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Magnetoresistive memory in ferromagnetic (Ga,Mn)As nanostructures

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Magneto-resistive nanostructures have been investigated. The structures were fabricated by electron beam lithography patterning and chemical etching from thin epitaxial layers of the ferromagnetic semiconductor (Ga,Mn)As, in shape of three nanowires joined in one point and forming three-terminal devices, in which an electric current can be driven through any of the three pairs of nanowires. In these devices, a novel magneto-resistive memory effect has been demonstrated, related to a rearrangement of magnetic domain walls between different pairs of nanowires in the device consisting in that its zero-field resistance depends on the direction of previously applied magnetic field. The nanostructures can thus work as two-state devices providing basic elements of nonvolatile memory cells.

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

1. Introduction

Discoveries of the giant magnetoresistance (GMR) effect [1] and the magnetoresistance tunnel junction (MTJ) [2] gave rise to the emerging field of magnetoelectronics. Based on these phenomena, multilayer devices composed of metallic ferromagnets have been successfully applied for development of magnetic sensors and nonvolatile random access memory cells [3]. On the other hand, recent advance in the low-temperature molecular beam epitaxy (LT-MBE) growth of ferromagnetic semiconductors based on III–V compounds [4] brought about a possibility for integrating electronic and magnetoelectronic devices, providing thus a basis for combining semiconductor-based information processing and magnetic-based data storage on the same chip.

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One of the most promising model semiconductors, in this respect, is (Ga,Mn)As, in which a few percent of Ga lattice atoms have been substituted by Mn impurities. Below a magnetic transition temperature, T_C, substitutional Mn^{2+} ions are ferromagnetically ordered owing to the interactions with polarized mobile charge carriers (holes) [5, 6]. The hole density, which is a fraction of the Mn concentration, influences all the magnetic properties of this semiconductor, including both the magnetic anisotropy and T_C. Although the highest T_C in (Ga,Mn)As remains so far below 200 K, it is expected that further optimization of the MBE-growth conditions and post-growth annealing will succeed in obtaining (Ga,Mn)As layers showing room-temperature ferromagnetism [7].

One of the rapidly growing directions of research that includes ferromagnetic semiconductors is the dynamics of individual magnetic domain wall (DW), i.e. a region of inhomogeneous magnetization, separating two ferromagnetic domains of different (homogeneous) magnetizations in nanowires [8–10]. In ferromagnetic nanowires, the magnetic shape anisotropy, caused by the long-range dipole interaction between localized magnetic moments, usually dominates over an intrinsic anisotropy of crystalline material. Thus, direction of magnetization is forced to be oriented along the wire axis. DW contributes an extra resistance to a wire, and, on the other hand, DW passing through a wire leads to the reversal of the direction of magnetization. Importantly, a DW motion in a wire can be actuated not only by a magnetic field but also by an electric current pulse.

In this paper, we demonstrate a novel magneto-resistive memory effect that appears in lithographically patterned nanowires forming a three-arm nanostructure, fabricated from ferromagnetic (Ga,Mn)As layers, and is related to a rearrangement of magnetic DWs between different pairs of nanowires in the structure.

2. Experimental

The nanostructures investigated in this work are junctions of three nanowires joined in one point at the angle of 120° (Fig. 1). That three-arm device (TAD) is frustrated in the sense that, upon going along any pair of the arms, one meets always with such a pair for which the direction of magnetization is reversed at the junction. In consequence, an electric current passing through that pair has to cross a magnetic DW at the junction.

We fabricated the TAD structures from a monocrystalline, 15 nm thick, $Ga_{0.96}Mn_{0.04}As$ layer grown by the LT-MBE method on the (001) face of GaAs substrate [11]. Such grown layers suffer from a compressive strain caused by a lattice mismatch on the interface and exhibit an in-plane easy axis of magnetization. The (001) face, being the plane of the layer, has crystalline symmetry of a square, which is not compatible with triangular shape symmetry of the TAD structure. So, all three arms of TAD cannot be fully magnetically equivalent owing to an additional in-plane magneto-crystalline anisotropy of (Ga,Mn)As layer imposed on the shape anisotropy of the device.

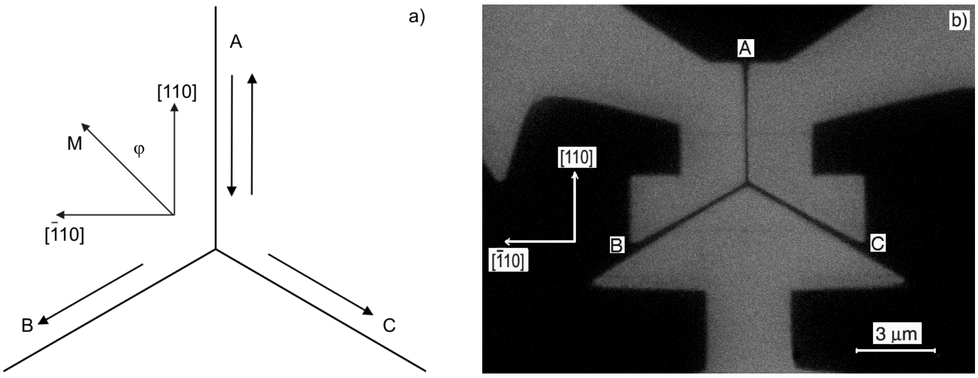

Fig. 1. Three-arm nanostructure: a) schematic view where arrows represent magnetization vectors, b) scanning electron microscope image where the darker contrast corresponds to the non-etched conducting areas of the structure

(Ga,Mn)As layers display rather complicated magneto-crystalline anisotropy, which changes with temperature, hole concentration, and even post-growth annealing. Based on recent thorough investigations [12–15] we may accept the following scheme of magneto-crystalline anisotropy in the investigated layer at liquid helium temperature. There are two equivalent easy axes along two in-plane ⟨100⟩ crystallographic directions (cubic anisotropy). Surprisingly, there is no magnetic equivalence between the [110] and [$\bar{1}$10] directions (uniaxial anisotropy). We indeed observed this non-equivalence in (Ga,Mn)As layers, similar to that used for the fabrication of TADs, by finding that the remnant magnetization and the coercive field are distinctly larger for [$\bar{1}$10] than for [110] direction [15]. Consequently, we have assumed that the in-plane directions ⟨100⟩ and [$\bar{1}$10] correspond to easy magnetization axes in our layer, while the [110] direction is the hard axis.

Accordingly, we designed the TAD structure in such a way that one arm, *A*, was along the [110] direction, i.e. along the hard axis, whereas arms *B* and *C* were oriented close to the [100] and [010] easy axes (Fig. 1a). Thus, the directions of magnetization in arms *B* and *C* are expected to be locked, while magnetization direction along the arm *A* can be easily switched into opposite one by a weak magnetic field. The structures having three arms, each about 200 nm wide and 3 to 5 µm long, were fabricated using electron-beam lithography patterning and chemical etching. The arm terminals were supplied with Ohmic contacts and we measured the resistance, *R*, between each pair of arms at the liquid helium temperature in function of a magnetic field, *H*, applied along the arm *A* in either of the two opposite directions. The results presented in this paper refer to the device with the arm length of 5 µm, whose scanning electron microscope image is shown in Fig. 1b. Additionally, we measured magnetization, *M*, of the investigated (Ga,Mn)As layer in function of *H* parallel to the [110] direction, using a superconducting quantum interference device (SQUID) magnetometer, whose run is shown in the inset in Fig. 2. The magnetic transition temperature of about 60 K was estimated from temperature dependence of sheet resistance of the layer.

3. Results

In strong magnetic fields our structures exhibit a pronounced negative magnetoresistance (MR), i.e. their resistivity decreases monotonously with field intensity, up to the highest available fields, as shown in Fig. 2. This is a common property of ferromagnetic (Ga,Mn)As layers [4,16,17], which is generally understood as a reduction of spin disorder scattering of charge carriers caused by ordering of localized Mn spins in an external magnetic field – a mechanism well known in ferromagnetic metals. Another mechanism which can dominate at the lowest temperatures is the magnetic field induced destruction of quantum interference contribution to the resistivity caused by the effect of weak localization [16,17]. MR features characteristic of individual samples appear only in a narrow range of magnetic field enclosing magnetization hysteresis. All the results presented hereafter refer to that weak-field range, but one must remember that they are imposed on a pronounced negative-MR background.

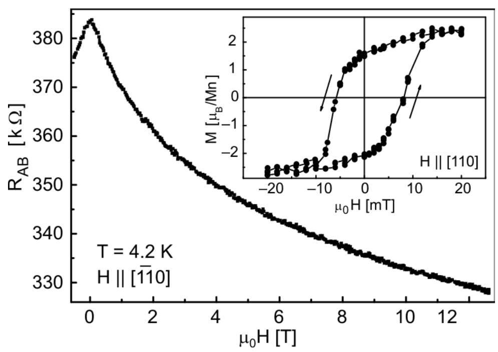

Fig. 2. Electrical resistance R_{AB} measured between terminals of the arms *A* and *B* of the TAD nanostructure in function of the in-plane magnetic field oriented perpendicular to the arm *A*. The resistance was measured applying a probing ac voltage of about 3 mV. Inset: magnetization hysteresis loop for $Ga_{0.96}Mn_{0.04}As$ layer measured with a SQUID magnetometer at 5 K after subtraction of diamagnetic contribution from the GaAs substrate

The most striking result observed in the TAD structures is the symmetry of the *R*(*H*) curves, which appears for the *AB* and *AC* pairs of arms. It is seen in Fig. 3 that the reversal of the direction of magnetic field applied parallel to arm *A*, is equivalent to the exchange of the pairs *AB* into *AC* and vice versa. All the *R*(*H*) curves display characteristic hysteresis loops corresponding to the hysteresis loops of magnetization. A remnant resistance should be noticed, an analogue to the remnant magnetization, that appears in zero magnetic field. This means that the resistance of either two pairs of arms can assume one of two stable values, depending on the previous magnetization direction in arm *A*. For comparison, we also show in Fig. 4 the *R*(*H*) curves for the *BC* pair at two opposite runs of the magnetic field applied parallel to the arm *A*, which do not display any remnant resistance. From the results presented in Figs. 3 and 4 we can deduce the coercive field in the nanostructure of about 12 mT for the magnetic field along the [110] axis, larger than the coercive field of about 8 mT for the (Ga,Mn)As layer; cf. inset in Fig. 2. This increase in coercivity obviously results from a contribution of the shape anisotropy of the nanowires to the layer magneto-crystalline anisotropy.

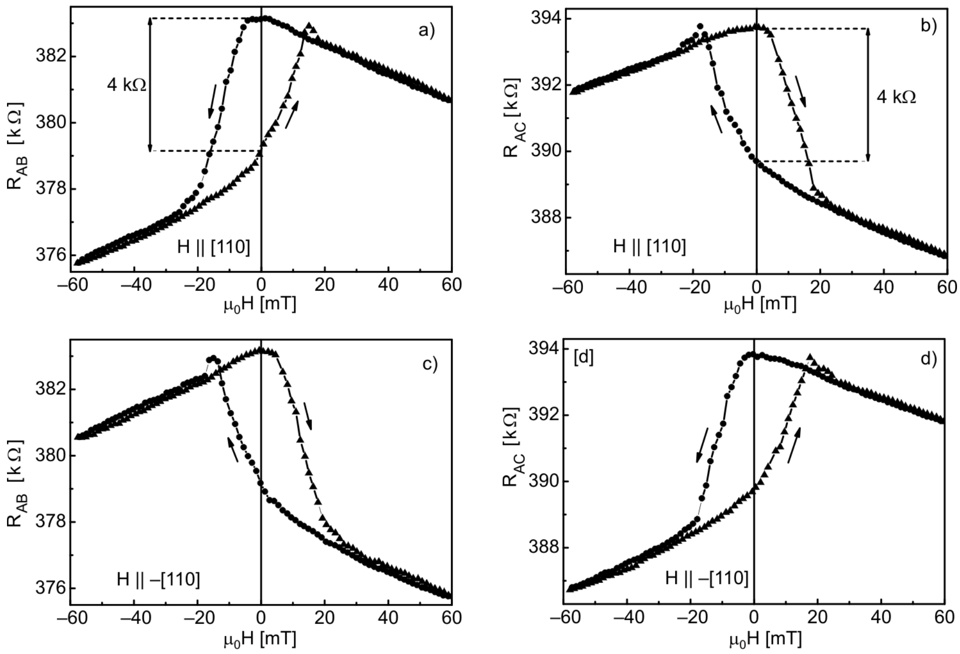

Fig. 3. Electrical resistances R_{AB} (a, c), and R_{AC} (b, d) measured between terminals of the respective arms *AB* and *AC* of the device in function of the magnetic field oriented along the arm *A* swept in two opposite directions (differentiated by triangles or circles). The direction of the magnetic field in (c) and (d) was reversed with respect to the cases (a) and (b). The magnitude of remnant resistance at zero magnetic field is marked

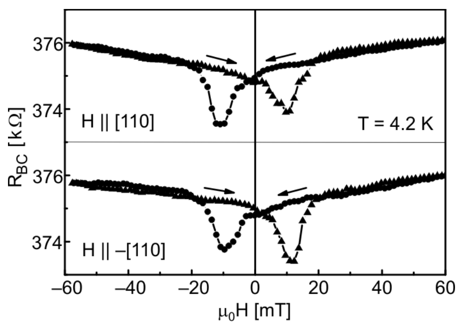

Fig. 4. Electrical resistance R_{BC} measured between terminals of the arms *B* and *C* of the device in function of the magnetic field oriented along the arm *A* swept in two opposite directions (differentiated by triangles or circles). The direction of magnetic field in the lower plot was reversed with respect to that of the upper plot. No remnant resistance appears

In the TAD nanostructure we have thus realized a bistable device, or a switch, in which momentarily applied weak magnetic field triggers transition from a lower to higher resistance in one pair of the arms and the opposite transition in the other pair. It is worth noting that the resistance jumps at the transition (remnant resistances) are very nearly the same for the both arm pairs (4 kΩ in the structure whose characteristics are shown in Fig. 3) despite their total resistances differing by several percent. Although the relative change in resistance at the jumps is rather small in the structures now fabricated, we hope it can be essentially enhanced by a suitable modification of the device geometry.

4. Discussion

By virtue of previous argumentation, an explanation of the observed behaviour of the TAD structure is straightforward. Epitaxial layers of (Ga,Mn)As display very simple domain structure even at macroscopic length scales. Therefore we may assume that each arm of TAD contains a single magnetic domain [18]. Because the arms *B* and *C* are oriented closely to the easy axes, the sense of magnetization vectors along the arms *B* and *C* has to be conserved independently of the magnetization direction in the arm *A* that is collinear with the hard axis. Whatever the latter direction, DW must always appear between relevant arms: either *A* and *B*, or *A* and *C*. This wall separates regions of (almost) opposite directions of magnetization, which may differ also in the magnitude of remnant magnetization. DW contributes an extra resistance to the total resistance of a wire. Thus, the effect appearing in TAD consists in a switching DW located at the junction from one current path into the other, i.e. from *AB* into *AC* or vice versa, driven by the reversal of magnetization direction in arm *A*. Accordingly, the remnant resistance marked in Fig. 3 represents the magnitude of the resistance of DW involved in this process. Its value, counted for unit area of DW, is about 12 $\Omega\cdot\mu m^2$.

The origin of the intrinsic resistance connected with DW in ferromagnetic materials has been of interest for many years. Nowadays this problem is attracting an increasing attention since DWs are expected to become important ingredients of future spintronic devices [19, 20]. In general, different effects can contribute to the DW resistance in a given material, in proportion depending crucially on such factors as diffusive or ballistic transport, the ratio of the Fermi wavelength of charge carriers to the DW width, and others. In ferromagnetic (Ga,Mn)As layers, the spin-dependent scattering of charge carriers, like that appearing in the GMR effect, is possibly an essential cause of the DW resistance [21, 22]. Interestingly, a contribution of DW to the wire resistance can also be negative [23, 24]. It occurs in the case when the dominant effect of DW is the local destruction of quantum weak localization of charge carriers passing through the wall [25]. A more detailed analysis of the DW configuration and geometry of spontaneous magnetization in our TAD structures, taking into account both magneto-crystalline and shape anisotropy constants, has been given elsewhere [26].

5. Conclusions

For the first time an effect of hysteretic magnetoresistance in (Ga,Mn)As nanostructure has been demonstrated, in which the zero-field resistance depends on the direction of previously applied magnetic field. The three-arm device that realizes this effect is in essence a two-state device, a basic memory element, in which a bit of information can be written magnetically and read electrically. It represents also a three-terminal device that has two complementary outputs, what means that when one pair of arms is in a high-resistance state, the other is in the low-resistance state, and vice versa.

Further effort is to be aimed at creation of the TAD structure fully controlled electrically, without the necessity of application of a magnetic field. The idea is to switch DW from one pair of arms to the other by passing a current pulse through relevant pair. This idea is motivated by the effect predicted theoretically [27, 28] and verified experimentally [8–10] that an electric current exerts a dragging force on a domain wall in a wire. Here, the crucial fact is that the critical current density necessary for actuation of the DW motion in (Ga,Mn)As layers is much lower ($\leq 10^5$ A·cm^{-2}) than that in metallic ferromagnets [10, 28].

References

[1] BAIBICH M.N., BROTO J.M., FERT A., NGUYEN VAN DAU F., PETROFF F., EITENNE P., CREUZET G., FRIEDERICH A., CHAZELAS J., Phys. Rev. Lett., 61 (1988), 2472.
[2] MOODERA J.S., KINDER LR.., WONG T.M., MESERVEY R., Phys. Rev. Lett., 74 (1995), 3273.
[3] PRINZ G.A., Science, 282 (1998), 1660.
[4] OHNO H., J. Magn. Magn. Mater, 200 (1999), 110.
[5] DIETL T., OHNO H., MATSUKURA F., Phys. Rev. B, 63 (2001), 195205.
[6] KITCHEN D., RICHARDELLA A., TANG J.-M., FLATTÉ M.E., YAZDANI A., Nature, 442 (2006), 436.
[7] JUNGWIRTH T., WANG K.Y., MAŠEK J., EDMONDS K.W., KÖNIG J., SINOVA J., POLINI M., GONCHARUK N.A., MACDONALD A.H., SAWICKI M., RUSHFORTH A.W., CAMPION R.P., ZHAO L.X., FOXON C.T., GALLAGHER B.L., Phys. Rev. B, 72 (2005), 165204.
[8] YAMANOUCHI M., CHIBA D., MATSUKURA F., OHNO H., Nature, 428 (2004), 539.
[9] HONOLKA J., MASMANIDIS S., TANG H.X., ROUKES M.L., AWSCHALOM D.D., J Appl Phys., 97 (2005), 063903.
[10] YAMANOUCHI M., CHIBA D., MATSUKURA F., DIETL T., OHNO H., Phys. Rev. Lett., 96 (2006), 096601.
[11] SADOWSKI J., DOMAGAŁA J.Z., Phys. Rev. B, 69 (2004), 075206.
[12] WELP U., VLASKO-VLASOV V.K., MENZEL A., YOU H.D., LIU X., FURDYNA J.K., WOJTOWICZ T., Appl. Phys. Lett., 85 (2004), 260.
[13] SAWICKI M., WANG K.-Y., EDMONDS K.W., CAMPION R.P., STADDON C.R., FARLEY N.R.S., FOXON C.T., PAPIS E., KAMIŃSKA E., PIOTROWSKA A., DIETL T., GALLAGHER B.L., Phys. Rev. B, 71 (2005), 121302(R).
[14] WANG K.-Y., SAWICKI M., EDMONDS K.W., CAMPION R.P., MAAT S., FOXON C.T., GALLAGHER B.L., DIETL T., Phys. Rev. Lett., 95 (2005), 217204.
[15] WOSIŃSKI T., MĄKOSA A., SADOWSKI J., PELYA O., OSINNIY V., FIGIELSKI T., TERKI F., HERNANDEZ C., CHARAR S., J. Alloys Compd., 423 (2006), 248.

[16] MATSUKURA F., SAWICKI M., DIETL T., CHIBA D., OHNO H., Physica E, 21 (2004), 1032.
[17] PELYA O., WOSIŃSKI T., FIGIELSKI T., MĄKOSA A., MORAWSKI A., SADOWSKI J., DOBROWOLSKI W., SZYMCZAK R., WRÓBEL J., TÓTH A.L., J. Alloys Compd., 423 (2006), 252.
[18] GOENNENWEIN S.T.B., RUSSO S., MORPURGO A.F., KLAPWIJK T.M., VAN ROY W., DE BOECK J., Phys. Rev. B, 71 (2005), 193306.
[19] VIGNALE G., FLATTÉ M.E., Phys. Rev. Lett., 89 (2002), 098302.
[20] RÜSTER C., BORZENKO T., GOULD C., SCHMIDT G., MOLENKAMP L.W., LIU X., WOJTOWICZ T.J., FURDYNA J.K., YU Z.G., FLATTÉ M.E., Phys. Rev. Lett., 91 (2003), 216602.
[21] LEVY P.M., ZHANG S., Phys. Rev. Lett., 79 (1997), 5110.
[22] CHIBA D., YAMANOUCHI M., MATSUKURA F., DIETL T., OHNO H., Phys. Rev. Lett., 96 (2006), 096602.
[23] TANG H.X., MASMANIDIS S., KAWAKAMI R.K., AWSCHALOM D.D., ROUKES M.L., Nature, 431 (2004), 52.
[24] WOSIŃSKI T., FIGIELSKI T., PELYA O., MĄKOSA A., MORAWSKI A., SADOWSKI J., DOBROWOLSKI W., SZYMCZAK R., WRÓBEL J., Phys. Stat. Sol. (a), 204 (2007), 472.
[25] TATARA G., FUKUYAMA H., Phys. Rev. Lett., 78 (1997), 3773.
[26] FIGIELSKI T., WOSIŃSKI T., MORAWSKI A., MĄKOSA A., WRÓBEL J., SADOWSKI J., Appl. Phys. Lett., 90 (2007), 052108.
[27] TATARA G., KOHNO H., Phys. Rev. Lett., 92 (2004), 086601.
[28] NGUYEN A.K., SKADSEM H.J., BRATAAS A., Phys. Rev. Lett., 98 (2007), 146602.

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