope of the constriction patterned by oxygen ion implantation; the darker contrast corresponds to the implanted areas

The extension and magnitude of the regions of enhanced resistance decrease with increasing temperature and they practically disappear at 15 K. MR of the constricted device shown in Fig. 4 displays an essentially different behaviour. In a narrow range of a magnetic field around $H = 0$, its resistance considerably increases forming a high bump while sweeping a magnetic field through the zero value. The height of this bump and its width, which extends from –50 to 50 mT at 1.5 K, decrease rapidly with increasing temperature. On a background of this increased resistance, abrupt jumps followed by regions of a lowered resistance appear. Positions of these jumps reflect, as for the reference device, the hysteresis loop of magnetization. Similar jumps of a lowered resistance have been revealed by us also for two other constricted devices measured under magnetic field perpendicular to the film plane and interpreted as resulting from a contribution of a magnetic DW, pinned at the constriction, to the resistance [10, 11].

4. Discussion and conclusions

Both positive [16, 17] and negative [10, 11, 18] contributions of DWs to the resistance have been recently revealed experimentally in microstructures fabricated from (Ga,Mn)As films. Several authors studied theoretically the effect of electron scattering at DWs on resistivity of ferromagnetic metals and semiconductors (cf. [19] and references therein). Theoretical calculations predict generally a positive contribution of DW to the resistivity, which can be efficiently increased in the case of thin DWs (on the scale of the Fermi wavelength of conducting charges) in ferromagnetic semiconductors owing to the presence of spin-orbit interaction, as shown in [19]. In turn, (Ga,Mn)As epitaxial films demonstrate extremely simple domain structure with large domains of the size of hundreds of micrometers, and thin and well-defined DWs [20]. The DW thickness in (Ga,Mn)As films has been determined to be about 15 nm both for the Bloch [21] and Néel wall [22], and almost independent of both the temperature and Mn content. This value is by a factor of two larger than the estimated value of Fermi wavelength in our (Ga,Mn)As film. In view of the above results, we believe that the jumps of enhanced resistance appearing in our reference device at the magnetic field corresponding to the coercive fields, i.e. when DWs are just nucleated, result from a DW contribution to the (Ga,Mn)As film resistance.

On the other hand, Tatara and Fukuyama [23] first predicted that a DW can destroy the charge-carrier phase coherence necessary for the quantum weak localization (WL), what leads to a negative contribution of DW to the resistivity. WL can coexist with ferromagnetism in our (Ga,Mn)As film. The maximum value of an internal magnetic induction, $B_{\mathrm{int}} \approx \mu_0 M_{\mathrm{s}} = 11$ mT, estimated from the magnitude of saturation magnetization, M_{s}, obtained from our SQUID measurements (Fig. 1), is small enough to be generally neglected in a WL correction to resistivity. An external magnetic field suppresses WL as it introduces a phase difference between the time-reversed paths, proportional to the enclosed magnetic flux, thus giving rise to an apparent negative MR. Consequently, we propose that the high bump of increased resistance occurring for the constricted device around $H = 0$ results from a contribution of WL in the constriction to the resistance.

In the constricted devices DWs tend to localize themselves in the constriction in order to minimize their energy, cf. [24], and their width, which is essentially determined by the constriction size, is of the order of the constriction width. Thus, the appearance of the jumps of reduced resistance imposed on a background of the bump of increased resistance in the constricted device can be understood as due to erasure of the quantum localization by a DW located at the constriction. Each region of a reduced resistance would extend over the field range, in which the DW remains pinned at the constriction.

In conclusion, we have argued that both the jumps of an enhanced resistance in the reference device and those of a reduced resistance in the constricted devices, which appear when the sweeping magnetic field crosses the regions of the coercive field of the film, represent a DW contribution to the (Ga,Mn)As film resistance. The opposite sign of this contribution revealed in the reference and constricted devices results from different properties of DWs formed in the two types of structures. Thin DWs formed in the non-constricted (Ga,Mn)As film give rise to the positive contribution to the film resistance. On the other hand, the diffusive charge transport through a thick DW pinned at the constriction results in the erasure of quantum localization effects, thus giving rise to the negative contribution of DW to the resistance in the constricted device.

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